CO2
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CCU

Polymers case study

Part B: polycarbonates and polyols

30/06/2025

1 Introduction

This case study addresses the use of CO_2 as a feedstock in the production of **polycarbonates and polyols**, which are used primarily for engineering plastic applications and as a building blocks in polyurethanes (PUR), respectively. Polycarbonates (PCs) are thermoplastic polymers with an adequate balance of properties such as good thermal resistance, excellent mechanical properties, and high optical transparency, which make them suitable as materials for commodity and engineering plastics. Bisphenol A-based PC is the most widely used polycarbonate.[1] On the other hand, polyols are essential raw materials for the preparation of flexible and rigid PUR foams, being one of the most versatile polymers used in many different sectors and application areas; coatings, paints, adhesives, footwear, insulation, automotive and biomedical components, etc. CO_2-based polyols are being developed as a sustainable alternative to traditional petroleum-based polyols in PUR foams. The characteristics of these foams largely depend on the types and properties of polyols.[2]

This CCU route is based on the **copolymerization of epoxides and CO_2**, leading to high selectivity (>90%) toward valuable polymer products. The synthesis of these CO_2-based polymers is based on the direct incorporation of CO_2 into the backbone of polymers or polymer precursors instead of breaking the strong C=O bonds in CO_2 using significant amounts of H_2, which applies to most conventional CCU pathways involving CO_2 hydrogenation (e.g., for methanol) or Fischer–Tropsch synthesis (e.g., in the context of e-fuel production). Therefore, this non-reductive approach has the advantage of a **low energy demand** compared to most other CCU methods since no H_2 is required. A second advantage is that most of these CO_2-based polymers are used in sectors with a long lifespan, for instance the use of PUR as insulation material in the construction sector. According to product lifetime distributions[3], CO_2 could easily be stored for decades and would in theory be eligible for carbon removal certifications (minimum storage duration of at least 35 years is required)[4]. In any case, these CO_2-based products could play their role in **long-term CO_2 storage** compared to common packaging plastics (such as PE, PP, PS or PET). In some cases, as in the production of aromatic CO_2-based polycarbonates, the synthesis procedure also appears to be **more eco-friendly** than the conventional method as the use of toxic phosgene is avoided.

2 Technology description

2.1 Overview

The direct chemical utilization of CO_2 as a co-monomer in polymerization reactions to yield tailor-made materials seems to be a particularly promising approach. Depending on the catalyst and the reaction conditions, the products of epoxide/CO_2 copolymerization can be either strictly alternating **polycarbonates (PC)** or **polyethercarbonates (PEC)** containing carbonate as well as ether linkages (Figure 1). In the presence of a multifunctional (or polyhydric) alcohol (e.g. glycerol), **polycarbonate (PC) polyols** or **polyethercarbonate (PEC) polyols** could be synthesised. The copolymerisation reaction of CO_2 and epoxides is strongly exothermic.[5] CO_2 efficiency for polymerisation can reach 85–95%, depending on formulation. In both reactions, cyclic carbonates may form as byproducts; however, their

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[1] Liu Y. et al. (2022), Chemical recycling to monomers: Industrial Bisphenol-A-Polycarbonates to novel aliphatic polycarbonate materials

[2] Lee D.H. et al. (2020), Carbon Dioxide Based Poly(ether carbonate) Polyol in Bi-polyol Mixtures for Rigid Polyurethane Foams

[3] Geyer R. et al. (2017), Production, use, and fate of all plastics ever made

[4] Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products

[5] Langanke et al. (2014), Carbon dioxide (CO_2) as sustainable feedstock for polyurethane production

formation is significantly reduced when specific catalysts are used, leading to relatively high selectivity toward polymers or polyols.[6]

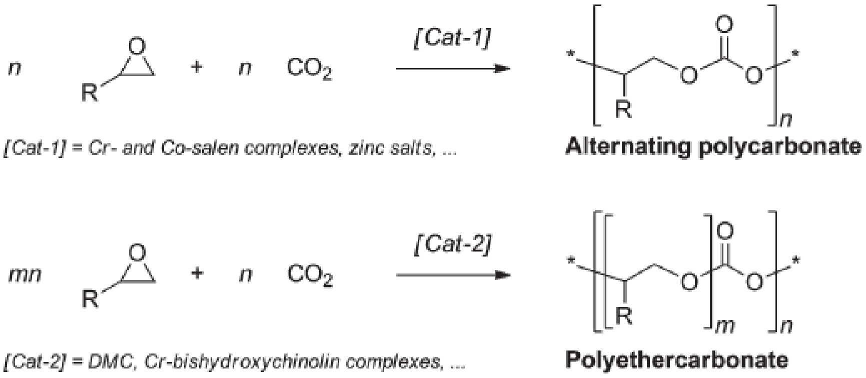

Figure 1. Copolymerization of epoxides and CO_2 to (top) alternating polycarbonates and (bottom) polyethercarbonates (= end group, m > 1). Adding a multifunctional alcohol as starter results in the formation of polycarbonate polyols and polyethercarbonate polyols (same principle).*[5]

Polyethercarbonate polyols produced from CO_2 and epoxides offer a sustainable alternative to conventional petroleum-derived polyether or polyester polyols, which are currently used in most PUR foams. Thus, the substitution of conventional polyols with CO_2-based polyols typically does not constitute a direct one-to-one replacement. Due to differences in chemical structure and polymer architecture, the resulting PUR foams may exhibit altered physicochemical properties, including variations in flexibility, tensile strength, and thermal stability. Consequently, additional formulation development and application-specific testing are often required to tailor the CO_2-based polyols to meet or even improve the performance criteria of traditional polyol/PUR systems.

The amount of CO_2 incorporated can reach up to 50% by weight for polyethylenecarbonate, an aliphatic PC, while aromatic PC have a lower CO_2 content (<20 wt%). Also polyols could have a CO_2 share between 20-50 wt%.[7] An LCA study conducted by von der Assen and Bardow (2014) reveals GHG reductions of 11-19% for a polyol with 20wt% CO_2 content compared to conventional polyether polyols (including CO_2 capture and compression).[6] The largest contributor to the total emissions for both polyols is the production of the fossil epoxides. The technology is at TRL 8–9, indicating it is already in the commercial deployment phase (see chapter 3 for commercial producers).

The reaction of epoxide and CO_2 can also be directed towards the formation of **cyclic carbonates**, which in previous mentioned copolymerisation reactions were considered as a byproduct. Specific catalysts are employed for the cycloaddition of CO_2 to epoxides (figure 2).

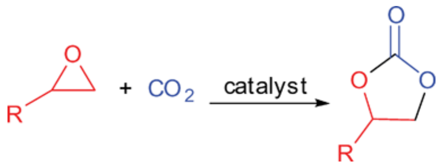

Figure 2. Synthesis of cyclic carbonates through cycloaddition of CO_2 to epoxides.[8]

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[6] von der Assen N. et al. (2014), Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study

[7] *Nevander (2021), http://urn.fi/URN:NBN:fi:aalto-202103212397*

[8] Pescarmona P.P. (2021), Cyclic carbonates synthesised from CO_2: Applications, challenges and recent research trends

Cyclic carbonates have a broad range of applicability as solvent: in the context of green chemistry as a sustainable alternative to conventional, more harmful polar aprotic solvents such as DMF, DMSO etc. In addition, they can undergo base-catalysed ring-opening reactions with alcohols and amines:[8]

- reaction of cyclic carbonates with aliphatic alcohols leads to a transcarbonation, which provides a route to bisphenol-A-based polycarbonates.
- reaction of cyclic carbonates with aliphatic primary and secondary amines generates urethane groups. With a diamine, this reaction generates poly(hydroxy)urethanes (PHU), also known as **non-isocyanate polyurethanes (NIPU)**. These latter are considered as a greener alternative to the conventional synthesis of polyurethanes (based on the reaction of toxic isocyanates with polyols).

Commercial PCs and PURs make use of the highly toxic phosgene in their traditional production process, which is here eliminated. The CO_2 uptake is generally lower than in the polyol case, depending on the used epoxide linkages (large bis-epoxides which only incorporates two CO_2 molecules per cyclic carbonate)[9]. TRL is estimated at 4-5 with major part still in the research/exploratory phase.

Another example of CO_2-to-polymers is the **BECCU (Bio-Energy Carbon Capture and Utilisation)** project in Finland, which focuses on the synthesis of polyols using **biogenic CO_2** captured from a CHP (combined heat and power) process.[10] By integrating renewable carbon capture with polymer production, BECCU demonstrates a circular and low-carbon value chain for polyol synthesis suitable for use in polyurethane foams and coatings. The project aims to produce **polycarbonate polyols with up to 100% carbon from CO_2**, hence not only is CO_2 incorporated in the polymers, but also the epoxides will be produced from CO_2, which is more energy intensive (figure 3). BECCU showcases how carbon capture from renewable sources can be directly valorised into high-performance materials, aligning with EU goals on carbon circularity and industrial decarbonisation. The purpose of the project (ended in 2022) was to increase the TRLs of the studied unit processes (from 3-4 to 6) and develop the profitability of the concepts.

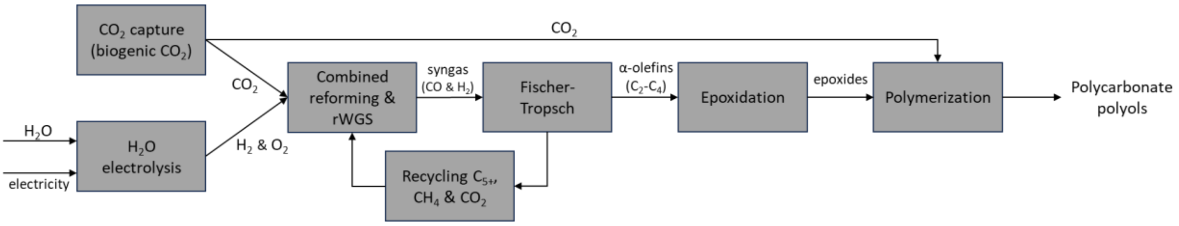

Figure 3. Block flow diagram of polyols (made from 100% CO_2 carbon)[10]

2.2 CO_2 input specifications

These catalytic conversions are usually quite sensitive to impurities and prefer high purity (>99%) and high CO_2 pressure (>15 bar) to operate optimally. A very high purity can reduce the pressure cost. Because metal-based catalysts are sensitive to traces of water, moisture must be kept as low as possible to prevent deactivation.[11]

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[9] Turnaturi R. et al. (2023), CO_2-derived non-isocyanate polyurethanes (NIPUs) and their potential applications

[10] Lehtonen J. et al. (2020), Polycarbonate polyols from biogenic CO_2 - Feasibility assessment

[11] https://patents.google.com/patent/US9260562B2/en

3 Market aspects

3.1 Market volumes & trends

The CO_2-based polymer market is expanding rapidly, with a 2/3 market share for polycarbonates and emerged as the fastest-growing segment.[12] CO_2-based polycarbonates are already commercially produced by several suppliers. Among them, aromatic polycarbonates—manufactured using technology licensed from Asahi Kasei—represent one of the largest production volumes, with an estimated capacity of 900 kt/year, accounting for approximately 16% of the global aromatic polycarbonate capacity. In parallel, multiple companies worldwide are producing aliphatic polycarbonates such as poly(propylene carbonate), which are used across diverse applications; high molecular weight PPC serves as a thermoplastic, while lower molecular weight grades are used as polycarbonate polyols, particularly in polyurethane foams and coatings.

According to nova-Institute[13], at least 14 companies—primarily located in Asia—are actively developing CO_2-based polycarbonates for commercial use. An overview of CO_2-based polycarbonates and polyols with current and expected production capacities are shown in Table 1. Commercial production of CO_2-derived polymers has already exceeded over **1 million tonnes**. Asahi Kasei, a Japanese company, alone is responsible for the majority of the volumes (about 70%), producing mainly aromatic polycarbonates, based on bisphenol A (BPA). Also quite some Chinese companies (e.g., Jinlong-Cas Chemical Co.) are investing heavily in this field. Covestro funded its own commercial plant in Dormagen (Germany), which went on stream in 2016 with an annual production capacity of 5000 tons of polyether carbonate polyol under the brand **Cardyon®**. The CO_2 used in the production of the polyol came from an ammonia-producing plant operated on the same site by the company Ineos. In the USA, NOVOMER is operating a commercial plant for polycarbonates and polyols.[13,14]

Table 1. CO_2-based polycarbonates and polyols: 2022 production capacity and 2030 outlooks[13]

Products	CO_2-based carbon content (%)	2022 Production capacity (kt/a)	2030 Outlook (kt/a)
Aromatic polycarbonates	5	900.5	1200
Aliphatic polycarbonates	11-12	120	300 (mostly PPC, PEC, high molecular weight)
Poly(ether)carbonate polyols	5-6	50	Increasing capacity (mainly low molecular for PUR)

In 2017 Dechema estimated that the potential global demand for poly(propylene carbonate) and cyclic carbonates to be around 50 and 80 kt/a (kilotons per annum), respectively.[14] The CO_2 requirement is approximately 0.43 t CO_2/t poly(propylene carbonate) and 0.50 t CO_2/t cyclic carbonate, which translates into a CO_2 demand of 21.6 kt/a, which is relatively minor (about 0.4% of the annual emissions from Port of Antwerp-Bruges today, 17 Mt CO_2 [15]). Based on the global production volumes for 2030 as mentioned above in table 1 (assuming a doubling of the polyol production compared to

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[12] https://www.techsciresearch.com/report/carbon-dioxide-based-chemicals-and-polymers-market/14529.html

[13] https://renewable-carbon.eu/news/the-rise-of-carbon-dioxide-co2-as-a-renewable-carbon-feedstock-more-than-1-3-million-tonnes-capacity-for-co2-based-products-already-exist-and-are-expected-to-at-least-quadruple-by-2030/

[14] Bazzanella et al. (2017), Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO_2

[15] https://www.portofantwerpbruges.com/en/our-port/climate-and-energy-transition/hydrogen

2022), CO_2 demand would only cover about 2% of the current CO_2 emissions in the Port of Antwerp. This suggests a rather scalable demand depending on market adoption.

According to the European Commission's 2021 "Sustainable Carbon Cycles" communication,[16] 20% of carbon used in chemicals and plastics should be from non-fossil sources by 2030. Currently, CO_2-based content in polymers is <0.1%, indicating significant upscaling potential for CO_2-based polymers. These materials provide an alternative or complement to bio-based chemicals in the pathway towards circular carbon use in the chemical industry. Another potential legislative driver is the **carbon removal certification framework** for storage of CO_2 in long-lived products (at least 35 years using atmospheric or biogenic CO_2).[4] Although this framework is mainly focused on permanent removals of CO_2 via CCS, CO_2 fixation in PUR insulation materials could in theory be eligible for certification. However, the actual certification of carbon removals is expected to begin in 2026, following the finalization of delegated acts defining methodologies for various carbon removal activities.

3.2 Commercial projects and pioneers

The industrial development of CO_2-based polymers has been driven by a few pioneering companies, such as Asahi Kasei and Covestro. Asahi Kasei was among the first to commercialize CO_2-based aromatic polycarbonates, developing technology to synthesize bisphenol-A (BPA)-based polycarbonates via a non-phosgene route. This method, which incorporates CO_2 through the use of dimethyl carbonate (DMC) as an intermediate, offers a safer and more sustainable alternative to traditional phosgene-based processes. The technology has been widely licensed and contributes a significant share of the global BPA-based polycarbonate market.

Covestro, on the other hand, advanced the field by developing and scaling up aliphatic CO_2-based polyethercarbonate polyols under the brand name Cardyon®[17]. These materials were used in applications such as polyurethane foams, coatings, and adhesives. Covestro achieved commercial production by incorporating up to 20 wt% CO_2 into the polymer backbone via the copolymerization of CO_2 with epoxides. However, despite its technological feasibility, Covestro is currently not pursuing this avenue[18], reportedly due to economic and strategic considerations, including the current lack of recognition for CO_2 stored in polymers under the EU Emissions Trading System (ETS). This highlights the challenges of bringing CO_2-based materials to market when carbon pricing and policy incentives do not yet fully support utilization pathways.

4 Economics

4.1 Key economic indicators

In literature, techno-economic studies were conducted for the production of CO_2-based polyethercarbonate polyols (20 wt% CO_2 content)[19] and polycarbonate polyols (close to 100% carbon from CO_2)[20]. Prices were normalized to 2025 using relevant inflation indices, and also electricity and raw materials prices (e.g., CO_2 feedstock price) were aligned for a consistent comparison between the two cases. Economic parameters (CAPEX and OPEX), together with energy consumption and CO_2 uptake (this is not the CO_2 footprint, but the capacity to embed CO_2) are found table 2.

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[16] https://climate.ec.europa.eu/system/files/2021-12/com_2021_800_en_0.pdf

[17] Driving with CO_2

[18] Presentation Jan Heijl (Covestro) on CCU pioneering sessions, 13/03/2025 (Ghent, Belgium) (Post | LinkedIn)

[19] Buchner G.A. et al. (2020), Techno-economic assessment of CO_2-containing polyurethane rubbers

[20] Nevander M. (2021), Process modelling and techno-economic evaluation of production of CO_2-based polycarbonate polyols

Table 2. Techno-economic parameters for two presented cases (adapted from existing literature)

	PEC polyols from CO_2 and petrol based epoxides	**PC polyols from CO_2 and H_2 (BECCU project)**
Energy use [GJ/t product]	1.3	95.2
CO_2 uptake [t CO_2/t product]	0.23	2.86
OPEX [EUR/t product]	1600-1700	3000-3200
CAPEX [EUR/t product]	150-160	450-600

From an economic perspective, polyether carbonate (PEC) and polycarbonate (PC) polyols have **different cost structures**. The main cost driver for PEC polyols is epoxide raw materials, whereas in the BECCU process polyols depend largely on energy costs, particularly the renewable energy required for H_2 production (assuming an electricity price of €70/MWh). The main energy costs in the PEC polyol production are the CO_2 compression (the copolymerisation reaction itself is exothermic) and the downstream processing of polyol product. As reference point, polypropylene glycol (a typical polyether polyol used in polyurethane manufacturing) is currently priced in the EU at around €1600/t[21]. It means that both routes, but in particular the CO_2 + H_2 based route, are more expensive than the conventional product. At the same time, that route delivers more CO_2 savings since all carbon in the polymer backbone is derived from CO_2. In other words, the route over CO_2 + fossil epoxides may deliver a short-term emission reduction while not requiring much renewable energy, while the CO_2 + H_2 may be an option for the longer term to realise more emission reductions.

In the early years of CO_2-based polyol production by Novomer in 2014 (i.e., Converge® PPC polyol), Novomer estimated a 20% cost reduction compared to the fossil-based polypropylene glycols due to savings in PO epoxides as raw material.[22] But it all depends if the savings from the epoxides are counterbalanced by the CO_2 raw material cost (high purity required), extra catalyst cost and, to a lesser extent, the higher energy cost. However, replacing conventional fossil-based PC polyols could be more promising, since these polyols are generally more valuable than other classes of polyols[23], with market estimates ranging from €2500 to 3000 per ton PC polyol.[20] Based on the preliminary TEA parameters in table 2, fully CO_2-based polyols (BECCU case) still struggle to compete with them. Due to the large amounts of H_2 required for polyol production, the economic viability of implementing such a process at industrial scale in Flanders or elsewhere in Europe remains limited under current market conditions.

Key challenge here is the high cost of (green) electricity (and the corresponding H_2 infrastructure). A general remark is the lack of consistent carbon valorisation mechanisms; use of fossil CO_2 in products is not recognised by the EU ETS or carbon removal certification framework. As a result, despite its climate benefits, this CCU pathway currently requires additional policy support or niche market incentives to become competitive with established fossil-based alternatives in the European industrial landscape.

4.2 Potential impact of on-site synergies

It seems advisable to put such production facilities close to a pipeline. Transport of CO_2 happens at elevated pressure and can even reduce the compression cost. A potential concern is whether the CO_2 transported via pipelines will comply with the purity specifications required for catalytic reactions, and whether an additional purification step can be avoided. At the moment, there is no commonly agreed specification for CO_2 transport by pipeline on the European level. Another option is sourcing low-cost

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[21] Propylene glycol price index - businessanalytiq

[22] Cherian A. (2014), *https://www.adhesivesmag.com/articles/93368-carbon-dioxide-based-polycarbonate-polyols-for-polyurethane-systems*

[23] https://www.gantrade.com/products/polyols/polycarbonate-polyols

CO_2 from nearby industrial plants with pure and high concentration CO_2 —for example, from ammonia (NH_3) or ethylene oxide (EO) production, where separation costs are low due to the high concentration of CO_2 in the process streams. In addition, there is also a need for storage infrastructure.

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