GIG KARASEK
A Member of Dr. Aichhorn Group

CO_2 utilization in industry

On the road to a decarbonized economy, there is no other option than to exploit the full range of what is technically feasible. The further development of efficient processes for capturing and utilizing CO_2 is one of the most promising solutions for driving forward the decarbonization of industrial processes.

This **white paper** provides you with information about the potential of capturing and utilizing CO_2 in industry, with a focus on converting CO_2 into useful products. The findings and results of this white paper provide valuable insights into how this innovative technology can help achieve a sustainable and decarbonized economy.

Chapter 1 highlights climate-related and economic aspects of the carbon dioxide problem, including the importance of CO_2 utilization for high-emission industries. **Chapter 2** describes the basic process of capturing and converting CO_2 into valuable products, followed by **chapter 3**, which covers the basics of the tremendous market potential for CO_2 products. **Chapter 4** examinespossible conversion technologies and comparisons between them are drawn. The last chapter is dedicated to the technical-economic analysis of CO_2 electrolysis and marketable CO_2 products.

SCAN ME

WHITE PAPER: CO_2 utilization in industry

The challenge: reducing CO_2 emissions

The release of CO_2 emissions from the burning of fossil fuels contributes significantly to the greenhouse effect and exacerbates climate change on a global scale. Companies that produce CO_2 emissions are required to pay for the emissions they create. Companies in emission-intensive industries are therefore looking for alternative strategies to reduce the costs associated with carbon emission prices.

The solution: innovative technologies for CO_2 utilization

Technologies for the capture and utilization of CO_2 offer enormous potential for reducing environmental impacts and, in combination with other technologies, can play a critical role in achieving emissions reductions. Furthermore, due to its unique properties, carbon dioxide is a versatile compound with a wide range of potential uses.

The utility: competitiveness through new market opportunities

The development of efficient methods for converting CO_2 into useful products can help both to reduce production-related CO_2 emissions and to increase the competitiveness of companies by opening up new market opportunities.

However, the technologies currently available for CO_2 capture and utilization are not yet sufficiently mature or efficient to meet the challenges of practical implementation. Nevertheless, there are convincing arguments that investments in this market can make sense for companies right now.

For this reason, GIG Karasek has initiated several research projects on the large-scale utilization of CO_2, with the aim of making the industrial application of electrochemical CO_2 utilization ready for the market. We are currently looking for cooperation partners for research and pilot projects to test the performance of the CO_2 conversion technology we have developed in a real industrial environment.

As a specialist for plant engineering in the field of thermal separation technology, we have the necessary know-how to obtain research results in an industrial environment as well as to produce CO_2 conversion products in high quality.

CONTENTS

1 The carbon dioxide problem

Minimizing the concentration of CO_2 in the atmosphere is one of the most important challenges of our time. One promising technology for mitigating climate change is carbon dioxide (CO_2) capture and utilization.

1.1 The necessity of CO_2 utilization

CO_2 emissions are the main drivers of global climate change. Around 37 billion tons of CO_2 were emitted worldwide in 2021. Of this, the EU-27 accounted for a total of 2.79 billion tons (Europe excl. EU-27: 2.51 billion tons, Germany: 674 million tons, Austria: 64 million tons). The resulting complex impacts will significantly affect not only society and ecosystems, but also the economy in the coming decades.

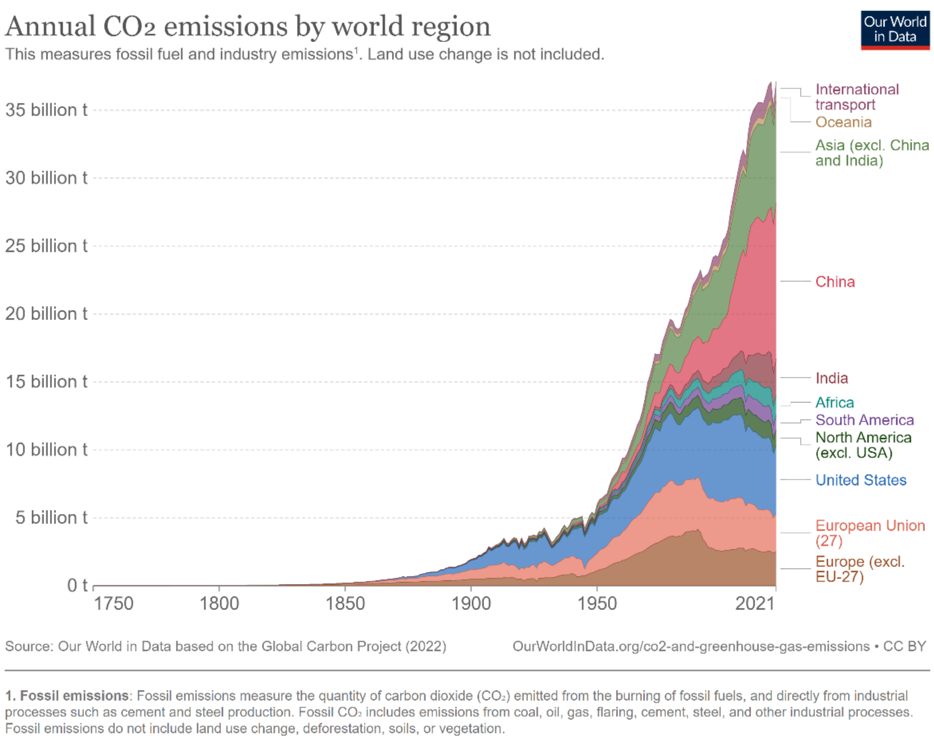

Figure 1: Total annual production-related CO_2 emissions excluding land-use changes.[1]

1.1.1 Record value of 421 ppm in 2021

Since the beginning of industrialization, more and more CO_2 has been emitted into the atmosphere worldwide through the combustion of fossil fuels. Natural carbon sinks such as oceans and forests, with their plants, algae, and microorganisms in the soil, are no longer able to bind or convert all of the additional CO_2 produced.

As a result, atmospheric carbon dioxide saturation has been steadily increasing, reaching another historic high in 2021. While in the 1950s the annual increase at the measuring station on Mauna Loa (Hawaii) averaged 0.55 ppm carbon dioxide, the world trend over the past 15 years has risen to an average of 2.24 ppm per year, and in Mauna Loa to 2.28 ppm per year. Compared to the 1950s, the global CO_2 increase has thus nearly quadrupled. The global CO_2 concentration has increased over the same period from about 315 ppm (1958) to the current 418.56 ppm (June 2022): an increase of about 100 ppm. This represents an increase of 30 percent. On April 8, 2021, the CO_2 concentration reached a record 421 ppm.[2]

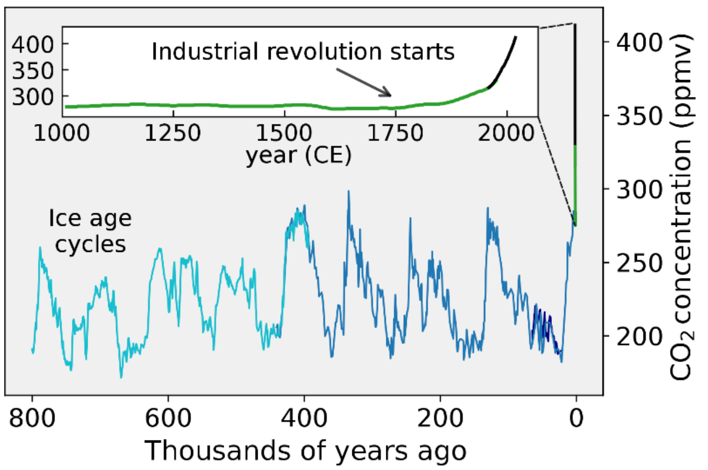

Figure 2: Increase in CO_2 concentration to 421 ppm in 2021. Adapted from [3].

1.1.2 Temperature increase by more than one degree

On a global average, the temperature of the earth's surface has already risen by more than one degree – despite enormous efforts over the last ten years. The goal of the Paris Climate Agreement is therefore not achievable by reducing CO_2 emissions alone.

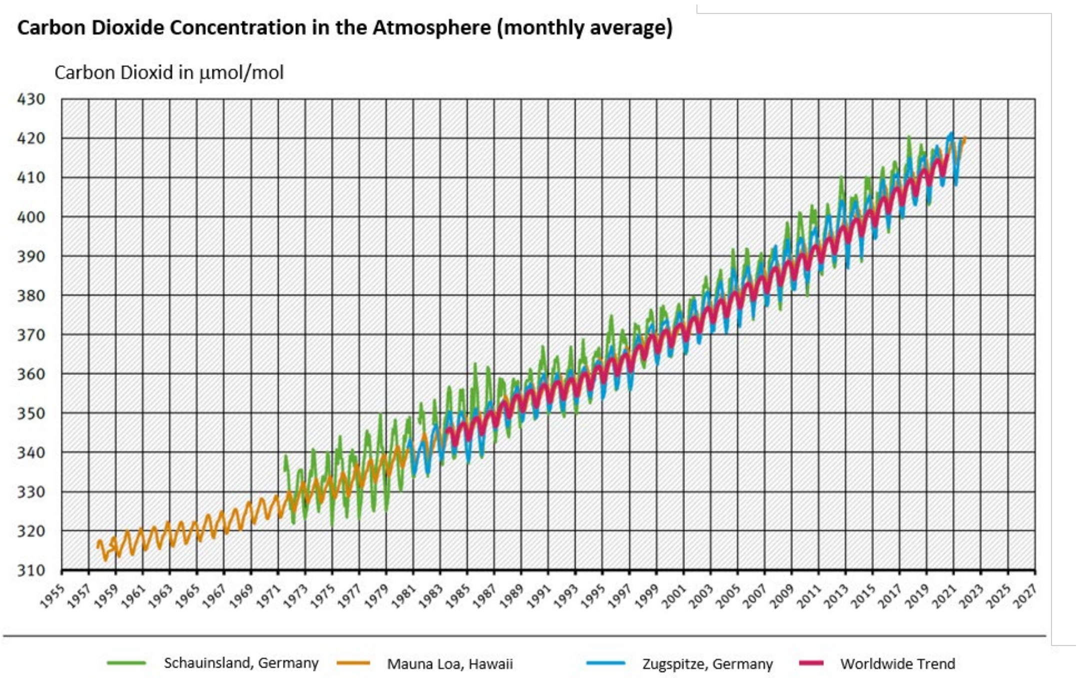

Figure 3: Monthly average atmospheric CO_2 concentration in Germany, Hawaii, and worldwide.[4]

1.1.3 The consequence: negative emissions of 10 Gt per year by 2050

The findings of the IPCC Special Report "*Global Warming of 1.5°C*" show that achieving net zero emissions by 2050 is not possible without large-scale deployment of CO_2 removal technologies:[5]

- To stabilize the climate, 10 Gt of CO_2 must be removed from the atmosphere annually by 2050, while not producing any new emissions at the same time.
- But even after that, the challenges will not abate, as a total of 730 Gt of CO_2 needs to be removed from the atmosphere from 2050 until 2100.
- This corresponds to about 20 times the amount of CO_2 that is emitted worldwide per year today.

As a result, no sector will be spared from making huge reductions in emissions. New technologies are needed to meet the required emissions targets. In addition to the energy and transport sectors, the CO_2 emissions of industry, especially those that are energy- and resource-intensive, are increasingly coming into focus.

One promising way to mitigate climate change is CO_2 capture and utilization (Carbon Capture and Utilization, or CCU for short). CCU refers to technologies that capture CO_2 from a gaseous medium, such as the atmosphere or flue gas, for subsequent conversion into valuable products.

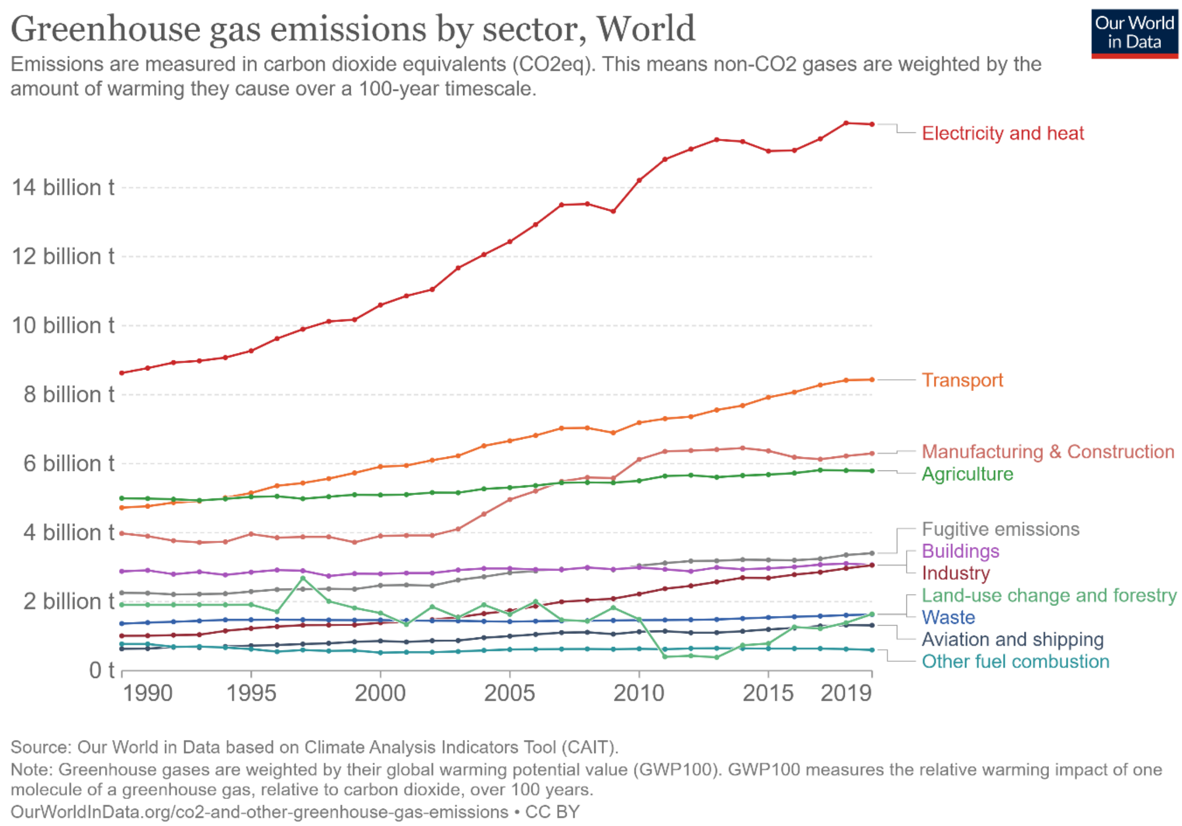

Figure 4: Global greenhouse gas emissions by sector based on the Climate Analysis Indicators Tool CAIT). Adapted from [6].

1.2 Economic aspects of the carbon dioxide problem

The consequences of climate change for businesses are of a diverse nature. Extreme weather phenomena can cause damage to production facilities, supply shortages, or supply chain disruptions. As society changes, new technologies, markets, and regulatory requirements emerge that create costs or have a direct impact on existing products, services, and assets. In particular, the rising carbon emission price is putting companies under increasing pressure.

1.2.1 CO_2 certificates at a record level

Europe introduced the European Emissions Trading System (EU ETS) for CO_2 taxation back in 2008. Under this scheme, all large electricity and heat producers and industrial plants, such as steel mills, chemical works, energy producers, or cement plants, are obliged to purchase CO_2 certificates.

The price of traded CO_2 certificates tripled over the course of 2021 and currently fluctuates between around 85 and 100 euros (as of May 23, 2023). The reason for the high demand for certificates is, on the one hand, the high gas prices, as a result of which electricity producers are switching to coal-fired generation. A significant part of the price increase is also due to policy reforms to meet European climate targets.

Figure 5: CO_2 emission allowances (in EUR) 7

1.2.2 Prices for CO_2 emission allowances set to climb further

The European Emissions Trading System (EU ETS) is a critical mechanism through which the EU intends to reduce net greenhouse gas emissions by 55 percent from 1990 levels by 2030. With the revision of the EU ETS as part of the "Fit for 55" package, further industries are to be included and free certificates are to be gradually phased out.[8]

Currently, there are still allocations of free certificates to avoid the migration of industrial operations to countries with less stringent emission restrictions (carbon leakage). In the future, the EU wants there to be less leeway in this regard: [9]

- By 2030, just under half of the free allocations will be eliminated, and by the end of 2034, there will be no free allocations at all for the high-emitting sectors covered by the new CO_2 tariff (Carbon Border Adjustment Mechanism – CBAM).
- The reform also envisages a gradual reduction in the quantity of CO_2 certificates in the EU Emissions Trading System (ETS-1) by 62 percent by 2030 compared with 2005 (previously 43 percent). In 2024, 90 million certificates will be withdrawn from the market, followed by another 27 million certificates in 2026.
- In addition, the total emissions cap will be lowered by 4.3 percent each year between 2024 and 2026, and then by as much as 4.4 percent starting in 2027.

The tightening of the supply of CO_2 allowances will exert considerable upward pressure on prices. It can therefore be assumed that carbon prices will rise much more dramatically in the future and that there is an urgent need for action for CO_2-intensive industries.

This is all the more true since efficient companies are to benefit from a free allocation, while inefficient plant operators must fear cuts if they do not implement measures.

The tightening of the EU ETS should thus be seen as a clear call to industry to invest now in decarbonizing their processes.

1.2.3 Successive increase in carbon taxes

In order to make fossil fuels more expensive and to promote climate-friendly alternatives, carbon taxes already exist in many European countries. With the National Emissions Certificates Trading Act 2022, the pricing of carbon emissions that are not already subject to the EU ETS was also introduced in Austria as of July 1, 2022.

The main products affected are gasoline, diesel, heating oil, natural gas, liquefied petroleum gas, coal, and kerosene. In the fixed price phase from July 2022 to 2025, the price per ton of CO_2 is predetermined. It will rise from 30 euros per ton from July 2022 to 55 euros per ton in 2025. From 2026, the price will then be determined by an emissions trading system.

1.3 CCU technologies for emission reduction

In recent years, large parts of the industries in Europe have developed strategies to decarbonize their companies and are already contributing to climate protection in a variety of ways. The focus is primarily on increasing energy efficiency and the increased use of renewable energies. However, these measures alone will not be enough to achieve the climate goals of the Green Deal.

1.3.1 The key role of energy-intensive industries

In order to limit the negative consequences of climate change and their costs, comprehensive solutions are required with regard to CO_2 management in companies. Energy-intensive or carbon-based industry is of particular importance in this context, as it plays a crucial role in the decarbonization of other sectors of the economy:

- If base materials are already produced in a climate-neutral way, this can reduce the carbon footprint of downstream economic activities.
- Furthermore, chemical base materials, steel, and cement are essential for the expansion of renewable energies.

Competitive technologies like CCU, in which process-induced CO_2 emissions do not occur in the first place, will therefore become indispensable in the future, especially in energy-intensive sectors. Not least in view of the revision of the European emissions trading system and rising carbon prices.

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1.3.2 Sustainable future model for carbon-based industries

The use of fossil fuel hydrocarbons as raw materials and energy sources is indispensable for many industries. Up to 75 percent of the manufacturing costs of various products are determined by the energy factor.

- As the price of carbon emissions rises, the production costs of energy-intensive industries in particular will inevitably increase.
- Were crude oil no longer to be processed in refineries as part of decarbonization, there would be a shortage of petrochemicals. Base products such as ethylene and methane, as well as all derivative products, would increasingly be subject to shortages (see Flowchart of chemicals / refinery).[10]

- CCU can accelerate decarbonization in the medium term as a bridging technology. In individual sectors, however, especially in the cement, steel, lime, and glass industries, emissions inevitably arise from energy-intensive industrial processes and are unlikely to be avoidable.
- In addition, there will continue to be products whose manufacture requires carbon, which is released again at the end of the product cycle. The length of time the CO_2 is locked up ultimately depends on the product. While in the case of fuels CO_2 is released again after days or weeks, this can take decades in the case of building materials.

CCU, as an important technology for achieving carbon neutrality, offers a solution towards managing unavoidable CO_2 emissions and meeting the ongoing demand for carbon-based products – without tapping into fossil sources.

CO_2 emissions from the industrial sector

Industrieller Sektor	Mt CO_2 per year produced
Cement	> 1.000
Oil refineries	850-900
Iron and steel	ca. 900
Fermentation	> 200
Ethene and other petrochemical processes	155-300
Ammonia	160
LNG sweetening	25-30
Ethylene oxide	10-15

Table 1: Oil refineries, cement, and steel industries offer the greatest potential for CO_2 utilization.[11]

1.3.3 Renewable carbon replacing fossil raw materials

Carbon becomes a renewable source through the utilization of CO_2 and meets the demand for carbon-based products, such as the chemicals in organic chemistry, in a less environmentally damaging way. CCU thus not only enables the avoidance of CO_2 emissions, but also replaces fossil raw materials (defossilization).

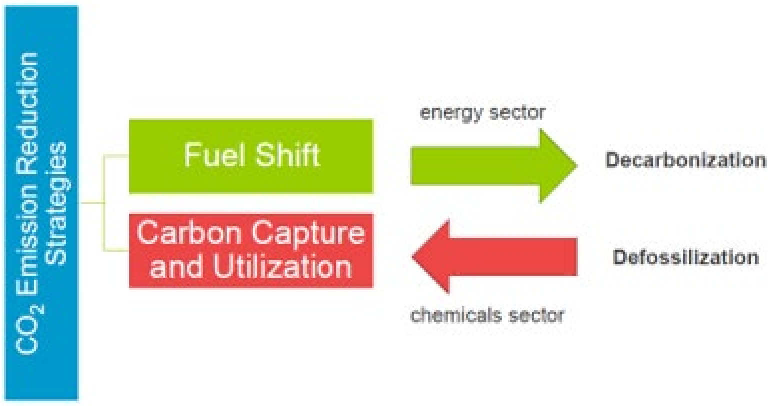


Figure 6: In the future, the carbon required for the production of chemicals and derivative products must come from renewable carbon (i.e., biomass, CO_2, and recycling of carbon-containing waste flows) rather than from fossil sources (in-house illustration).

1.4 Conclusion: investments in carbon-neutral technologies

Against the backdrop of drastically increased prices for CO_2 certificates, it is worth considering CCU technologies as an additional option, especially in carbon-based industries. Due to the successive shortage of freely allocated certificates, the share of purchased CO_2 certificates will increase over time, making investments in climate-neutral technologies necessary.

2 How to make CO_2 a valuable material again

The capture and subsequent utilization of CO_2 opens up a wide range of economic opportunities. CO_2 can be used as a raw material for a range of products and services, and its use can be direct or indirect by converting CO_2 into useful CO_2 products.

2.1 CO_2 sources and types of use

An example of the direct use of CO_2 is in fire-extinguishing systems or greenhouses. Indirect use includes the synthesis of energy sources and of basic chemicals or (intermediate) products of the chemical industry.

CO_2 can either be captured at polluters, for example in steel mills, or extracted from the air using direct air capture (DAC). The higher the proportion of CO_2 in the air, the easier it is to filter it out.

Since the CO_2 content in the atmosphere is very low at 0.04 percent, the cost of filtering it from the ambient air is correspondingly high. DAC will therefore remain a niche from the vantage point of the present.[12]

In comparison, CO_2 extraction from exhaust gases, where the concentration is usually more than 10 percent, is much cheaper than DAC. Capture point sources are the primary CO_2 sources, e.g., flue gas outflows in power plants or industrial processes that produce CO_2 as a by-product.

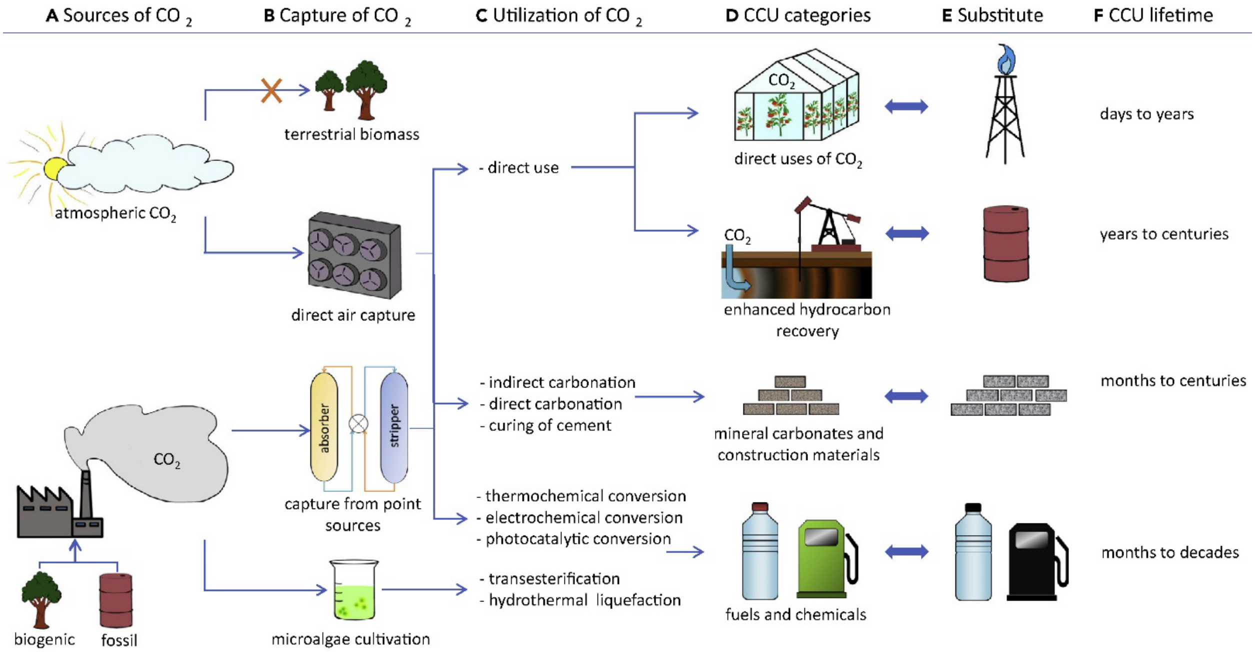


Figure 7: This overview includes CO_2 sources (A), CO_2 capture (B), and examples of utilization processes (C) leading to different CCU products in four categories (D), each with the substitute product in the conventional economy (E) and lifetime (F). Adapted from [13].

2.2 Entire CCU process using flue gas as an example

A CO_2 reduction system can be used in many industrial sectors. CCU is most easily implemented in industrial processes where CO_2 is concentrated and produced in large quantities as a flue gas. The diagram below illustrates the entire CCU process using the example of the electrochemical conversion of CO_2 from flue gas:

- → The flue gas is fed into the reactor cell, which is powered by green energy, and converted.
- → The resulting product outflow contains a wide variety of substances and must then be separated, distilled, and concentrated.
- → The end product is hydrogen, ethanol, methane, and other carbon-rich compounds. These can be further processed into plastics or stored as fuels and transported for further use as needed.
- → By-products include chemical raw materials such as formic acid, acetic acid, and a variety of other chemicals that can be sold on the market at high prices.

With this technology, companies can convert millions of tons of CO_2 per year into high-value chemical products that can be directly reused in industrial processes or alternatively used to manufacture a wide range of products.

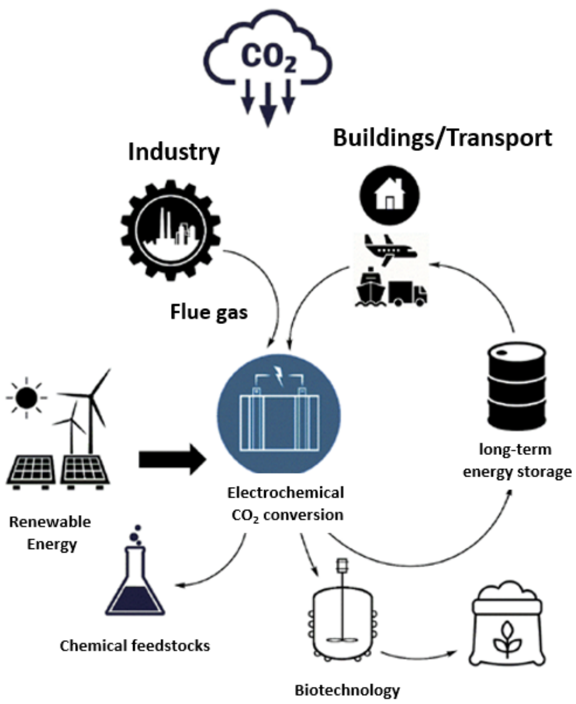


Figure 8: Entire process of CO_2 capture and utilization using the example of flue gas from industrial plants © JKU Linz [14]

2.3 Pilot plant for CO_2 conversion with novel catalysts

A pilot plant for the conversion of concentrated CO_2 into valuable products, which is being developed by GIG Karasek in cooperation with Johannes Kepler University Linz (JKU Linz), will soon demonstrate how this innovative technology can work. The pilot plant consists of an electrochemical reactor cell and associated periphery that act as the heart of the technology.

2.3.1 Research cooperation with JKU Linz

The project was launched by JKU Linz and GIG Karasek to make a sustainable contribution to reducing global CO_2 emissions. The goal is to recover CO_2 through electrochemical reduction into basic chemicals such as CO, formic acid, acetic acid, and fuels such as hydrogen, methane, methanol, and ethanol.

In addition to the development of novel catalysts, the research cooperation of this project includes the planning of a pilot plant for testing and optimizing the process solution. A first plant with several cells connected in series should be ready for industrial use by the end of 2023. The pilot plant in turn provides the basis for the design and dimensioning of large-scale industrial plants. A market launch is then possible on the basis of this scale-up concept.

2.3.2 Green, profitable process plant solution through "Dream Reaction"

The CO_2 is utilized by the so-called "Dream Reaction" with the aid of a specially designed electrocatalyst and a suitable reactor cell. If the electrical energy required for this conversion is supplied from renewable energy sources, this enables a completely sustainable and climate-friendly cycle.

Chemists refer to a reaction in which a product is made from inexpensive building blocks in a single step as a "dream reaction." Valuable materials can therefore be produced in a much more energy-efficient manner using this catalytic process. Hydrogen, for example, can be generated directly, whereas in other processes it has to be produced in a further, energy-intensive step.

However, the reactor cell with integrated catalyst on its own does not make the technology. Optimal integration into the surrounding periphery is crucial to ensure the most energy-efficient and clean operation possible. The reactor cell forms the core, but must be made operational in terms of application technology in the overall system.

Figure 9: Sustainable and profitable process plant solution through "Dream Reaction" (in-house illustration).

2.3.3 CO_2 utilization for storing renewable energy

Electrochemical CO_2 utilization can also be considered as a possible solution for storing fluctuating renewable energy. Surplus wind or solar energy that cannot be fed directly into the power grid and used could be converted electrochemically into methanol, for example.

Under ideal conditions, almost 1,400 kWh of energy could be stored by the conversion of 1 ton of CO_2 equivalents.[15] If required, the methanol can then be used again, for example, as fuel in a direct methanol/ethanol fuel cell (DMFC).

2.4 Conclusion: quicker ROI due to increasing CO_2 costs

Companies that invest in such process solutions will not only reduce their CO_2 emissions but also benefit from marketable products. In view of rising certificate prices, it can be assumed that the return on investment (ROI) will materialize sooner rather than later. In addition, process solutions like these form the basis of affordable, profitable, and environmentally friendly solutions for generations to come.

3 The market potential of CO_2 products

The future market for CO_2-based products and services is not easy to assess due to the early stage of technology development for many applications and the dependence on political framework conditions. Global estimates range from less than 1 Gt of CO_2 per year to 7 Gt of CO_2 per year by 2030, depending on underlying assumptions.

3.1 Huge global market for CO_2 products

In the study *"CO_2 Capture & Utilization: The Emergence of a Carbon Economy",* for example, Lux Research, a global provider of technology-assisted research and consulting services, forecasts the adoption of CCU technology in building materials, chemicals, carbon additives, fuels, polymers, and proteins.[16]

The global market for CO_2 utilization will reach $70 billion by 2030 and $550 billion by 2040, according to Lux Research. As governments and industry turn to technology, cement and other building materials are seen as having the greatest investment potential.

According to the findings of the "*Global Roadmap for Implementing CO_2 Utilization*" study, strategic measures to accelerate the commercialization of CO_2-based products open up significantly greater market potential. For example, in the best-case scenario, five recycled products (concrete, carbon additives, polymers, fuels, methanol) could create a market of over $800 billion by 2030.[17]

By 2025, for example, this would mean quadrupling the market for CO_2-based fuels (from $50 billion to $200 billion), which could simultaneously increase CO_2 reductions 15-fold (from 0.03 billion tons to 0.5 billion tons).

3.2 Potential revenues of relevant product groups

The following table shows the orders of magnitude and ranges of potential revenues based on an extrapolation of the aforementioned studies. The sectors with by far the highest economic and environmental potential are construction materials, fuels, and chemicals.

However, in addition to numerous other factors, the following two criteria must be fulfilled in principle for meaningful utilization:

- **CO_2 footprint:** The CO_2-based product must have a lower environmental footprint than the established products. The use of CO_2 as a raw material does not automatically lead to a negative overall CO_2 footprint. The inclusion of CO_2 capture when calculating the carbon footprint is therefore essential.
- **Cost-effectiveness:** The production and sale of the product must be competitive with the established product.

Potential for CCU products		
Total Opportunity: 0,5 bis 2 trillion USD per year and 2 to 8 Gt of CO_2/year		
	Annual Market Opportunity / USD Billions	Annual CO2 Consumption / Million Tons
Construction materials	165-550	900 - 5.000
Fuels	10-250	700-2.100
Chemicals	200-750	135-565
Engineered materials	140-400	30-84
Polymers	2-25	1-20
Agriculture & food	>25	>40

Table 2: Projection of economic and environmental potential for CCU products based on a previous market assessment. Adapted from [18].

3.3 Market potential for renewable carbon using the chemicals industry as an example

The use of captured CO2 as a feedstock in the chemical industry for the synthesis of certain chemical products offers an opportunity to avoid several million tons of CO_2 emissions annually while increasing independence from fossil fuels. For this reason, the interest of the chemicals industry in using CO_2 captured in this way is growing.

An interesting look at the sales markets of the future is provided below by the 2050 carbon supply scenario:

→ Under the premise of more moderate growth, Figure 11 shows a global increase in demand for embedded carbon (carbon bound in the molecular structure) for chemistry from 450 million tons per year today to 1,000 million tons per year in 2050.[19]

→ Mechanical and chemical recycling will become the most important future carbon sources at 55 percent, followed by direct CO_2 use at 25 percent and biomass at 20 percent.

The extent to which this scenario can be implemented by 2050 depends primarily on the policy framework and investments in the recycling economy, CCU technologies, and the bioeconomy.

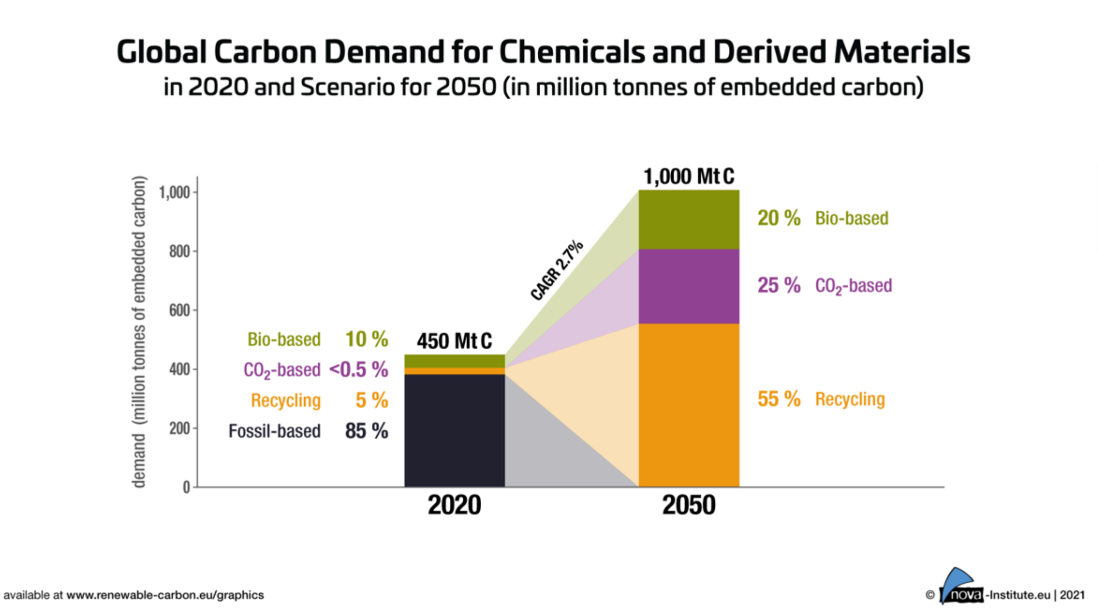


Figure 10: Under the premise of moderate growth, the scenario forecasts a global carbon demand for chemicals and derivative products of 1,000 Mt per year in 2050. Adapted from [20].

Renewable carbon sources also bring other feedstocks into play, promoting new structures in the chemical industry. These raw materials and energy sources include CO_2, but also hydrogen, ethanol, and especially methanol, sugar, cellulose, vegetable oils and waste fats, and oils, as well as chemical recycling.

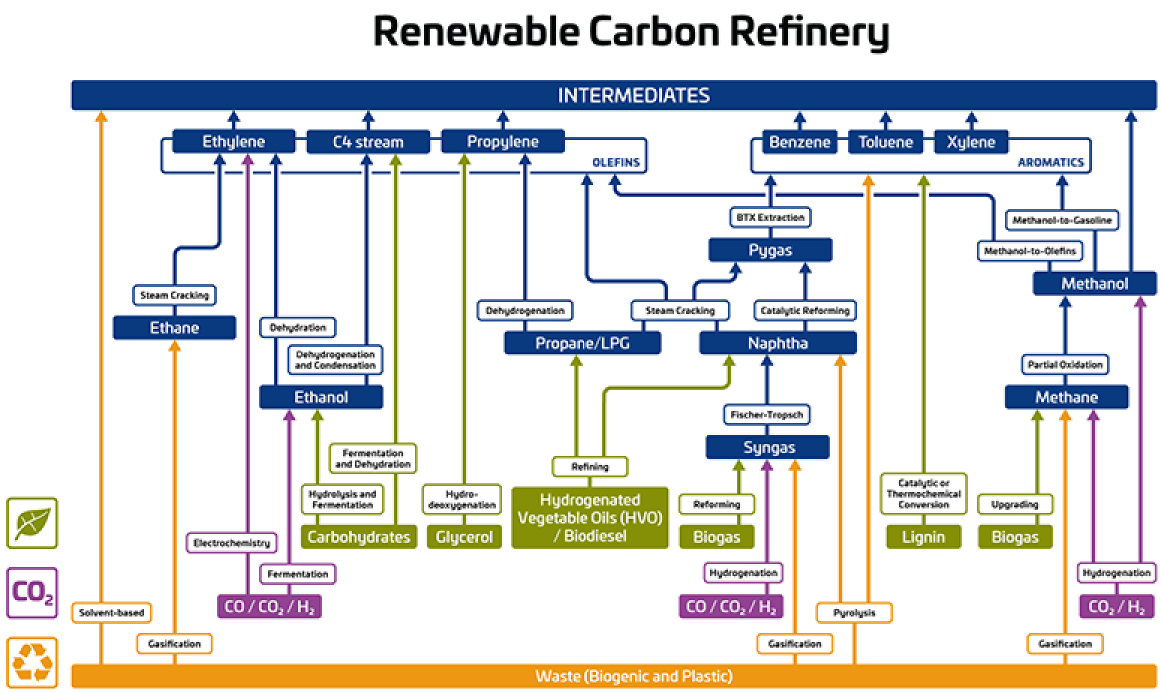


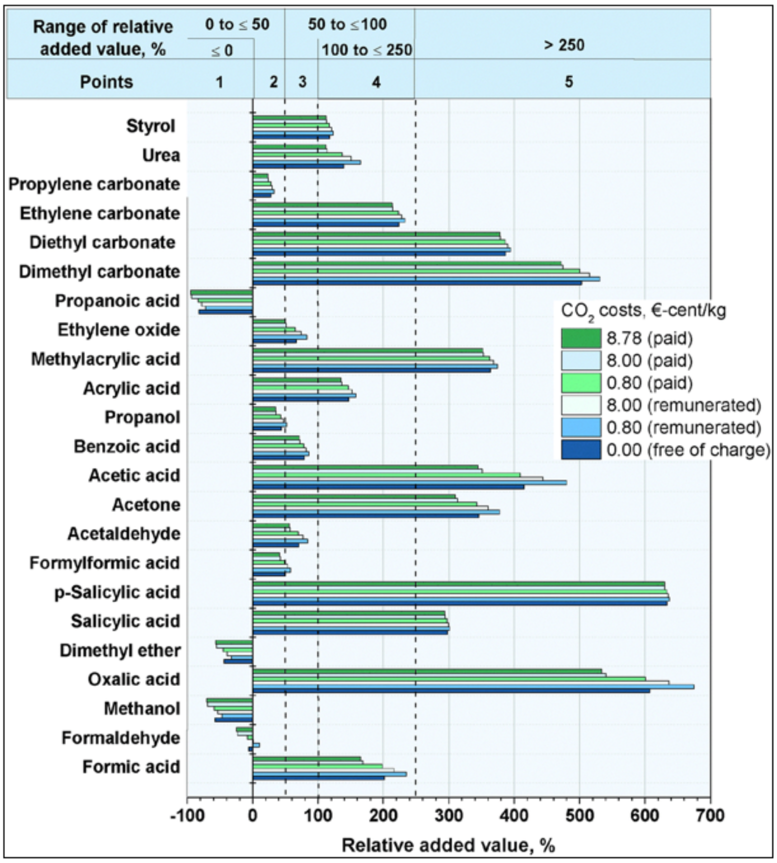
Figure 5: The graphic shows possibilities to fully cover the demand of today's large-scale chemical industry also with biomass, CO_2, and recycled raw materials. Adapted from [21].

3.4 The relative added value of different CO_2 products

The relative added value of products from CO_2 conversion is a simple measure of profit and takes into account the economic aspect of the valuation. The higher the relative added value, the more attractive the reaction is for industrial implementation.

A calculation of the relative added value as part of the study *"Closing the loop: captured CO_2 as a feedstock in the chemical industry"* came to the following conclusion:[22]

- → The change in CO_2 prices does not have a significant impact on relative added values.
- → The calculated results for p-salicylic acid, oxalic acid, and dimethyl carbonate are the three highest among all 23 chemicals/fuels calculated.
- → The relative added values of products such as dimethyl ether, propionic acid, formaldehyde, and methanol are negative because the value of the products is lower than the cost of the reactants.



$$\text{Relative added value} = \frac{(m_P \cdot W_P) - \sum_i^n (m_{E,i} \cdot W_{E,i})}{\sum_i^n (m_{E,i} \cdot W_{E,i})}$$

m_P = mass of product, kg; $m_{E,i}$ = mass of educt i, kg;
W_P = specific value of product, € per kg; $W_{E,i}$ = specific price of educt i, € per kg.

Figure 12: The graph shows the relative added value of different chemicals/fuels at different CO_2 prices. A point system is used to assign points between 1 and 5 in ascending order for certain value ranges, which indicate the potential of CO_2 utilization reactions. Adapted from [22] [23].

Note: The relative added value is defined as the difference between the product value and the price of the required reactants (CO_2 and other reactants) divided by the product value. The calculated value serves theoretical economic evaluations. To calculate the "real" relative value added, all manufacturing costs incurred in the process would have to be taken into account.

3.5 An initial assessment of CO_2 conversion technologies

CO_2 utilization involves a variety of processes and chemical reactions. In this context, the following overview of the study "*CO2 Utilization Technologies in Europe: A Short Review*" provides an analysis of the technical-economic feasibility, sustainability, and social opportunities of CO_2 utilization in Europe.

The evaluation of the study is based on the latest developments in CO_2 utilization and examines CO_2-based technologies with a high degree of maturity.[24] Seven indicators frequently cited in the relevant literature were defined for the assessment, covering technological, economic, environmental, and social aspects.

The following indicators thus provide a first quick overview of the performance of the CO_2 conversion technologies discussed in the study.

- **State of the art**: This indicator is based on the maturity level (TRL) and covers the time frame until implementation.
- **Energy performance:** This indicator is used to evaluate the energy demand. It also includes energy storage potential, particularly in the context of power-to-fuel technology.
- **Investment costs:** This indicator refers to the capital investments; i.e. the non-consumable components for implementing the CCU technology (CAPEX).
- **Operating costs:** This indicator refers to the costs for the ongoing operation of the CCU technology (OPEX).
- **CO_2 utilization:** This indicator is based on the mass of CO_2 required to produce one kilogram of a product (given by stoichiometry).
- **Sustainability**: This indicator examines the use of additional solvents, catalysts, or toxic compounds that can lead to negative impacts on the environment and the use of scarce natural resources. It also evaluates whether it is possible to avoid fossilized carbon as a feedstock for reactant production.
- **Social acceptance:** This indicator examines the general perception of CCU technology by end users. Positive public perception is an important component for the successful commercialization of these products. CO_2-based products, such as soaps made from CO_2, are still perceived as "dirty" in some cases.

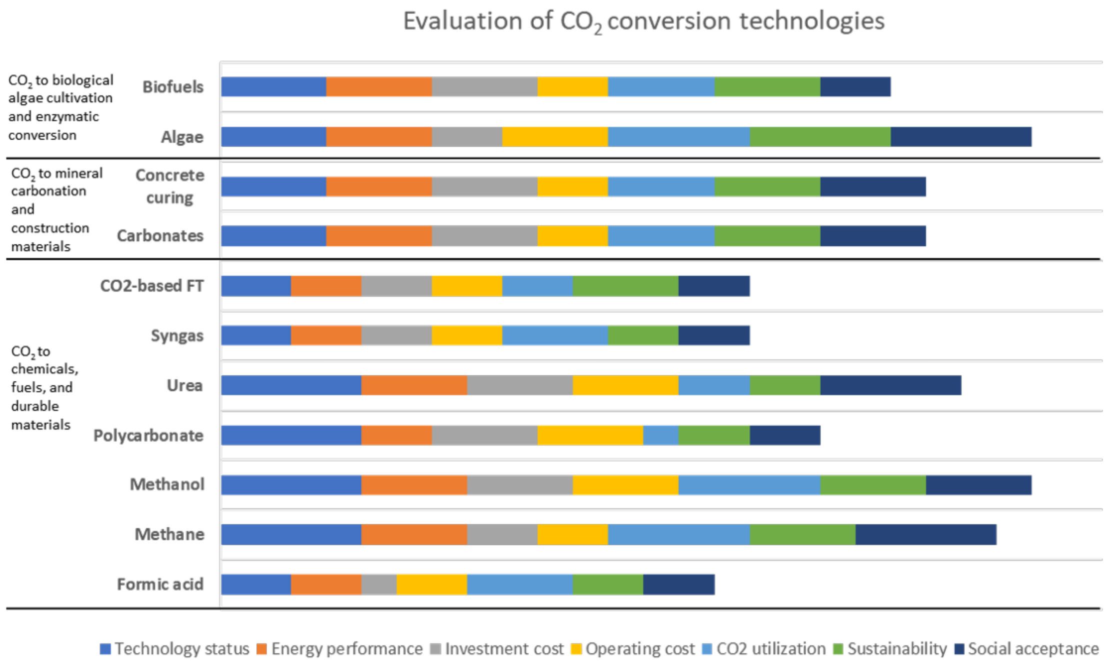


Figure 13: Evaluation of the technical-economic feasibility, sustainability, and social opportunities of CO_2 utilization in Europe. Adapted from [24]

3.6 Market introduction of CCU technologies picks up speed

The growing interest in CCU technologies is reflected in the increasing number of research publications published each year and is a clear indicator of positioning toward market introduction.

However, numerous projects fail to make the necessary transfer from working prototype to marketable product, because the research readiness of universities rarely exceeds levels 3–4 of the scale for technological maturity (TRL – Technology Readiness Level). At the same time, interest from industry and investors usually only starts at TRL 6 or higher. This gap, referred to as the "Valley of Death," delays the transfer process from the lab to the field and can cause a technology to disappear.

Currently, many CCU technologies are in development, and some already have sufficient maturity for market introduction. To bridge the "Valley of Death" and accelerate the transfer to marketable technology, cooperation between science and industry, but also the creation of public awareness and political support for CCU technologies are necessary.

The growing interest from governments, industry, and investors currently offers the best conditions for developing CCU technologies to market maturity. In North America, the NRG COSIA Carbon XPrize supports the development of novel CO_2 utilization opportunities with a $20 million global competition. Governments in Canada, Japan, the United Kingdom, and the United States, as well as the European Commission, also provide significant R&D support for CO_2 utilization.

Technology readiness levels for CCU technologies			
1	**basic principles observed**	idea; opportunities identified, basic research translated into possible applications	methanol via photocatalytic conversion
2	**technology concept formulated**	concept; technology concept and/or application formulated, patent research conducted	ethanol and methanol via electrochemical reduction
3	**experimental proof of concept**	proof of concept; applied laboratory research started, functional principle/reaction (mechanism) proven, predicted reaction observed (qualitatively)	ethylene via electrochemical reduction, DME via syngas
4	**technology validated in lab**	preliminary process development; concept validated in laboratory environment, scale-up preparation started, shortcut process models found	PCC and PMC
5	**technology validated in relevant environment**	detailed process development; process models found, property data analyzed, simulation of process and pilot plant using bench scale information	formic acid via electrochemical reduction in an aqueous environment, sodium bicarbonate using flue gas directly
6	**technology demonstrated in relevant environment**	pilot trials; pilot plant constructed and operated with low-rate production, products approved in final application, detailed process models found	Fischer-Tropsch fuels, urea from steel gases
7	**system prototype demonstration in an operational environment**	demonstration and full-scale engineering; parameter and performance of pilot plant optimized, (optional) demo plant constructed and operating, equipment speciation, including components that are type conferrable to full-scale production	CO and syngas via the reverse water gas shift reaction, methane and methanol via hydrogenation of CO2
8	**system complete and qualified**	commissioning; products and processes integrated in organizational structure (hardware and software), full-scale plant constructed	Polyols, construction materials from carbonated steel slag
9	**actual system proven in an operational environment**	production; full-scale plant audited (site acceptance test), turn-key plant, production operated over full range of expected conditions in industrial scale and environment, performance guarantee enforceable	CO2 enrichment in agricultural greenhouses, CO2 EOR

Table 3: Technology readiness level (TRL) and examples of CCU technologies for every TRL. Adapted from [13]

3.7 Conclusion: High market potential of CO_2 products

New options for using CO_2 in the development of products and services are attracting the attention of governments, industry, and investors. CCU technologies enable companies to convert millions of tons of CO_2 per year into high-value products that can be directly reused in industrial processes or used to manufacture other products.

Fuels, chemicals, and carbon additives offer enormous potential, but innovation is needed for widespread adoption of the technology. Companies that get involved now will not only reduce their CO_2 emissions, but also benefit from marketable products.

4 New technologies for converting CO_2

The use of technologies for CO_2 utilization has gained a great deal of attention around the world over the past few years. In the long term, they will be an indispensable component for future economic activity. Below, we show different CO_2 conversion and utilization pathways and explain why GIG Karasek is pushing electrochemical CO_2 conversion in various research projects.

4.1 Why GIG Karasek focuses on CO_2 utilization

CCU technologies are essentially based on two steps isolated from each other: the capture step and the conversion step. Although the overall efficiency of the CCU process depends on the combination of these steps, CO_2 capture and utilization have so far mostly been researched independently of one another.

This circumstance has led to the fact that separation systems have already been developed on an industrial scale, while utilization or conversion technologies are still at various stages of development.

GIG Karasek therefore does not focus its research projects on CO_2 capture, but on the development of innovative processes for CO2 utilization. The main focus here is on electrochemical CO_2 conversion, which we will discuss in more detail below after presenting currently researched conversion pathways.

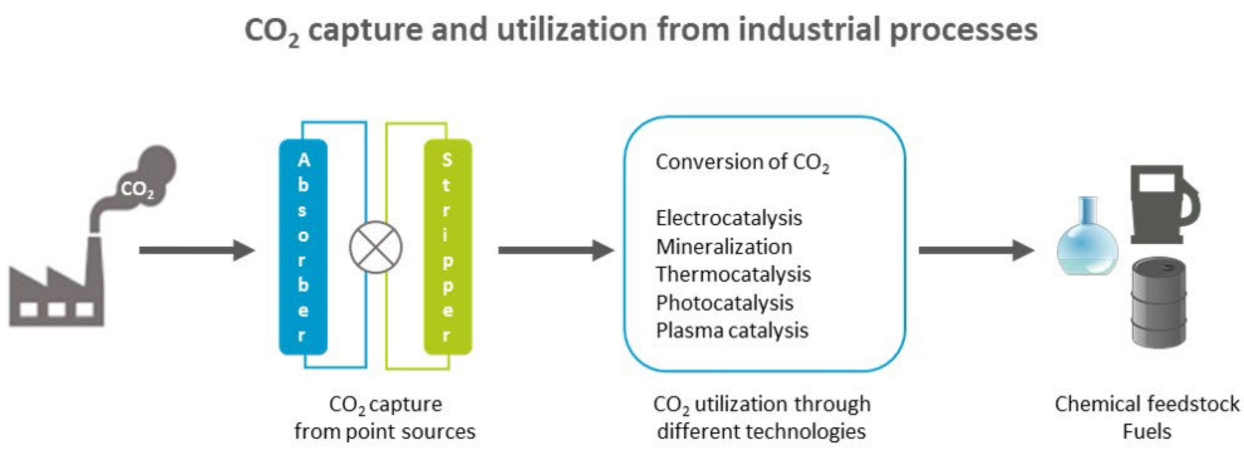


Figure 14: CO_2 capture from point sources and subsequent utilization of CO_2 via various conversion pathways (self-representation).

4.2 Conversion paths and their technological maturity

Since CO_2 is a thermodynamically stable compound, the conversion of CO_2 usually takes place through a catalytic process with additional input, e.g. from renewable energy sources. Below is an overview of the main recycling technologies currently under investigation, including their technological readiness level (TRL):

4.2.1 Thermochemical CO_2 conversion (TRL 5–9)

Thermochemical CO_2 conversion uses catalysts and a combination of heat and pressure to convert CO_2 into valuable products. With a technology readiness level between 5 and 9, this is currently the most mature technology for CO_2 conversion. Challenges with this reaction pathway include reversibility and thermodynamic limitations of reactions.

4.2.2 CO_2 mineralization (TRL 4–8 concrete ingredients, TRL 7–8 concrete curing)

CO_2 mineralization processes are based on the reaction of metal cations (e.g. Mg, Ca, Fe) with CO_2 to form solid and stable carbonate minerals and thus permanently store CO_2. The resulting carbonates are potentially versatile, for example as fillers, cement additives or for land reclamation projects. CO_2 mineralization will nevertheless continue to make only a small contribution towards the decarbonization of industry; it will not be able to offset the CO_2 balance sheet on its own.

4.2.3 Electrochemical CO_2 conversion (TRL 4–8 C1 products, TRL 1–3 C2+ products)

Electrochemical or electrocatalytic CO_2 reduction (eCO_2R) is a reaction in which CO_2 is converted into a species with a lower oxidation state by using electricity as an energy source and is thus reduced electrochemically (species = a certain type of particle, e.g. molecules). The promising process enables a very broad product spectrum (e.g. methanol, formic acid, CO, methane).

4.2.4 Bioelectrochemical CO_2 conversion (TRL 1–3 one-step, TRL 4–7 two-step)

In the bioelectric conversion of CO_2, the processes of electrolysis and fermentation are combined. For CO_2 conversion, microorganisms are used that can reduce CO_2 to methane in a one-step or two-step process.

Hydrogen is produced in the first step of the two-step process. Then, in a second step, this is fed together with CO_2 to a bioreactor containing anaerobic methanogenic bacteria for methane production. The one-step process is still poorly developed. The two-step process is close to commercialization, but the process is rather slow compared to the electrochemical system.

4.2.5 Photocatalytic CO_2 conversion (TRL 1–3)

The photocatalytic conversion of CO_2 is currently still at the research stage. Using additives, a new raw material base is to be developed by making CO_2 usable as a raw material for chemicals in a solar-powered recycling process. The targeted products are methane, synthesis gas and hydrocarbons.

4.2.6 Plasma catalytic CO_2 conversion (TRL 1–3)

Plasma catalysis technology is another novel approach to CO_2 utilization. In this process, a weakly ionized plasma, which is very reactive, is generated by supplying electricity. The conversion of CO_2 into basic chemicals, such as methanol and ethylene, is activated by free electrons contained in the plasma. However, plasma chemistry is very complex and a better understanding of plasma reactions and interactions between the plasma and catalyst is needed.

Technology	Energy input	Main products	TRL
Thermocatalysis	Heat and pressure	Methanol Methane Urea	Methanol: 5-9 Methane: 8-9 Urea: 9
Mineralization	Chemical (reaction with metal cations)	Carbonate-sals	Components of concrete: 4-8 Curing of concrete: 7-8
Electrocatalysis	Electricity	CO, syngas, formic acid, other C1 and C2+	CO/syngas/ formic acid: 4-8 C2+: 1-3
Bioelectrocatalysis	Electricity	Methan	4-7
Photo(electro)catalysis	Solar with or without electricity	Methanol Methan	1-3
Plasma catalysis	Weakly ionized plasma	CO Methanol Ethylene Other C2+ procucts	1-3

Table 4: CO_2 conversion technologies, including the technical readiness level (TRL), prepared according to [25].

4.3 The advantages of electrochemical CO_2 conversion

From the range of utilization methods presented, the electrocatalytic or electrochemical conversion of CO_2 (eCO_2R) is gaining increasing interest in the scientific community. The following factors in particular are key to this:

- **One-step conversion:** The process enables the one-step conversion of CO_2 into C1, C2, and even C2+ products (complex hydrocarbons). The electrochemical reduction of CO_2 thus also produces products containing two or more carbon atoms per molecule (e.g. ethanol CH_3-CH_2-OH) in just one conversion step.
- **Range of products:** The electrochemical process therefore potentially allows the production of a wide range of products.
- **Flexible use of electricity:** Surplus renewable energy can be stored in the form of chemical energy and used again when needed. This enables a more flexible use of electricity (i.e. demand-side management).

Also, compared to other technologies, electrochemical CO_2 reduction offers a number of significant advantages, which are discussed in more detail below.

4.4 Electrochemical CO_2 conversion in comparison

Electrochemical reduction is an attractive technology because it can be carried out under mild conditions (near room temperature and ambient pressure) in aqueous solutions, using water instead of molecular hydrogen (H_2) as the hydrogen source.

Furthermore, electrochemical conversions are more attractive than other recovery technologies for several reasons, both in terms of energy efficiency and cost:

- **Controllability:** The main advantage of the CO_2 reduction reaction (CO_2RR) is the possibility to precisely control the conversion process (production of the desired products) through electrolysis parameters (potentials applied to the cathode, current density, and electrolysis time), reaction temperatures, and other parameters.
- **High efficiency and scalability:** The electrochemical conversion systems are modular, compact, highly efficient, easy to operate, demand-driven, and scalable (i.e. the components of the electrochemical reactions are easy to use on a large scale).
- **Use for fuels:** The products obtained from chemical synthesis or energy storage can be used for fuels.
- **Recyclability of components:** The components of the electrolysis baths can be completely recycled, so that the total consumption of reagents can be minimized.

Figure 15: Advantages of electrochemical CO_2 conversion (self-representation).

The previously mentioned alternative CO_2 utilization technologies have some disadvantages compared to electrocatalytic conversion, which make them less attractive from GIG Karasek's point of view:[26]

- **Thermochemical CO_2 conversion** requires high pressure and high temperatures, which results in corresponding costs. The method is also not sustainable due to the use of a non-renewable energy source.
- The main disadvantage of the **bioelectrocatalytic process** is its high cost. Currently, biological methanation is even more expensive than thermochemical methanation, which is very cost-intensive anyway.
- The **photocatalytic process** is not possible for large-scale implementation and night-time operation due to the lack of solar radiation. The process is also less user-friendly and product isolation and separation is comparatively difficult.
- **Plasma catalysis technology** as another novel process is physically very complex and requires more research to fully understand the process.

For the reasons given, GIG Karasek relies on electrochemical CO_2 conversion as a recycling technology. Below we provide a brief insight into the strategy pursued by GIG Karasek on this path.

4.5 Focus on formic acid and carbon monoxide

As already mentioned, electricity is applied in the electrochemical conversion of CO_2 in order to use CO_2 as a raw material for chemical syntheses. Depending on the catalyst material used, the reaction pathway, the amount of CO_2 feedstock and the energy, there are a variety of eCO_2R products that can be produced.

GIG Karasek has selected formic acid (HCOOH) and carbon monoxide (CO) as two of the most promising products for the application of CCU technology:

- **Formic acid** is a bulk chemical that is of great interest for energy storage (formic acid fuel cells) and as a base material for the chemical industry.
- **Carbon monoxide** can be used in combination with hydrogen (H_2) to produce synthesis gas and as a chemical base material.

Furthermore, CO and formic acid record the highest market price per electron used, although the market price is lower than for other products such as methanol and ethanol. They are therefore good candidates for the development of CCU technologies.

Products	Number of electrons per CO_2	Average market price ($/kg)	Normalized market price ($/electron) x 10^{-3}	Global production per year (million tons)	Product Mol ** Weight/Electron
Carbon monoxide	2	0,60	8,00	*	14,00
Formic acid	2	0,74	16,10	0,60	23,01
Methanol	6	0,58	3,10	11,00	5,34
Ethylene	6	1,30	3,00	140,00	2,33
Ethanol	6	1,00	3,80	77,00	3,83
n-Propanol	6	1,44	4,80	0,20	3,33

* CO is mostly produced in captive plants and not marketed in large quantities. Therefore, estimated production quantities are not given.
** Mol is the unit of the amount of substance in chemical reactions.

Table 5: Electrochemical CO_2R-products, adapted from [27].

4.6 Innovative research project: direct electrolysis of CO_2

GIG Karasek is currently involved in several research projects dealing with innovative approaches to the electrochemical conversion of CO_2 into valuable materials. In chapter 3, we presented the research cooperation with the Johannes Kepler University Linz (JKU Linz) on CO_2 utilization based on the so-called "Dream Reaction".

As part of another project for the direct electrolysis of CO_2, GIG Karasek is developing an expanded CCU system based on a new type of electrolysis cell in cooperation with three companies from Upper Austrian and the University of Innsbruck:[28]

→ The aim of the project is to optimize the energy/cost ratio of CO_2 capture and utilization of flue gases by means of direct CO_2 electrolysis, by eliminating intermediate steps such as thermal desorption and product separation or processing.

→ The capture and electrochemical conversion of CO_2 thus no longer takes place in two separate steps, but is integrated into one unit.

→ The innovative technology is based on a symbiotic CO_2 absorption and electrolysis cell that significantly streamlines the process and increases energy efficiency.

→ This mini-plant system serves as the basis for the next scale-up steps for industrial research with the aim of establishing CO_2 utilization as a future business sector and taking an innovative step in waste gas purification.

GIG Karasek contributes its expertise in industrial plant construction with regard to separation technology and cell periphery construction with its production sites in Attnang-Puchheim and Gloggnitz and a planning office in Graz.

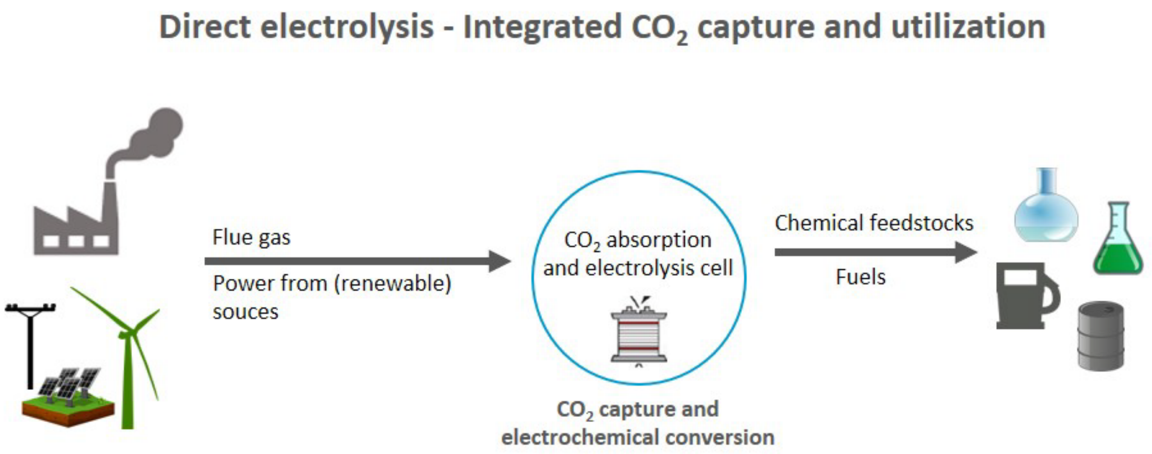


Figure 16: In direct electrolysis, CO_2 capture and conversion to valuable products takes place in just one step. Ideally, the process is fed from renewable energy sources (self-representation).

4.7 Challenges of eCO_2R in industry

The most important bottleneck on the way to industrializing the electrochemical CO_2 reduction process is system integration and optimization at system level. The reactor cell with integrated catalyst forms merely the basis of the technology.

The greater challenge is to optimally integrate the reactor cell into the overall system and make it operational. Selectivity, activity and stability of catalysts are key parameters in this respect:

- **Activity** describes the performance of a catalyst at a given energy input.
- **Selectivity** defines whether and how many contaminating by-products are generated.
- **Stability** indicates how efficient a catalyst is in the long term.

An exclusive focus on high selectivity, activity, stability, costs or scalability does not lead to the desired results. Ultimately, achieving the optimum requires a compromise between all parameters.

Another challenge in the industrialization of eCO_2R is the current density. The industrial production of value products from CO_2 requires an increase in current density from milliamperes (mA) to several amperes (A). This is still a challenge for most systems.

To work out the best possible option, it is necessary to realize this technology on a large scale in pilot plants or demonstration electrolyzers.

Within our pilot plant and our research projects, we therefore investigate and improve every parameter. The focus here is on the type of electrocatalyst, the morphology of the electrocatalyst, the electrolyte composition and the process conditions.

4.8 Outlook for the CO_2 utilization industry

The economic feasibility of CCU concepts depends not only on technological readiness, but also on the creation of political framework conditions. These include, in particular, carbon tax policies, government support for technology development, and incentives for environmentally friendly production pathways.

Industrial eCO_2R is not yet competitive compared to fossil fuel alternatives for the chemical industry and energy storage.

However, as soon as the electrical energy required for conversion can be fed from renewable energy sources, competitive production is possible. This is especially true in view of enormously rising prices for energy from fossil sources.

Of course, the electrification of the chemical industry is a challenging path in terms of economic competitiveness with industries based on fossil fuels or non-electrochemical pathways.

Nevertheless, GIG Karasek is convinced that the development of large-scale electrochemical technologies (e.g. eCO_2R) that run on emission-free electricity is necessary in the future, given the enormous environmental impact and the unavoidable CO_2 emission costs.

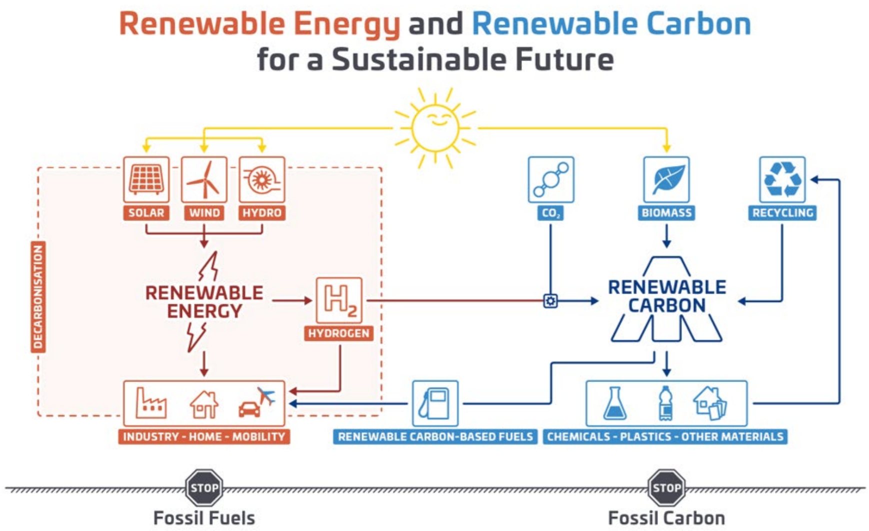


Figure 17: CCU technologies in the context of a sustainable chemical industry, adapted according to [29] © nova-institute.eu.

4.9 Conclusion: CO_2 utilization as a new business sector

CO_2 can be made usable as a raw material in the medium term through innovative technologies; for example, for plastics, building materials or fuels. Decisive advantages for CO_2 utilization as a future business sector are offered by technologies that can use electrical energy generated from renewables directly for CO_2 conversion.

Electrochemical CO_2 conversion at moderate process temperatures is a particularly efficient and environmentally friendly method for this. Research and development of this CO_2 conversion pathway must, however, take place now in order to be prepared for the future.

5 CO_2 electrolysis: technical-economic analysis of the technology and marketable CO_2 products

Electrochemical CO_2 reduction represents a promising way to make CO_2 usable as a raw material for chemicals and fuels. Below, we look at the technical-economic aspects of CO_2 electrolysis and highlight the profitability of some reaction products in different scenarios.

5.1 Evaluation criteria for CO_2 electrolysis

Various criteria are used in the relevant literature to evaluate CO_2 conversion technologies. Based on these indicators, we provide below an overview of the technical, energy-related and economic performance of electrochemical CO_2 reduction (eCO_2R):

- State of the art
- Energy performance
- CO_2 usage
- Sustainability
- Investment costs (CAPEX)
- Operating costs (OPEX)

5.2 State of the art and energy performance

Electrochemical CO_2 reduction is one of the simplest and most technically mature technologies for converting CO_2 into useful products.

→ Technological maturity (or the Technology Readiness Level – TRL) for C1 products is 4–8 (formic acid, synthesis gas); for C2+ products it is 1–3.[30]

→ Electrochemical conversion systems can be specifically controlled via electrolysis parameters and are easy to handle and scalable.

→ The environmentally friendly process uses water as the hydrogen source and can be carried out under mild conditions at close to room temperature and ambient pressure.

→ The technology offers major advantages due to its high efficiency at moderate process temperatures and the possibility of using renewable energy sources directly for CO_2 conversion.

In comparison with alternative conversion technologies, CO_2 electrolysis systems have a low energy demand and are highly efficient. Furthermore, CO_2 products can be used as fuel or for energy storage (e.g. formic acid fuel cells).

5.3 CO_2 usage and profitable products

CO_2 can be converted via electrochemical reactions to simple compounds, for example formic acid, CO, methanol, propanol or even ethanol and ethylene. There is always great market potential for these CO_2 electrolysis products, with formic acid (HCOOH) and its salts (formates), as well as carbon monoxide (CO), having emerged as the most economically viable products.

5.3.1 Market price

Based on normalized market prices (stored energy and market size), CO and formic acid are the most profitable products. Normalization to the number of electrons needed to manufacture the products takes into account the electricity costs for manufacturing a product.

Although the market for these two products is limited, the possibility of turning CO and folic acid into more useful products makes them an attractive target product. This assessment is based on various analyses, which we discussed in chapter 4 .

5.3.2 Selectivity and process parameters

In addition to the market price, selectivities and process parameters also play a decisive role in the conversion of CO_2 into value-added products. An important parameter is the faradaic efficiency (current efficiency) of a product:

- → A high degree of efficiency is desirable in order to minimize the separation processes required afterwards and thus keep capital and operating costs as low as possible.
- → The faradaic efficiencies for CO and HCOOH are at least 80 percent at a current density of at least 300 mA/cm^2.
- → 2 moles of CO_2 form 1 mole of formic acid and 1 mole of synthesis gas (mole = number of particles in a substance). Comparatively, formic acid and CO therefore have the best CO_2 utilization values in terms of substance quantity.

The Faraday efficiency of a particular product shows the selectivity of the reduction of CO_2 to that product:

$$\varepsilon = \frac{z \cdot n \cdot F}{Q}$$

z: Number of electrons required to produce a given product
n: Number of moles of the product
F: Faraday constant
Q: Charge released

Figure 18: Faraday efficiency und selectivity of the reduction of CO_2; in-house illustration

5.3.3 CO offers further advantages for CO_2 electrolysis

Carbon monoxide is currently the most promising product for CO_2 reduction, for the following reasons:

- CO is gaseous at ambient pressure.
- It is separable from aqueous electrolytes.
- It can be selectively produced with Ag catalysts.
- CO is an important chemical reactant that is widely used in today's chemical industry.
- CO can be converted into synthetic fuels and hydrocarbons using established Fischer-Tropsch processes.

5.4 CAPEX & OPEX: Detailed analysis of different CO_2 products

In order to obtain a long-term overview, we have analyzed various technical-economic results of CO_2 electrolysis from the literature for different products and different process assumptions. Particularly meaningful are the results of the following analysis, which examines the process costs, including material consumption, capital and electricity costs, for various conversion products.[31]

5.4.1 Process assumptions for the CO_2 electrolysis model

Two sets of parameters form the basis of the analysis: a baseline scenario, which is based on current raw material prices and the performance of the electrolyzer; and an optimistic scenario, which takes into account how these values might look in the future.

Process Assumptions for CO_2 Electrolyzer Model

Parameter	Base Case	Optimistic Case
Production Rate (ton/day)	100	100
Lifetime (years)	20	20
Operating time (days/year)	350	350
Electricity Price ($/kWh)	0,05	0,03
Current Density (mA/cm^2)	200	300
Cell Voltage (V)	2,3	2
Product Selectivity (%)	90	90
Conversion (%)	50	50
CO_2 Price ($/ton)	70	40
Interest Rate (%)	10	10
Electroyzer cost ($/m^2)	1 840	920

Table 6: Process assumptions for a CO_2 electrolyzer model, adapted from [31]

- **Production rate:** A rate of production of 100 tons per day equates to large-scale production. The capital costs are cheaper and the differences between the products are more recognizable, while the power requirement of the electrolysis system is at the scale of the largest commercial systems (~100 MW).

- **Service life and operating time:** The service life of the electrolysis system was assumed to be 20 years, with two weeks off per year for maintenance work.
- **Electricity price:** An electricity price of $0.05 per kWh for the baseline scenario equates to the cheapest available electricity price at the time of the analysis (2018). Under the premise that renewable energy sources become cheaper, an electricity price of $0.03/kWh was chosen in the optimistic scenario.
- **Power density / cell voltage:** The electrolyzer's total current density of 200 mA/cm^2 has been demonstrated in numerous laboratory reactors at about 2.3 V. For the optimistic case, a current density of 300 mA/cm^2 at a cell voltage of 2 V was assumed, which falls within the range of commercial water electrolyzers.
- **Product selectivity:** Faradaic efficiencies of 90 percent have been demonstrated for numerous CO_2 reduction products (e.g. CO, formic acid, methanol).
- **Conversion:** A baseline reactor conversion rate of 50 percent was chosen for the analysis, assuming that high selectivity can be achieved at this rate of conversion. An improved electrolyzer design could potentially increase CO_2 conversion to well over 50 percent.
- **Net present value:** In the financial model of the analysis, the net present value (NPV) of the system at the end of its life was calculated. It was assumed that the construction of the system would be completed in the first year and production would start in the second year. The working capital was assumed to be 5 percent of the capital investment, as well as an overall effective tax rate of 38.9 percent. Profit was calculated as the income from product sales minus the annual operating costs of the system.

5.4.2 Net present value

The net present value (NPV) analysis for the most important products shows that under the conditions of the baseline scenario, CO and formic acid would be the only profitable products for the CO_2 electrolysis system. This is because CO and formic acid have the highest market value per electron. Improved catalytic performance is necessary for the profitability of alcohols.

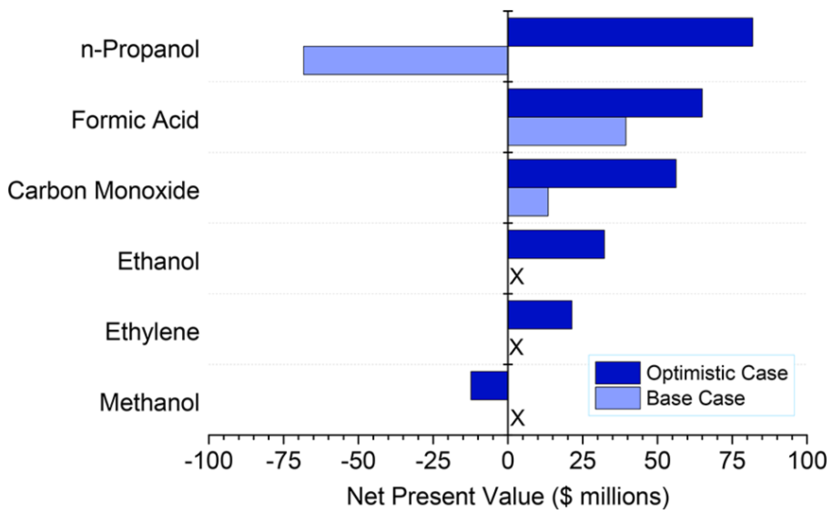


Figure 19: End-of-life net present values of various chemicals produced by eCO$_2$R under baseline and optimistic conditions. "X" means that the net present value has not been calculated because the annual net yield would be negative and thus production would be unprofitable. Adapted from [31]

5.4.3 Investment and operating costs

In the detailed breakdown of process costs for each product, it is clear that formic acid and CO have the lowest electricity demand per kg of product, reducing the electricity costs and size of the electrolyzer. In comparison, the low profitability of ethylene, for example, is caused by high electricity consumption and high demand for CO_2 feedstock.

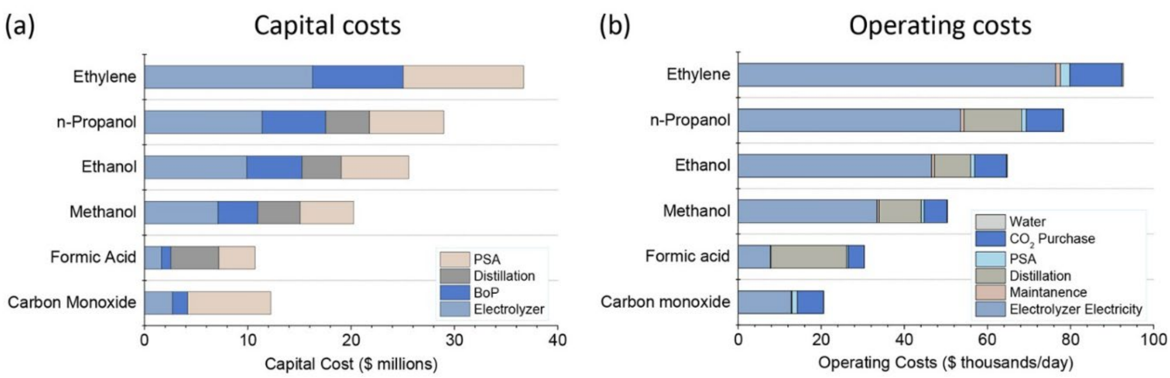


Figure 20: Investment and operating costs for the production of various chemicals under optimistic conditions. Adapted from [31]

The Balance of Plant (BoP) costs were assumed to be 35 percent of the total costs of the electrolysis system. The BoP includes all supporting components and auxiliary systems of the CO_2 electrolysis system.

It should also be noted that while distillation and PSA systems for separating liquid and gaseous products have similar investment requirements, pressure swing adsorption (PSA) has significantly lower operating costs. Although PSA is the cheaper process, the additional compression of the gas products required for transport and storage would probably drive up costs considerably.

5.4.4 Sensitivity analysis: Influence of parameters on the net present value

The sensitivity analysis illustrates the influence of different parameters on the profitability of the process. The range of values considered for each parameter is shown in the table below.

Sensitivity Parameters	Worse	Base	Better
Electric Price ($/kWh)	0,04	0,03	0,02
Selling Price ($/kg)	-15%	Base	+15%
Selectivity (%)	80	90	100
Voltage (V)	2,3	2	1,7
Electrolyzer Cost ($/m²)	1 840	920	460
CO_2 Cost ($/ton)	70	40	0
Current Density (mA/cm²)	100	300	500
Conversion (%)	30	50	70

Table 7: Value range for the sensitivity analysis of the net present value. Adapted from [31]

The most important results of the sensitivity analysis show the following picture:

→ For all products, a 15 percent deviation in sales price had a significant impact on the NPV at the end of the service life. CO, n-propanol and formic acid, however, remained profitable despite falling sales prices.

→ Furthermore, electricity is the most important operating cost for all products, with the exception of CO and formic acid, which means that there is a strong economic dependence on the price of electricity.

→ For all other parameters, it can be seen that CO and formic acid have a significantly lower sensitivity compared to other products. Ethylene, for example, is strongly dependent on the current density: a reduction to 100 mA/cm^2 would result in a $42 million reduction in NPV, while an increase to 500 mA/cm^2 would only add an additional $8 million.

→ From an economic-technical point of view, carbon monoxide and formic acid are the most promising candidates for large-scale chemical production.

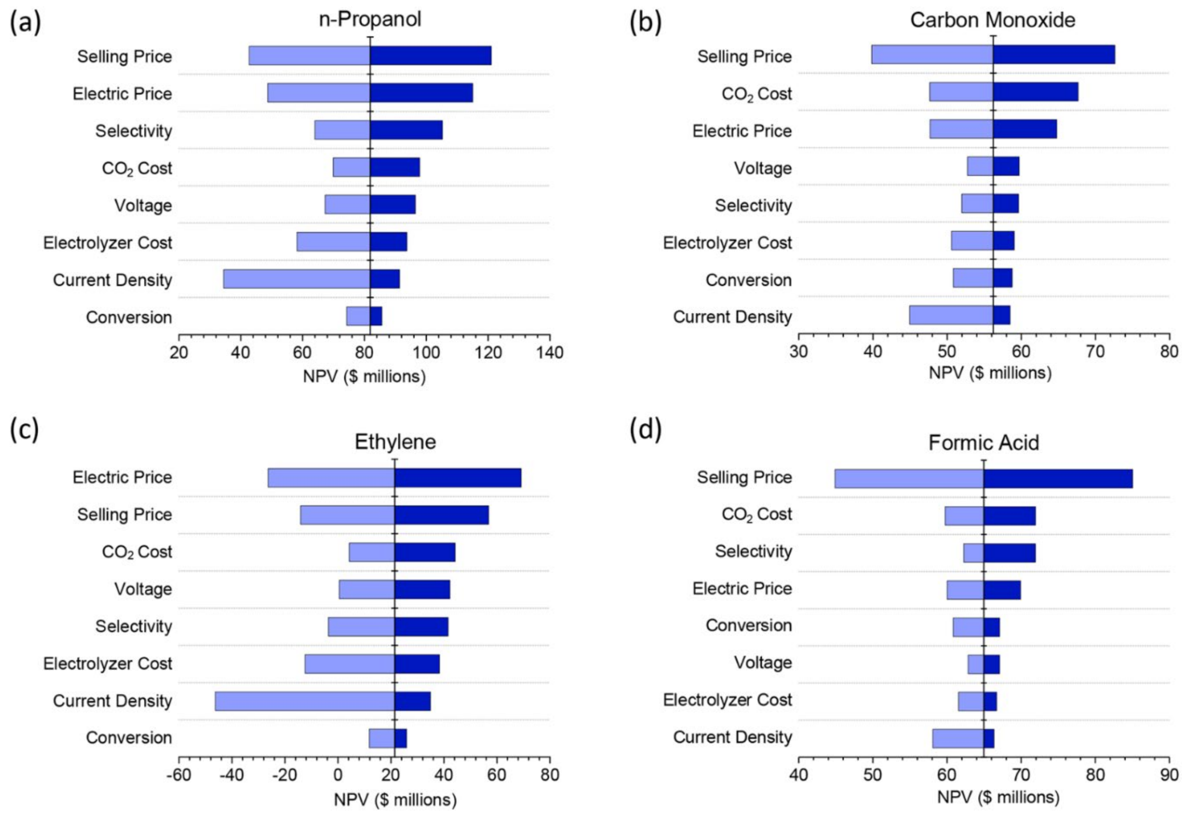


Figure 21: Sensitivity analysis of the net present value under optimistic conditions at the end of the service life for products from CO_2 conversion (cf. Fig. 2). The center line represents the net present value based on baseline sensitivity parameters. The dark blue bars show the effects of the parameters on the net present value in the "better" scenario; the light blue bars, the effects in the "worse" scenario (cf. Tab. 2). Adapted from [31]

5.5 International trends and challenges

Electrochemical CO_2 reduction is an emerging technology that is highly likely to contribute to both energy storage and the supply of basic chemicals in the future. In particular, the reduction of CO_2 to CO with subsequent processes to produce further value-added products, for example Fischer-Tropsch processes, can be a profitable avenue.

To bridge the "Valley of Death" and enable the commercial future of these processes, the focus of research must shift to materials that can be used on a large scale and are affordable. Close, interdisciplinary cooperation between science and industry is necessary to ensure technological progress in the field of CO_2 electrolysis.

Product separation is also a complex and cost-intensive process, which is why it is desirable to obtain highly concentrated individual products. In the case of CO and formic acid, this criterion can already be met on a large scale.

5.6 GIG Karasek is looking for collaborators

Nobody can shape the future on their own. That is why GIG Karasek is looking for partners from research and industry to demonstrate the performance of CO_2 conversion technology on a larger scale.

→ With research cooperations and pilot systems, we want to accelerate technological progress and the market introduction of CO_2 electrolysis.

→ As a company active in plant and equipment engineering, GIG Karasek is able to "translate" research results and implement them on an industrial scale.

→ As a specialist in the field of thermal separation technology, we have the necessary know-how to produce CO_2 conversion products to a high quality and concentration.

We take over the entire project management, provide support in terms of operations and ensure the development of employees' skills. GIG Karasek thus offers added value over the entire service life of the system.

Figure 22: Example project sequence for research cooperations and pilot system projects © GIG Karasek.

5.7 Conclusion: bring CO_2 electrolysis to market maturity

Simple products such as CO and formic acid are the most profitable under current economic conditions and based on the current state of the art in electrocatalysts. However, in order to bring the industrial application of CO_2 electrolysis to market maturity, further research and pilot projects in a real industrial environment are required.

We look forward to hearing from those interested in a cooperation!

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GIG Karasek is a globally acting Austrian supplier of high-quality industrial plants for thermal separation and focuses on the design and manufacturing of falling-film, thin-film-, short-path-, distillation and drying technology.

Our machinery and plants are mainly applied in the production processes of the pulp (kraft, sulfite, dissolving), (bio)refinery, fiber, alternative fuel, chemical, (bio)plastic, food and feed industry as well as for processing industrial wastewater.

GIG Karasek, part of Dr. Aichhorn Group, has completed numerous projects around the globe – ranging from pilot plants and skid units to turnkey plants on EPC basis.

GIG Karasek runs an own technical center for trials and R&D and offers technology for transforming CO_2 in valuable products like chemicals and fuels.

Our experts are available for an in-depth analysis of your specific requirements and for any initial expert advice!

GIG Karasek GmbH
Neusiedlerstrasse 15-19
A-2640Gloggnitz
+43 / 2662 / 42780
office@gigkarasek.at

www.gigkarasek.com