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Main authors
Elin Svensson, Stefan Heyne and Karin Eriksson, CIT Renergy

Mathilde Luneau, Chalmers, Applied Chemistry

Project participants
Lia Detterfelt and Andreas Hellström, Renova

Fredrik Starfelt, Vattenfall

Oleg Pajalic, Perstorp

Geir Tangenes, Inovyn

Anna-Karin Jannasch, Uniper

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Electrochemical reduction of CO_2

Summary

Electrochemical reduction of CO_2 refers to the chemical reaction where CO_2 is converted to different chemicals using electrolysis. Once further developed, the technology for electrochemical conversion of CO_2 could provide opportunities for utilization of captured CO_2. It also offers a possibility for chemical storage of intermittent renewable energy through the electrified production of chemicals. With direct conversion of CO_2 in one step, operating conditions close to ambient temperatures and pressures, and a wide range of possible target products, CO_2 electrolysis could potentially provide advantages compared to other CO_2 conversion options.

This report is structured in two parts: I) a state-of-the-art analysis on electrochemical CO_2 reduction, and II) a techno-economic evaluation and discussion of potential future integration of this technology in West Swedish industry. The report is based on a literature review, interviews with project partners and researchers, a survey of ongoing research projects and companies active in the field, project workshops and techno-economic modelling. The two parts of the report are summarized below.

Part I – State-of-the-art analysis

Electrochemical CO_2 conversion is still in an early development phase, although, in recent years, a development is seen towards more industrially relevant research and development. This can be seen, for example, by interest from larger companies as well by the emergence of start-ups. Especially the development of gas diffusion electrodes, which allow for significantly higher reaction rates and new reactor designs, has been important for the advancement of the technology. Recent developments of catalysts, materials and reactor setups have also allowed for rapid improvements in efficiencies and conversion rates.

The highest maturity for low-temperature electrolysis of CO_2 has been reached for production of carbon monoxide and formic acid (TRL around 6). Today, the largest demonstration facility in Europe for electrochemical conversion of CO_2 is the 10 kW electrolyzer that was inaugurated by VoltaChem in 2023. In the test facility carbon monoxide and formic acid can be produced. For other products, however, the maturity is lower, and more research is needed to reach acceptable performance levels.

For the technology to be a viable future option for production of chemicals, the performance needs to improve, which requires further development of catalysts, electrodes and membranes, as well as of the full electrolyzer design. For example, there is a need to develop catalysts that can provide higher yields to specific target molecules (higher selectivity). This to avoid that the product flow will consist of a mix of different substances, which then need to be separated. To develop catalysts and membranes with

better durability and stability is another key challenge. Furthermore, the overall system efficiency needs to increase, also at higher reaction rates (current densities). Substantial development also remains regarding the scale up from single reactor cells to stacks with multiple cells. Here, one of the challenges is to ensure that the flow management and temperature control of the multi-cell electrolyzer stacks allow for reaching the performance levels demonstrated in lab-scale.

Part II – Economics and integration

A techno-economic assessment was performed to estimate potential future costs for producing ethanol, carbon monoxide and ethylene through CO_2 electrolysis in West Sweden. Considering the low maturity of the technology, the analysis is subject to many uncertainties, both related to the potential technical performance and related to future prices of CO_2, electricity and products. However, the results point to some key conclusions.

First of all, it is clear that products from the electrochemical route will have difficulties competing with conventional, fossil-based products based on current market prices. Some kind of price premium will most likely be required for economic feasibility.

Furthermore, development of low-cost electrolyzers with high current density will be critical to keep capital costs for the electrolyzers at a reasonable level. If this is made possible, then lastly, access to low-price electricity will be a determining factor for cost competitiveness.

The three products that were investigated in the techno-economic analysis were chosen as relevant for potential integration into the chemical industry in Stenungsund. Carbon monoxide and ethylene are both important building blocks in the cluster, and would feed into existing downstream conversion processes. Ethanol has the advantage of, as a liquid product, being easily transported and stored. It could be produced at one site with access to CO_2 and cheap, low-carbon electricity and then transported to Stenungsund. There it could be further converted to ethylene via the ethanol-to-ethylene process, potentially integrated with ethylene production from bio-ethanol.

Sammanfattning

Elektrokemisk reduktion av koldioxid syftar på den kemiska reaktion där koldioxid omvandlas till olika kemikalier genom elektrolys. Tekniken för elektrokemisk omvandling av koldioxid kan, när den har blivit mer utvecklad, vara en möjlig processväg för att tillverka produkter från infångad koldioxid. Den innebär också en möjlighet att kemiskt lagra förnybar energi från exempelvis vindkraft genom elektrifierad produktion av kemikalier. Med direkt omvandling av koldioxid i bara ett processteg, processförhållanden nära omgivande temperatur och -tryck, och en bredd av möjliga produkter, har koldioxidelektrolys en potential att vara fördelaktig jämfört med andra alternativ för omvandling av koldioxid.

Den här rapporten består av två delar: I) en nulägesanalys av forsknings- och utvecklingsläget för elektrokemisk koldioxidreduktion, och II) en tekno-ekonomisk utvärdering och diskussion kring potentiell framtida integration av denna teknik i västsvensk industri. Rapporten baseras på en litteraturstudie, intervjuer med projektpartners och forskare, kartläggning av pågående forskningsprojekt och aktiva företag inom området, projektworkshops och tekno-ekonomisk modellering. De två delarna av rapporten sammanfattas nedan.

Del I – Nulägesanalys

Elektrokemisk koldioxidomvandling är fortfarande i en tidig utvecklingsfas, även om man under de senaste åren ser en utveckling mot mer industriellt relevant forskning och utveckling. Det går till exempel att se både intresse från större företag och en framväxt av startups inom området. Särskilt utvecklingen av gasdiffusionselektroder, som möjliggör betydligt högre reaktionshastigheter och nya typer av elektrolysörer, har varit ett viktigt framsteg i teknikutvecklingen. Vidareutveckling av katalysatorer, material och reaktorutformning har också möjliggjort en snabb förbättring av processens verkningsgrad och effektivitet.

Högst teknisk mognad för lågtemperaturelektrolys av koldioxid har uppnåtts för produktion av kolmonoxid och myrsyra (TRL runt 6). Den största demonstrationsanläggningen för elektrokemisk omvandling av koldioxid i Europa idag är den elektrolysanläggning på 10 kW som invigdes av VoltaChem 2023. I testanläggningen kan just kolmonoxid och myrsyra produceras. För andra produkter är teknikmognaden dock lägre, och mer forskning behövs för att nå en acceptabel prestanda.

För att tekniken ska kunna bli ett rimligt alternativ vid framtida produktion av kemikalier behöver prestandan förbättras, vilket kräver vidareutveckling av såväl katalysatorer, elektroder och membran som av själva elektrolysörens utformning. Till exempel behövs utveckling av katalysatorer som ger högre utbyte av specifika önskade målmolekyler

(högre selektivitet). Detta för att undvika att produktflödet består av en blandning av olika ämnen som sedan behöver separeras. Att utveckla katalysatorer och membran som håller bättre över tid är en annan viktig utmaning. Dessutom behöver systemets totala energieffektivitet öka, och det även vid högre reaktionshastighet (strömtäthet). Det återstår också mycket utveckling när det gäller uppskalning från enkla reaktorceller till stackar med flera celler. En av utmaningarna är att kontrollera materialflöden och temperaturer genom de enskilda cellerna i stacken så att den prestanda som demonstreras i labbskala kan uppnås.

Del II – Ekonomi och integration

En teknoekonomisk utvärdering genomfördes för att uppskatta möjliga framtida kostnader för produktion av etanol, kolmonoxid och eten genom koldioxidelektrolys i Västsverige. Med tanke på teknikens låga mognadsgrad påverkas analysen av många osäkra faktorer, både relaterat till den framtida tekniska prestandan och relaterat till framtida priser på koldioxid, el och produkter. Resultaten pekar dock på några viktiga slutsatser.

För det första står det klart att elektrokemiskt framställda produkter kommer att få svårt att konkurrera med konventionella, fossilbaserade produkter baserat på nuvarande marknadspriser. Någon form av prispremie kommer med största sannolikhet att krävas för att processen ska vara ekonomiskt gångbar.

Dessutom kommer utveckling av billiga elektrolysörer som tillåter hög strömtäthet att bli avgörande för att hålla kapitalkostnaderna för elektrolysörerna på en rimlig nivå. Om detta blir möjligt kommer slutligen tillgången på el till låga priser att vara en avgörande faktor för kostnadseffektiviteten.

De tre produkter som undersöktes i den teknoekonomiska analysen valdes ut som relevanta för potentiell integration i den kemiska industrin i Stenungsund. Kolmonoxid och eten är båda viktiga byggstenar i klustret och skulle kunna matas in i befintliga omvandlingsprocesser nedströms. Etanol har fördelen att det är en flytande produkt som är lätt att transportera och lagra. Den skulle kunna produceras på en plats med tillgång till koldioxid och billig el och sedan transporteras till Stenungsund. Där skulle den kunna omvandlas vidare till eten via etanol-till-eten-processen, potentiellt integrerat med etenproduktion från bioetanol.

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List of abbreviations

AEM	Anion Exchange Membrane
BPM	Bi-Polar Membrane
CAPEX	Capital Expenditure
CCU	Carbon Capture and Utilization
CD	Current Density
CO_2RR	Carbon Dioxide Reduction Reaction
CV	Cell Voltage
ETS	Emissions Trading Scheme
EUA	EU ETS Allowances
FE	Faradaic Efficiency
GDE	Gas Diffusion Electrode
HER	Hydrogen Evolution Reaction
MEA	Membrane Electrode Assembly
MTO	Methanol-To-Olefins
PEM	Proton Exchange Membrane
PSA	Pressure Swing Adsorption
SOEC	Solid Oxide Electrolyzer Cell
TEA	Techno-Economic Assessment
TRL	Technology Readiness Level

Introduction

The conversion of CO_2 into different products offers an opportunity for utilization of captured CO_2, i.e., what is commonly referred to as CCU (Carbon Capture and Utilization). With electricity as a key input to the process, this also enables the conversion of renewable electricity into products that can be easily transported and stored.

Electrochemical reduction of CO_2 refers to the one-step conversion of CO_2 into chemicals and fuels via electrocatalytic reactions. As illustrated in Figure 1, this is an alternative to the more well-known and mature thermocatalytic pathway for CO_2 conversion, where water electrolysis is first used to produce H_2, which then reacts with CO_2 in a hydrogenation step.

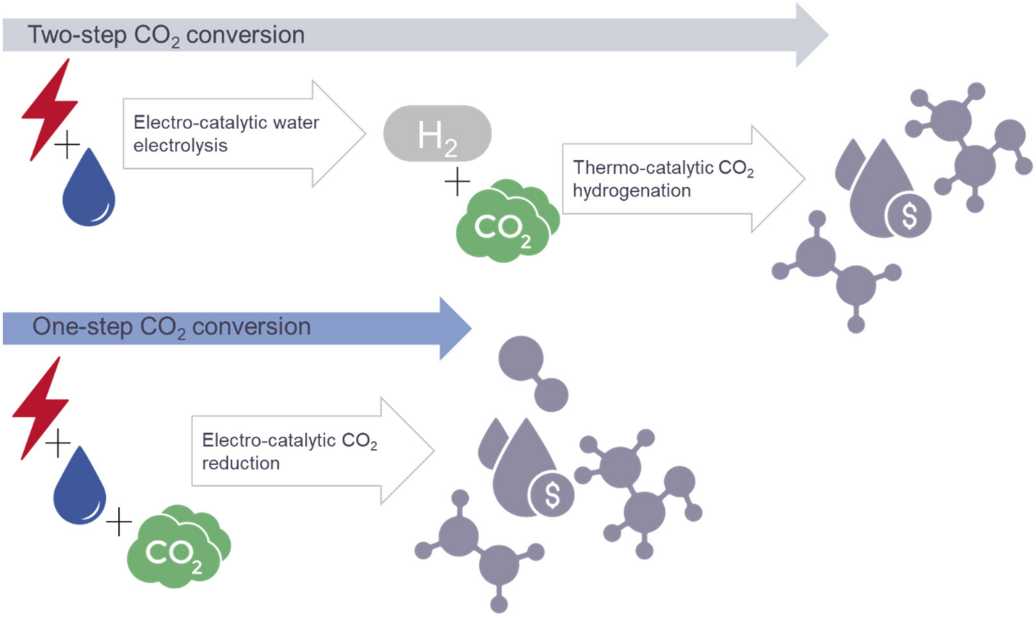


Figure 1. Two-step thermocatalytic hydrogenation pathway (top) and one-step electrocatalytic reduction pathway (bottom) for CO_2 conversion.

The electrocatalytic CO_2 conversion route can potentially reduce the number of process steps compared to thermocatalytic pathways via H_2. With fewer conversion steps, there is also, at least theoretically, a potential to reduce conversion losses and reach higher overall efficiencies. Similar to water electrolysis for hydrogen production, CO_2 electrolysis is a highly modular technology, which should be flexible in terms of scalability and attractive for decentralized operation. In contrast to thermal catalysis, electrocatalytic CO_2 reduction can be driven under mild conditions, i.e. close to ambient pressures and temperatures (Gao et al., 2022).

Similar to water electrolyzers for hydrogen production, CO_2 electrolyzers could potentially also offer opportunities to operate flexibly in response to intermittent supply of renewable electricity or varying electricity prices. However, the effect on performance and equipment wear of frequently switching on and off operation or varying the power load has been very scarcely studied (see Section 2.4).

While electrochemical CO_2 reduction has a promising potential, the technology maturity is still relatively low (see Section 3), and several challenges remain to be solved before the technology can reach industrially relevant performance levels (see Section 1.1). In order to be economically attractive, upstream and downstream processes along the carbon capture and utilization value chains must also be considered. External conditions such as electricity prices and policy instruments affecting the cost of emitting CO_2 will also set important framework conditions for the competitiveness of the technology once the technical challenges have been resolved.

This report is structured in two parts. The objectives of Part I State-of-the-art analysis are:

- To introduce the technology and basic concepts related to electrochemical conversion of CO_2 and its performance.
- To provide an overview of potential products, their markets and commercialization opportunities (and barriers).
- To present and discuss the maturity of the technology.
- To discuss remaining challenges, which need to be solved to further develop and scale-up the technology.

The objectives of Part II Economics and Integration are:

- To identify a selection of potential target products from electrochemical reduction of CO_2 that may be of interest for the industry in West Sweden.
- To introduce a method for a evaluating the potential economic performance of the technology in future scenarios for West Swedish industry.
- To present results from the techno-economic assessment (TEA) that considers expected future performance levels and market conditions for the target products.
- To discuss opportunities for integration in Stenungsund’s chemical cluster for chosen target products.

To meet the objectives, the following activities have been completed within the project:

- Interviews with project partners (Perstorp, Inovyn, Vattenfall, Renova, and Uniper) and researchers from RISE, KTH, and Stockholm University.
- A survey of relevant research literature focusing primarily on recently published review papers (2019 or later).
- A survey of companies active in the field of electrochemical CO_2 reduction and of European projects aiming at further development the technologies.
- Workshops with the project group to define assumptions for the TEA, to identify target products and to discuss preliminary results.
- Use of techno-economic models to estimate future production costs for identified target products.

Part I.

State-of-the-art analysis

1 Electrochemical reduction of CO_2

An electrolyzer used for CO_2 reduction (also referred to as an electrochemical reactor or cell) consists of the following main components (Garg et al., 2020):

- a *cathode* with a catalyst, where CO_2 reacts to form different products (e.g. CO or formic acid)
- an *anode* with a catalyst, where typically water reacts to produce O_2
- a (traditionally aqueous) *electrolyte* that conduct ions
- an *ion-exchange membrane* to separate the cathode and anode electrodes
- a *voltage source* to transfer electrons (e^-) from the anode to the cathode

Figure 2 shows a type of electrolyzer used in research laboratories. In this kind of electrolyzer, the electrolyte is also used to dissolve and transport the CO_2 to the cathode.

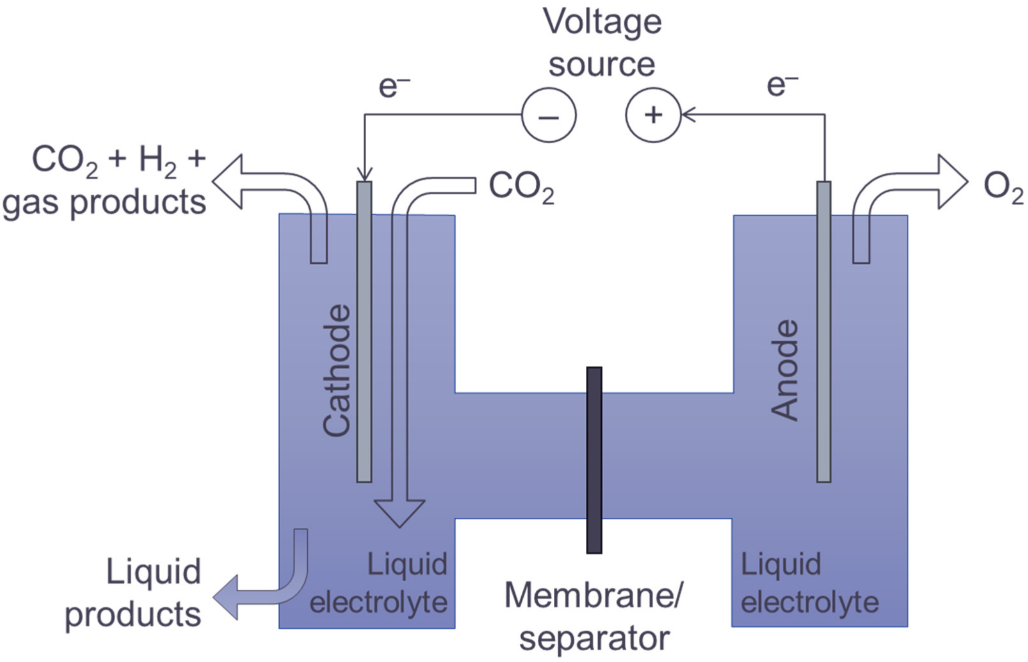


Figure 2. Principles of an electrochemical reactor for CO_2 reduction of a type that is commonly used in research laboratories (H-cell).

The electrochemical reduction of CO_2 to various products – the *CO_2 reduction reaction (CO_2RR)* – can be described by the following general reaction:

$$x\,\mathrm{CO_2} + 2y\,\mathrm{H^+} + 2y\,\mathrm{e^-} \rightarrow \mathrm{C}_x\mathrm{H}_{2(y-z)}\mathrm{O}_{2x-z} + z\,\mathrm{H_2O} \qquad (1)$$

Depending on the number of proton and electron transfer steps (the value of y), this reaction can form a variety of products, including CO, formic acid (formate), methane, methanol, ethylene, ethanol, acetate acid (acetate), and n-propanol (Gao et al., 2022).

1.1 Challenges of electrochemical CO_2 reduction

One of the main challenges of the CO_2RR (1), is that the reaction competes with the hydrogen evolution reaction (HER), i.e., the protons (H^+ ions) needed for the CO_2 reduction reaction (CO_2RR) can also react at the cathode to produce hydrogen. “Maintaining the right balance [of water as a proton source and CO_2 as a substrate for reduction] and ensuring suitable mass transport of the reactants to and products from the electrode thus plays a key role in the cathodic process of CO_2 electrolysis” (Gawel et al., 2022).

Furthermore, the electrochemical reduction of CO_2 typically leads to a mix of different products being obtained. To avoid costly downstream separation and maximized yields of desired products, further improvements in selectivity will therefore be one key to further develop the technology. In particular, selectivity improvements are needed for products with two or more carbon atoms (C2+ products) (Gao et al., 2022). However, the reaction pathways are highly complex and still not well understood on a fundamental level, especially for these higher-order products involving multiple proton and electron transfer steps. This makes it challenging to intentionally design catalysts that are selective for specific products.

In addition to development of new and improved catalysts that can achieve higher selectivity towards different products, there are also other challenges that need to be addressed. These include developments of the general setup of the electrolyzer cell, including (but not limited to), the flow configuration of reactants and products, the type of membranes used, and the operating conditions (Gawel et al., 2022).

One challenge of using CO_2 as a feedstock for electrolysis is that CO_2 has a low solubility in water, and easily forms bicarbonate and carbonate in the aqueous solutions that are used as electrolytes. The low solubility of CO_2 in water and the challenge of carbonate formation complicates the design of CO_2 electrolyzers. The low solubility means that it is difficult to achieve a sufficiently high concentration of CO_2 at the cathode, which means that the reaction rate will be limited by the CO_2 concentration. To achieve higher reaction rates and selectivity for reduced CO_2 products, CO_2 electrolyzers must consequently be designed so that the CO_2 can be transported effectively to the cathode catalyst in high enough concentrations (Stephens et al., 2022, chap. 1). The carbonate formation is associated with several challenges. Firstly, carbonates may precipitate in salt form and block the catalyst surface. Secondly, depending on the type of membrane used to separate the cathode and anode side of the electrolyzer, carbonate ions may transfer to the anode through the membrane. If they do, the carbonates will react back to CO_2 again at the anode, thereby leading to low carbon efficiencies due to carbon losses (Gao et al., 2022).

1.2 Key indicators

Several indicators are used to characterize the performance of CO_2 electrolyzers.

Current Density: Measures the rate of reaction. Current Density (CD) is the total current per unit area of the cathode. It is a measure of the rate of reaction, and thereby an important parameter to determine the potential throughput, electrolyzer size and capital cost (Garg et al., 2020). The minimum CD required for economic operation of CO_2 electrolyzers where the product is the result of two-electron transfers (e.g. CO or formic acid) is typically considered to be around 200 mA/cm^2, while for multi-carbon products, which requires multi-electron transfer, even higher CDs will be required (Gawel et al., 2022). It has also been suggested that an industrial implementation of electrochemical CO_2 reduction will require a partial CD of about 300 mA/cm^2 to be economically competitive (Kibria et al., 2019; Gawel et al., 2022).

Faradaic efficiency: Measures the product selectivity of the reaction. The Faradaic Efficiency (FE) is the share of the applied charge (i.e., the percentage of electrons) which is used to form one particular product (Garg et al., 2020; Gawel et al., 2022). It is an indicator for product selectivity, and thereby an important parameter affecting requirements for downstream separation, which influence economic feasibility of the overall process. To reduce costs associated with product separation, a high selectivity, meaning a high FE is desired (Gawel et al., 2022).

Cell voltage: Indicates the energy needed to operate the electrolyzer. The required Cell Voltage (CV) is a function of the thermodynamics of the reactions, the catalyst and membrane used, the operating conditions and the CD. It is the sum of the *equilibrium potentials* of cathode and anode reactions, i.e. the *reversible cell voltage*, the *overpotentials* required to activate the reaction at the cathode and anode respectively, and the *Ohmic voltage losses* (resistances) in, primarily, the electrolytes, the cell membrane, and the electrodes (Bushuyev et al., 2018). An energy efficient electrolysis process requires operating with low CV, i.e. with low overpotentials and voltage losses (Gawel et al., 2022).

Carbon efficiency: Expresses how much of the carbon in the supplied CO_2 is converted into products. The carbon efficiency measures the efficiency of the conversion from CO_2 into products (Wakerley et al., 2022). To reach a high carbon efficiency, it is important that CO_2 is transported effectively to the cathode catalyst, so that it does not pass the reactor without being converted. Furthermore, loss of carbon through carbonate formation should also be avoided.

Durability of operation: Hours of stable continuous operation. To be viable in commercial operation, the reactor design and the materials used in the reactor need to allow for thousands of hours of stable continuous operation. This makes durability of catalysts and electrode materials as well as other components of the reactors a key factor to be able to scale up the technology. It has been suggested that the key to durability lies in design of the reactor and the materials used to transport and separate flows, rather than in the catalyst itself (Wakerley et al., 2022).

1.3 Cell architectures

Low-temperature CO_2 electrolysis can be performed in different types of electrochemical reactors with different cell configurations: H-type cells, flow cells, and membrane-electrode assemblies (MEA) (Ozden et al., 2022). High-temperature solid-oxide electrochemical cells (SOECs) can be considered a special application (Gawel et al., 2022).

1.3.1 H-type cells

These liquid-phase electrolyzers (see Figure 2) are widely used in fundamental research on the electrochemical CO_2 reduction, especially for catalyst characterization. CO_2 is transported to the catalyst surface on the cathode via the electrolyte. The cell setup is convenient to use for testing, particularly for studies that require screening of, e.g., different catalyst designs.

Because of the low solubility of CO_2 in water under atmospheric conditions, the reaction rate in H-type cells is typically limited by mass-transport limitations, which makes it irrelevant to apply higher (more industrially relevant) CDs. “H-cell electrolysers are limited to low reaction rates, only several tens of mA/cm^2 due to the limited solubility of CO_2 in aqueous solutions” (Ozden et al., 2022). The dissolved CO_2 also requires the use of neutral or acid electrolytes, since the OH^- ions of basic electrolytes would react with the CO_2 to form carbonates. “The consequences are not only a loss of CO_2 but additionally a reduced CO_2RR activity, a lower conductivity of the electrolyte, and a shift of the pH value toward a more acidic milieu” (Gawel et al., 2022). Since key reaction conditions differ, results obtained in an H-type cell cannot be directly transferred to estimate performance under industrially relevant conditions. To test catalysts under higher CDs (industrially more relevant), alternative cell setups are required.

1.3.2 Flow cells

In flow cells (see Figure 3a), the transport of CO_2 to the catalyst takes place via the gas phase and is therefore not limited by the solubility of the gas in an electrolyte (Gao et al., 2022; Ozden et al., 2022). CDs well above 200 mA/cm^2 can be reached. Feeding of CO_2 in gaseous phase also favors the CO_2RR relative to the HER since the concentration of CO_2 increases at the catalyst interface (Stephens et al., 2022, chap. 3). With flow cell configurations, individual electrolyzer cells can be stacked for large scale applications.

A key component of flow cell electrolyzers are the *gas diffusion electrodes* (GDEs), by which the CO_2 is transported to the catalyst via a *gas diffusion layer*. While this allows for higher CDs, other challenges remain when using GDEs together with liquid electrolytes. For example, the liquid phase electrolyte is associated with high ohmic losses (leading to low energy efficiency), the produced liquid products are diluted by the electrolyte, and problems may occur due to precipitation of salts (Ozden et al., 2022). Furthermore, the transport processes of a GDE are complex and sensitive to relatively minor changes in different properties of the design, which makes it difficult to optimize the composition and structure of the GDEs (Gawel et al., 2022). One common problem related to this electrode structure is *flooding* of the electrodes, which means that the liquid electrolyte blocks the CO_2 diffusion paths in the electrode (Gawel et al., 2022). This severely impacts performance by reducing the availability of CO_2 at the catalyst, thereby favoring the HER.

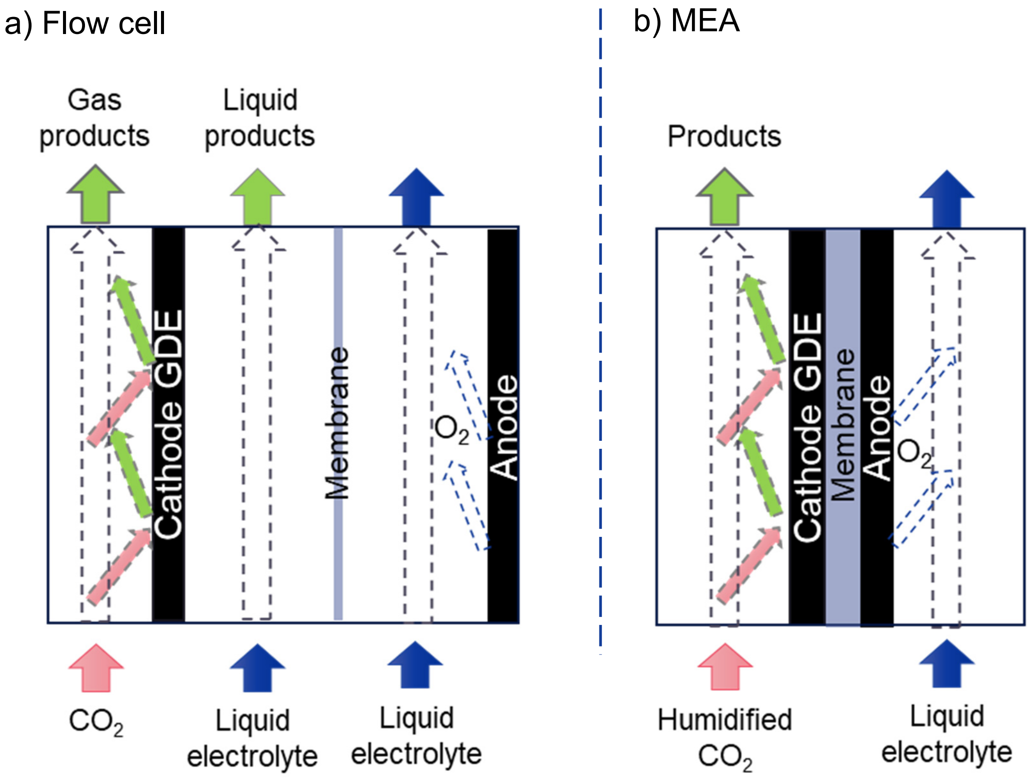


Figure 3. Schematic diagram of a) a flow cell configuration for CO_2 electroreduction and b) a membrane electrode assembly (MEA).

1.3.3 Membrane electrode assembly (MEA) or zero-gap cell

The membrane electrode assembly (see Figure 3b) is an emerging electrolyzer configuration. In a MEA cell, the membrane also functions as electrolyte, and is in direct contact with the cathode (which is a GDE) and the anode (Gawel et al., 2022). Because of the direct contact, this is also referred to as a zero-gap configuration (Ozden et al., 2022).

Through the use of GDEs, mass transfer limitations due to low solubility of CO_2 in water are avoided in MEAs. By also omitting the liquid electrolyte, ohmic losses (resistances) across the electrolyte, problems with flooding and formation of carbonates, and dilution and loss of liquid products are reduced (Ozden et al., 2022). Another potential advantage is that some catalysts, which do not work well in combination with aqueous electrolytes, could possibly be reconsidered when the aqueous electrolyte is removed from the setup.

In an MEA electrolyzer, the water, which is the source of protons for the CO_2RR, is usually supplied together with the CO_2 stream. The supply of water via the humidified CO_2 provides a way to better manage the balance of reactants (CO_2 and protons) through better control of the proton availability (Gawel et al., 2022). This in turn allows for higher conversion rates and operation at significantly higher CDs also at high FEs.

The advantages described above make MEA a promising configuration for CO_2 electrolyzers, and a potential key to scaling up and industrializing the technology. However, the majority of catalysts studied for CO_2RR has not been tested in MEAs, and few studies on MEAs have been performed at the high CDs relevant for industrial applications (Gawel et al., 2022).

There are also other drawbacks of the MEA setup. For example, at high CDs, liquid products or water (e.g., migrated from the anode) can potentially block the GDE structure and thereby the transport of CO_2 to the catalyst. This, and changes in the cathode environment may limit the selectivity and CDs that can be reached also in MEAs (Gawel et al., 2022). Furthermore, crossover of liquid products can occur also in MEAs, with the products passing through the membrane to the anode where they are reoxidized, thereby leading to carbon loss and lower efficiency (Gawel et al., 2022).

1.3.4 Solid-oxide electrolysis cells (SOECs)

In solid-oxide electrolysis cells (SOECs), the cathode and anode are separated by a solid electrolyte. The electrolyte is a dense layer of oxide (or ceramic) that conduct oxygen ions, but to achieve sufficient conductivity, temperatures above 600 °C are needed (Gawel et al., 2022).

With SOECs, syngas can be produced from CO_2 and water at high CDs, since the high temperatures also improve the reaction kinetics. However, the potential for other CO_2 reduction products than syngas from SOECs is limited. On the other hand, carbon monoxide (CO) or syngas produced in SOECs, could be further converted in subsequent process steps to other products (see also Section 1.6.2).

Drawbacks of SOECs include various challenges associated with the high temperatures, such as high energy demand, problems with reactor sealing and degradation of the electrolyte, and material property requirements (Gawel et al., 2022).

1.4 Membranes

Essentially all types of CO_2 electrolyzers have ion exchange membranes. These prohibit products generated at the cathode to be transported back to the anode and to be reoxidized, dividing the cell in two *half-cells* with different reaction environments. However, the membranes must allow ions to pass in order for the electric circuit to be closed. Membranes thus have an important role in regulating the mass transport within the cell, but also affect the electrical resistance, and thereby the required CV, which in turn affects the energy efficiency for the overall electrolysis process. A distinction is usually made between three types of ion-exchange membranes: Anion-exchange membranes (AEM), Proton-exchange membranes (PEM) and Bipolar membranes (BPM). A comparison of advantages and disadvantages of different types of membranes used in CO_2RR was presented by (Gawel et al., 2022), with key characteristics summarized here.

1.4.1 Anion-exchange membranes (AEM)

AEMs are the membranes primarily used for CO_2 electrolysis. This type of membranes allows anions, i.e., negatively charged ions, to pass through the membrane. The desired ion transport is that of OH^- ions. However, one basic problem when using AEMs is the crossover of carbon atoms from the cathode to the anode side (Gawel et al., 2022). On the cathode side, CO_2 easily forms carbonate (CO_3^{2-}) and bicarbonate (HCO^{3-}) anions. When these are transported through the AEM, they are reoxidized to CO_2 at the anode. Some of the products of the CO_2RR can also pass through an AEM. *Crossover* of carbonates and products followed by their reoxidation at the anode is detrimental to overall efficiency and CO_2 utilization.

1.4.2 Proton-exchange membranes (PEM)

PEMs enable protons (H^+ ions) to flow through the membrane from the anode to the cathode. The most common reaction at the anode, the oxygen evolution reaction, leads to the formation of protons (H^+ ions), which in turn are needed for the CO_2RR at the cathode. With PEMs, crossover of carbonates and product anions to the anode is inhibited. Instead, PEMs are associated with other challenges. The flow of protons from the anode to the cathode electrolyte (the catholyte), leads to a decrease of the pH on the cathode side. Such acidic environment favors the HER and thereby limits the possibilities of high selectivity for CO_2 reduction products (Gawel et al., 2022).

1.4.3 Bi-polar membranes (BPM)

BPMs are produced by combining a PEM and an AEM. This is done to prevent product crossover by stopping ions from flowing from one electrode to the other. Instead, water is split into OH^- and H^+ ions in a layer between PEM and AEM. The OH^- ion is transported through the AEM towards the anode, and the H^+ ion is transported through the PEM towards the cathode. However, crossover cannot be completely avoided (Gawel et al., 2022).

1.5 Catalysts

The catalyst used on the cathode is at the core of the electrochemical CO_2RR, with the composition and design of the catalyst being central in determining which products will be formed (Stephens et al., 2022, chap. 3). The binding energy between the surface of the catalyst and the reaction intermediates is a key factor in this. Enhanced selectivity for specific products will depend on the development of new and better catalyst designs. Other than selectivity, the catalytic activity is also an important property of the catalyst.

There are plenty of studies on a variety of catalysts for CO_2RR. Briefly, studies of copper-based cathodes are dominating the field for production of ethylene and ethanol due to copper’s high selectivity towards C2+ chemicals. Gold and silver-based cathodes in turn have been shown to present higher selectivity for CO and syngas production (Raya-Imbernón et al., 2024) while high selectivity towards formic acid has been demonstrated over tin-based electrocatalysts (Fernández-Caso et al., 2023). But up until recently, the evaluation of catalysts has only been done in lab-scale experiments. This means, there is still a need for better understanding of how these catalysts will work in the operational environment of industrial-scale, flow-cell, zero-gap electrolyzers.

For a material to be promising as a catalyst for electrochemical production of commodity chemicals, it not only needs to be effective; its availability and affordability are also important factors to consider. To be economically and environmentally viable, the catalysts should be possible to manufacture in a sustainable way in large amounts, and at low costs.

1.6 Process concepts for improved overall system efficiencies

Electrochemical reduction of CO_2 might be combined with other conversions to increase overall efficiencies. A first priority is to ensure that a valuable product is obtained also at the anode of the electrolyzer. This may involve looking at other products than oxygen.

One of the challenges with electrochemical reduction of CO_2 is carbon loss, especially due to carbonate formation in alkaline electrolytes. This limits the potential single-pass conversion of CO_2 to target products that can be achieved. Strategies to overcome this limitation were reviewed by Ozden et al (2022) who analyzed four different carbon-efficient pathways: CO_2 regeneration from carbonate, CO_2 reduction in acidic media, cascade processes involving CO_2 reduction to CO and CO reduction to further products, and finally CO_2 reduction directly from a capture liquid. The latter concept, i.e. integrated capture and electrochemical conversion of CO_2 was also reviewed by (Gutiérrez-Sánchez et al., 2022). Below, the opportunities of cascade processes, and integration of the CO_2 capture and electrochemical conversions process are described a little bit further.

1.6.1 Other products at the anode

The electrochemical CO_2RR is most commonly paired with the oxygen evolution reaction at the anode. This is the same anodic reaction that takes place in water electrolysis where hydrogen is produced at the cathode. However, other reactions could be considered for the anode. For example, Garg et al. (2020) mentions water purification, where the anode reaction could oxidate organic pollutants in wastewater, as one possibility, and oxidation of chloride to chlorine (similar to chlor-alkali cells) as another.

1.6.2 Cascaded conversion processes

The use of a two-step electrochemical conversion process is sometimes referred to as cascade or tandem processes. The most common, and maybe most promising, example of such cascaded electrochemical conversions is to first convert CO_2 to CO, and then CO to products such as ethylene or ethanol. This way, CO is first produced electrochemically from CO_2, which can be done with high selectivity. Then, CO instead of CO_2 is used as a substrate for electrochemical reduction to higher-order products. This eliminates the production of formate as a side product, and has the potential to significantly increase selectivity for higher-order products such as ethanol and n-propanol (Gawel et al., 2022).

The electrochemical conversion of CO_2 to CO can be done in high-temperature SOECs, while the second step can be done in low-temperature electrolyzers (e.g., MEAs). This way, the advantage of high-temperature electrolysis for CO_2 activation can be combined with the advantages of low-temperature electrolysis for obtaining the desired products (Gao et al., 2022). For example, the cascading of CO_2-to-CO in a SOEC and CO-to-ethylene in a MEA electrolyzer has been shown to reduce energy input by almost 50% compared to a direct CO_2-to-ethylene conversion route (Gawel et al., 2022). This efficiency improvement is achieved because when carbonate formation is avoided, the need for reprocessing of the electrolyte and anode product gas stream to avoid is eliminated.

An alternative could be to use an acidic MEA electrolyzer for the first CO_2-to-CO step, and an alkaline MEA electrolyzer for the second CO-to-C2+ step. In this case the advantage of avoiding carbonate formation in acidic CO_2 electrolysis is combined with the advantage of improved C2+ productivity in alkaline CO electrolysis (Gao et al., 2022).

1.6.3 Integrated capture and electrochemical conversion

One of the main costs of electrochemical CO_2 conversion is the cost of CO_2, which typically must be captured from a flue gas (or the atmosphere), concentrated, and delivered in pure form to the electrolyzer. In the CO_2 capture plant, the regeneration of the capture solution to release a concentrated stream of CO_2 is an energy-demanding process, which consequently decrease the overall efficiency of a CO_2 capture and conversion process.

One strategy to overcome this could be to use the CO_2-rich capture media directly as a CO_2 source for the electrochemical reactor. More precisely, instead of sending pure CO_2 to the electrolyzer, CO_2 captured in the form of carbonates (capture using alkaline hydroxides) or carbamates (capture using amines) are sent to the reactor (Gutiérrez-Sánchez et al., 2022).

Li et al. (2022) conducted a case study on the coupled amine scrubbing and CO_2-to-CO electrochemical conversion. They estimated that “a directly coupled CO_2 capture and electrochemical conversion could potentially save close to 44% energy consumption and 21% energy cost versus a sequential process based on the state-of-the-art gas-fed CO_2 electrolysers, if the integrated electrolysis performs similarly to the gas-fed electrolysis (3 V and 90% FE for CO) and has a high single-pass conversion efficiency to achieve the CO_2-lean state of the amines.”

However, this idea is only at a very conceptual level. Until recently, the concept was almost non-existing in literature (Gutiérrez-Sánchez et al., 2022).

2 Products, techno-economics, and markets

The electrochemical reduction of CO_2 can lead to a variety of products. Examples of products that have been obtained through direct electrochemical conversion of CO_2 include carbon monoxide, methane, formic acid, ethylene, ethanol, acetate and n-propanol (Bushuyev et al., 2018). The products obtained depend on the catalyst being used.

2.1 Potential pathways to different products

The conversion of CO_2 to different end products may go through many potential pathways, where electrochemical reduction of CO_2 can be combined with other types of conversion steps below shows potential production pathways involving electrochemical CO_2 reduction. For example, smaller building-block molecules can be upgraded in further thermocatalytic processes such as the Fischer-Tropsch or methanol-to-olefin (MTO) process (Bushuyev et al., 2018). Figure 4 illustrates some of these pathways.

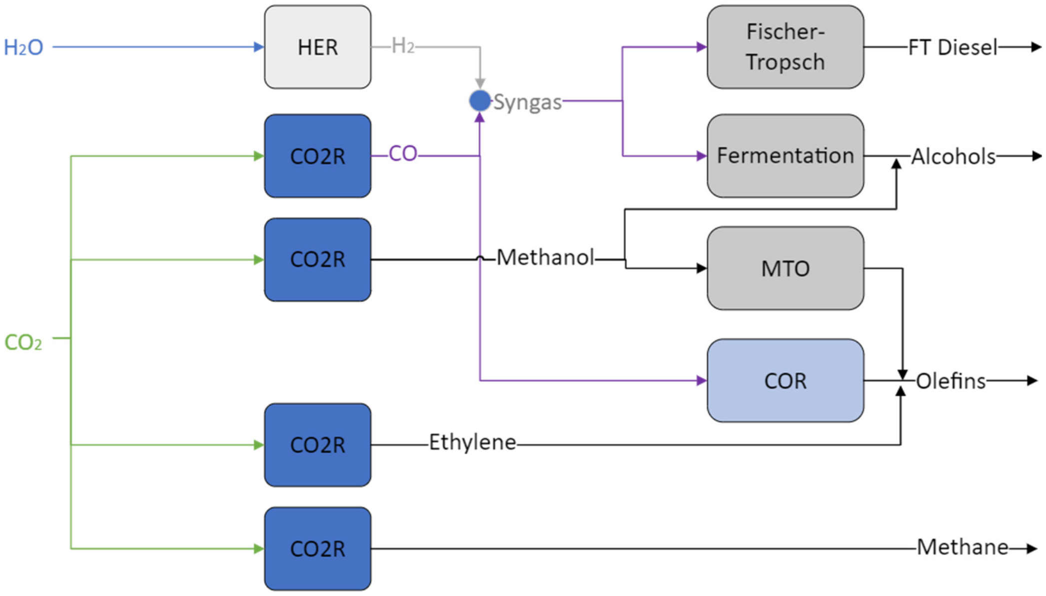


Figure 4. Pathways for production of different commodity chemicals from CO_2 via electrocatalytic conversion. (CO2R=CO_2 Reduction, COR=Carbon Monoxide Reduction, FT=Fischer Tropsch, HER=Hydrogen Evolution Reaction, MTO=Methanol-To-Olefins). Inspired by (De Luna et al., 2019).

Several of these pathways are based on using *carbon monoxide* (CO) produced via electrochemical CO_2 reduction as an intermediate. CO can then be used in further thermochemical, biological, or electrochemical processes. By mixing CO with H_2, a syngas is obtained, which can be used for Fischer-Tropsch synthesis or fermentation to produce large-volume products such as diesel or alcohols. Syngas fermentation using enzymes and bacteria can also generate more high-value chemicals such as acetic acid, butyric acid, ethanol, butanol, and biodegradable polymers (De Luna et al., 2019). CO as a product from the electro-conversion step would be in gaseous form at ambient conditions, and would therefore also be easier to separate than products that are dissolved in electrolyte (Stephens et al., 2022, chap. 3). When syngas is targeted as the intermediate, competition with the hydrogen evolution reaction would not be too problematic, since H_2 is also desired. This would allow for co-generation of H_2 and CO. However, obtaining a specific $CO:H_2$ ratio in one electrolyzer would come at the expense of lower selectivity towards CO. Consequently, techno-economic analyses show that it is likely more beneficial to maximize production of CO in one reactor, and supplement with H_2 from a separate electrolyzer (De Luna et al., 2019).

Alcohols can be used as chemical precursors, drop-in fuels, and solvents, with relatively large markets, which make them an attractive product group. Currently, alcohols are mainly made through the conversion of petrochemicals or by fermentation of sugars. The fermentation pathway is an alternative to the fossil-based production route but is challenged by competition for sugars with food production, slow production rates, high water intensity, and the microorganisms being highly sensitive to the operating conditions. Electrocatalytic production of alcohols can therefore be a promising alternative for replacing current fossil-based conversion processes. Experiments have shown that short-chained alcohols (methanol and ethanol) can be produced through electrochemical reduction of CO_2 with relatively high selectivity. However, increases in selectivity will still be needed and product separation may nonetheless remain a challenge. And while electrochemical CO_2 reduction to alcohols shows many promising aspects, another remaining challenge is to find a viable business case as long as it still competes with low-cost fossil-based processes (De Luna et al., 2019).

Ethylene is a petrochemical commodity, which is a building block of the most common plastic used today: polyethylene. Ethylene is primarily priced based on feedstock cost. In regions where naphtha is the main feedstock, and feedstock prices consequently are higher and sometimes volatile, electrocatalytic conversion shows greater promise. Several alternative pathways for production of ethylene are being developed, but further improvements are generally needed to make these cost competitive. Electrochemical CO_2 reduction has only recently been demonstrated at industrially relevant CDs. With further improvements in energy efficiency, selectivity and conversion rates and operational durability, the electrocatalytic pathway could become another alternative for sustainable production of ethylene (De Luna et al., 2019).

2.2 Energy efficiency and selectivity

A fundamental difference between products, if they are to be produced electrochemically from CO_2, is the number of proton-electron transfer steps required. For example, production of one CO molecule requires only two electrons being transferred, while ethylene or ethanol involves transfer of 12 electrons (Stephens et al., 2022, chap. 3). This is also linked to the number of carbon-carbon bonds in the target molecules, with higher-carbon products requiring more proton-electron transfers. The energy requirements as well as the reaction complexity increase with the number of proton-electron transfer steps.

Electrochemical production of higher-carbon products has a substantial electricity demand because of the many electron transfers required. This is to some extent also reflected in the higher energy density of such products (Bushuyev et al., 2018). However, as shown by Figure 5 below, the relative increase in energy density does not correspond to the increase in electron transfers. Consequently, the gain in energy density cannot by itself motivate the increase in energy demand for the electrosynthesis. Furthermore, more complex products typically also require higher overpotentials, i.e., the more complex the product is, the more energy is needed relative to the thermodynamic minimum requirements (Bushuyev et al., 2018). Consequently, higher-order products may store energy more efficiently, but are produced less efficiently. “Simply put, the larger you go, the more energy you need to get there, and the less efficient you become” (Stephens et al., 2022, chap. 3). Stephens et al therefore suggest prioritizing simple, small molecules that can be used as building blocks for production of larger molecules.

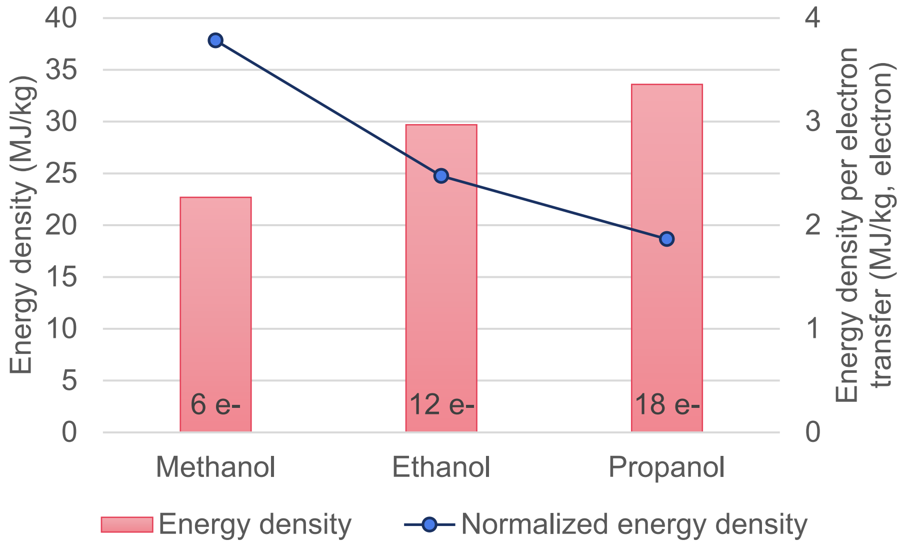


Figure 5. Comparison of energy density and normalized energy density for short-chained alcohols. Adapted from (Bushuyev et al., 2018)

Since reaction complexity increases with more proton-electron transfers, it is also easier to reach high selectivity, measured as Faradaic Efficiency (FE), for low-order molecules. For example, for C1 products, FEs above 95% have been reported, for C2 products, current state-of-the-art is around 60% FE, while for higher order products, FE is still below 10% (Bushuyev et al., 2018). This implies that if these higher-order molecules are produced, there will also be a range of other molecules in the product mix, thus leading to substantial needs for downstream separation. Figure 6 illustrates FEs for different products, which have been achieved using different catalysts and reported in literature. The figure also illustrates the corresponding CDs. Difficulty to reach competitive levels of selectivity for more complex target molecules is yet another reason to focus on smaller building-block molecules such as methanol, CO, ethylene, or aldehydes (Bushuyev et al., 2018).

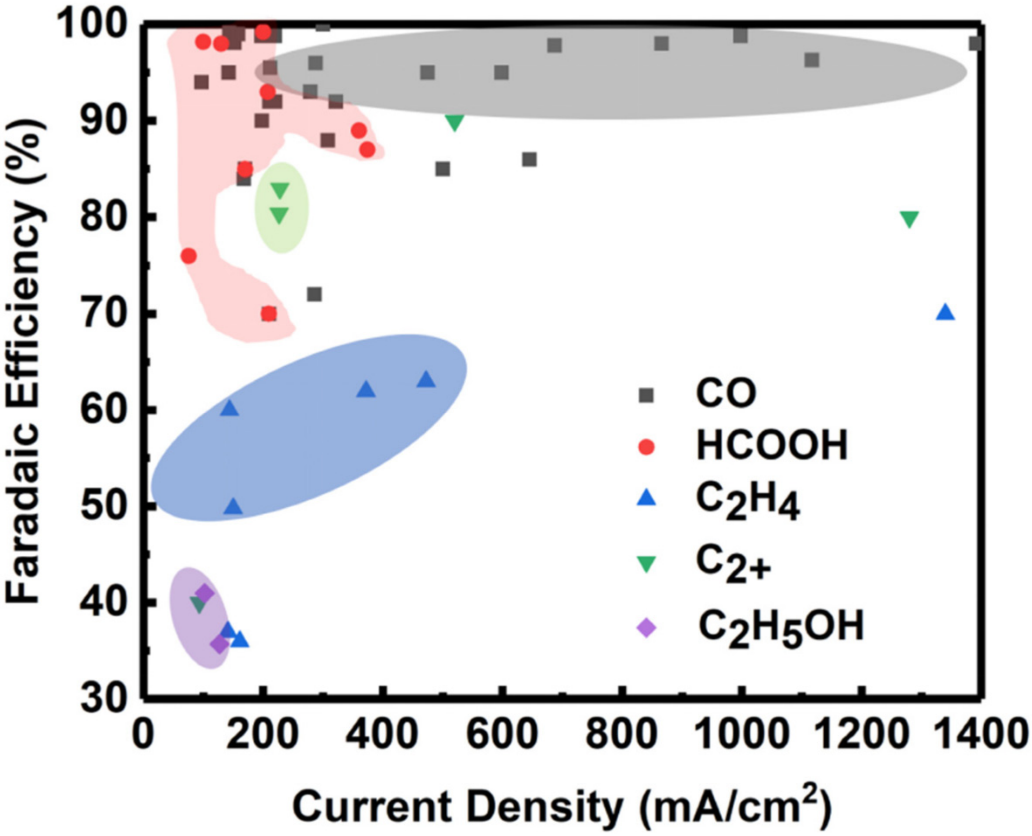


Figure 6. FE and corresponding CD for different products obtained via CO_2 electrolysis (Chemical notation in legend: CO is Carbon monoxide, HCOOH Formic acid, C_2H_2 Ethylene, C_{2+} refer to any products with more than 2 carbon atoms, C_2H_5OH is Ethanol). Source: (Lin et al., 2022)

2.3 Economics and markets

The economic feasibility of producing a certain product through electrocatalytic conversion of CO_2 depends on many factors including investment costs for the electrolyzer and for downstream separation and purification. However, the margin between the expected market price and the main operating costs (costs for CO_2 and electricity) gives a simple indication of the potential to reach profitable operation.

In Figure 7, estimated market prices (normalized to carbon content) for different products are plotted against the energy content of these products. The energy content (i.e., the higher heating value for the different molecules normalized to carbon content) indicates a theoretical minimum electricity requirement for their production in a CO_2 electrolyzer, and thus sets a lower limit for the cost of production. The size of the marker indicates the size of the global market. The lines represent the cost of CO_2 and electricity at different electricity prices. Note that all quantities are normalized to one tonne of carbon. Investment costs and other operating costs than CO_2 and electricity are not included, and no consideration is given to carbon and energy conversion losses. However, products above the line at least have a potential to be economically feasible, since there is a margin between the market price and the lower theoretical limit for the cost of operation.

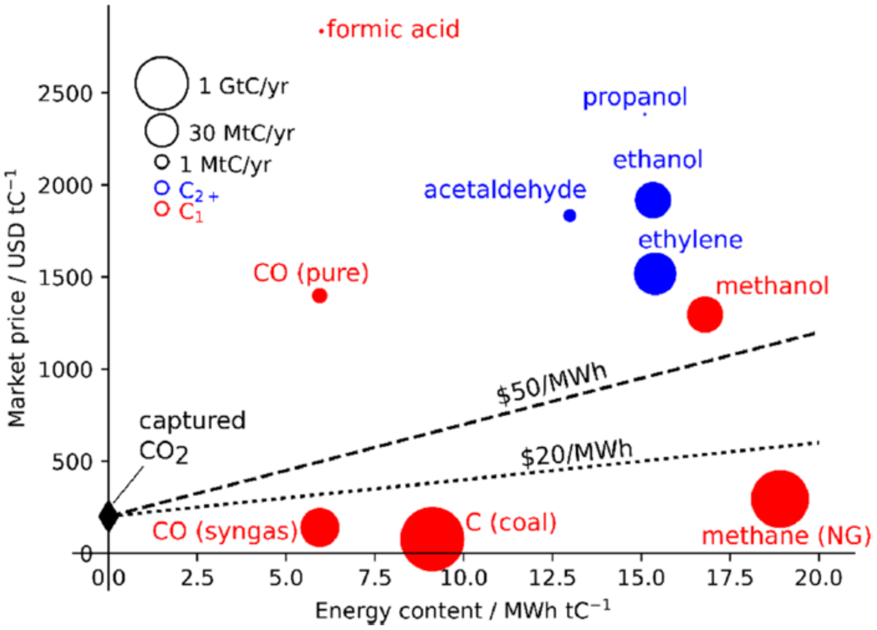


Figure 7. Market price of CO_2 electroreduction products as a function of energy content. Lines represent minimum energy and CO_2 costs. Capital costs are not considered. Source: (Nitopi et al., 2019)

Figure 7 clearly shows the best product margins for specialty chemicals such as formic acid and propanol, for which, however, the market is very small. More promising in terms of market size, while still showing some potential economic margin, are commodity chemicals like ethylene and ethanol. Both ethylene and ethanol have been widely studied as products from CO_2 electroreduction

More comprehensive techno-economic assessments (TEAs) for different products from CO_2 electrolysis have been presented in several recent studies (e.g., Bushuyev et al., 2018; Kibria et al., 2019; Shin et al., 2021; Detz et al., 2023). These consider, besides costs for CO_2 and electricity, also costs for separation, capital, maintenance and operation, based on assumptions about electrolyzer performance characteristics.

Similar to the analysis presented by Nitopi et al. (2019) in Figure 7, Bushuyev et al (2018) identified CO and formic acid as economically viable. They also showed that ethylene glycol and propanol could be attractive target molecules with market prices significantly higher than estimated production costs. Kibria et al. (2019) concluded that the most economically promising products are CO, formic acid, ethylene and ethanol. Their TEA also indicates that for electrochemical CO_2 reduction to be competitive, further development should aim at reaching Faradaic efficiencies of at least 90%, cell voltages below 1.8 V, current densities above 300 mA/cm^2, and stable operation for at least 80 000 hours.

Shin et al. (2021) estimated production costs for CO and formic acid to US$0.44 and 0.59 per kg, respectively, which they claim fall within the range of current market prices. While their results indicate economic feasibility for these C1 products, their estimated production costs for the C2 products ethylene and ethanol are considerably higher than current market prices. Shin et al. (2021) found that the production cost is most sensitive to variations in electricity price. A roadmap for reaching closer to production cost targets for ethylene and ethanol was presented, with the main opportunities related to intermittent operation to be able to utilize low-price electricity, and improvements in cell performance at high CDs to keep investment costs down, while allowing for energy efficient operation.

Detz et al. (2023) presented a techno-economic comparison of six different routes for electrochemical CO_2 conversion: low-temperature production of CO, formic acid and ethylene, high-temperature production of CO and syngas production, and a tandem approach to produce ethylene. Unlike the other studies cited above, which found that at least CO and formic acid are economically promising products for low-temperature CO_2 electrolysis, Detz et al. (2023) concluded that low-temperature electrolysis processes are very far from competing with current technologies (for all products), and that especially investment costs would need substantial reductions (see Figure 8). And while Shin et al. (2021) found that the estimated production cost is most sensitive to the assumptions about electricity price, Detz et al. (2023) found that capital costs dominate the production cost for low-temperature routes.

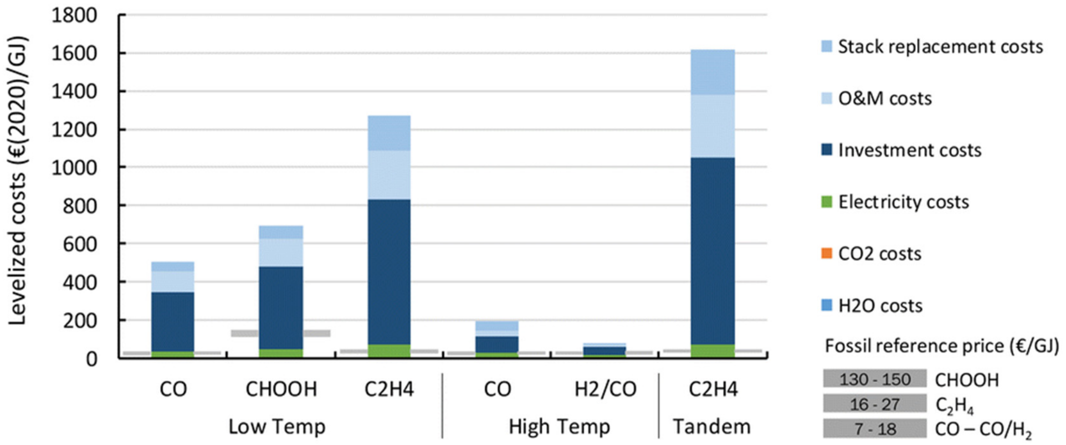


Figure 8. Production costs of different CO_2 electrochemical conversion routes. Source: (Detz et al., 2023).

The fundamental differences in results and conclusions from different TEA studies highlight the large uncertainties in future performance levels and the difficulty of making assumptions for technologies that are still in a very early development phase.

2.4 Operational flexibility

In principle, flexible operation of CO_2 electrolyzers in response to varying electricity supply or prices should be possible (Samu et al., 2022). Dynamic responses of electrochemical reactions are generally fast (Roh et al., 2022), and low-temperature electrolyzers are particularly promising for dynamic operation, since challenges related to thermal management are significantly reduced compared to high-temperature processes (Samu et al., 2022).

However, up until now, flexible or dynamic operation of CO_2 electrolyzers has been very scarcely studied. While some aspects of flexible operation can be compared to that of water electrolyzers, there are several notable differences that may cause additional challenges for CO_2 electrolyzers. For example, rapid load ramping might cause local fluctuations in the conditions at the cathode surface, which may cause flooding in the gas diffusion electrodes of gas-fed CO_2 electrolyzers (Samu et al., 2022). Another challenge is that the composition of the product stream may vary depending on the applied power load (current density). Such variations of the product composition would not only imply deviations in the yield of the desired production, but may also negatively affect the efficiency of downstream separation processes (Roh et al., 2022). Furthermore, the process for separation of unreacted CO_2 is likely to have a slower response than the electrolysis reaction, and would therefore limit the ramping speed unless intermediate storage is implemented between the electrolyzer and the CO_2 separation unit (Roh et al., 2022)

On the other hand, it has recently been demonstrated that a zero-gap design of the CO_2 electrolyzer cell (a membrane-electrode assembly, MEA) could enable efficient intermittent operation for a week without any significant performance loss (Samu et al., 2022). Furthermore, the modularity of the electrolysis technology is an advantage, which to some extent could be used to avoid challenges related to part-load operation. It could, for example, be possible to enable flexibility by switching on and off operation of individual stacks rather than varying the individual loads.

Nevertheless, design for flexible operation would imply additional considerations, not only related to the necessary overdesign of the electrolyzer itself. Like for water electrolyzers (see e.g. Edvall et al., 2022), it is likely that frequent on/off switching would lead to increased wear of the materials and components in the electrolyzers. Varying operation would also create a demand for additional storage, both of the CO_2 to be fed to the electrolyzer, and of the product streams before and/or after separation of unreacted CO_2. The feasibility and cost of having such storage strongly depends on the targeted product and its properties, with liquid products generally being expected to be easier to store.

3 Technology maturity

The vast majority of studies on electrochemical CO_2 reduction are based on experiments using H-type cells with CO_2 dissolved in an aqueous electrolyte. However, in recent years, a development is seen towards more industrially relevant research and development. The increased focus on industrial development is seen, for example, from corporate interest and the emergence of start-up companies in the field (Wakerley et al., 2022). Appendix A lists companies that are pursuing commercialization of CO_2 electrolysis technologies or are active in research and development projects in the field.

Especially the adoption of gas diffusion electrodes (GDEs) has allowed for breaking the limitation of CO_2 solubility, enabling significantly higher throughputs (Wakerley et al., 2022). The GDEs have also opened the possibility for new reactor designs including membrane electrode assemblies (Nørskov et al., 2019). Recently, multi-cell CO_2 electrolyzer stacks have also been demonstrated. With these developments of components, materials and reactor setups, efficiencies and conversion rates have seen rapid improvements (Ozden et al., 2022) and are expected to further increase (Gao et al., 2022). For example, record-high current densities (CDs) for ethylene and CO production have been reported, with values above 1000 mA/cm^2, which is comparable to that of water electrolyzers for H_2 production (Wakerley et al., 2022). However, most reported energy efficiencies and operational lifetimes are insufficient for industrial implementation, and carbon conversion efficiencies and product selectivities need to be further improved to keep separation costs at reasonable levels (Wakerley et al., 2022).

The most developed technology for electrochemical reduction of CO_2 are electrolyzer/ catalyst combinations that can reduce CO_2 by two electrons to make CO or formate/ formic acid. In lab-scale, production of CO or formic acid can reach performance levels targeted for industrial applications, including high CDs, low cell voltages, high output concentrations and long lifetimes (Stephens et al., 2022, chap. 1). For example, CO_2-to-CO conversion has been demonstrated with high selectivity and small overpotential with gold as a catalyst. However, gold is both scarce and expensive, making silver a more promising catalyst for industrial applications (Stephens et al., 2022, chap. 3).

Currently, CO_2-to-CO electrolyzers are being developed for both low-temperature, aqueous electrolyte systems (5 kW, TRL 5-6), and high-temperature via Solid Oxide Electrolyzer Cells (SOECs) (TRL 8-9) (Nørskov et al., 2019). High-temperature SOEC electrolyzers for CO_2-to-CO production are, for example, marketed by Haldor Topsoe under the eCO brand (see Appendix A, Haldor Topsoe). These target low-volume industrial applications, where it would typically replace importing CO in tube trailer or cylinders (Mittal et al., 2017). The next step would be to further scale-up the technology to the MW scale, which involves yet further challenges, e.g. going from cell sizes of cm^2

to m^2 scale, avoiding loss of CO_2 in the electrolyte as carbonate, and increasing the CO concentration of the gas product. (Stephens et al., 2022, chap. 3)

For low-temperature CO_2 electrolysis, a breakthrough was achieved when Siemens, Covestro and Evonik demonstrated a system where CO_2 reduction was carried out at industrially relevant CDs (300 mA/cm^2) with near 100% Faradaic Efficiency (FE) for syngas (De Luna et al., 2019). The 2.5 kW CO_2-to-CO electrolyzer had a capacity to produce around 0.3 kg/h of CO, and Siemens plans to further scale up production (Kuhn, 2020) .With regards to production of formic acid, an important step was taken when a 10 kW demonstration facility (TRL 6) for CO_2 electrolysis was installed in 2023 (VoltaChem, 2023). This facility, called ZEUS, consist of a CO_2 electrolyzer stack with 15 cells and is designed for continuous production of up to 1 kg/h of formate.

For other products, more research and development are needed to improve electrolyzer setups and catalysts. For example, production of light organic molecules such as methanol, ethanol, oxalic acid, ethylene has received considerable academic interest, but is currently only at TRL 3 approximately (Nørskov et al., 2019). While these products may show promising performance for some key indicators, they typically lag behind on others. For example, the electrochemical production of ethanol from CO_2 has been demonstrated at high CDs, but further improvements are needed to achieve sufficiently high selectivity, with FE currently around 50%, and energy efficiency (Stephens et al., 2022, chap. 3). This means there is still much to be done to improve ethanol electrosynthesis in terms of efficiency, selectivity, and stability.

In 2019, the Energy-X project presented a roadmap on the research needs towards sustainable production of fuels and chemicals, with a significant focus on the electrochemical synthesis route (Nørskov et al., 2019). The roadmap integrates the views of over 180 scientists. It is openly available, and highly recommended for the interested reader. Table 1 (from that report) summarizes the state-of-the-art (in 2019) for electrochemical CO_2 reduction and specific targets for continued development.

Table 1. State-of-the-art and targets for further development of electrochemical CO_2 reduction. Source: (Nørskov et al., 2019)

	State-of-the-art	**5-years**	**10 years**
Catalysts	Ag, Cu, Fe and Co based molecular catalysts	Metallic, non-metallic, molecular, bio & hybrid	
Current density	100-300 mA/cm^2	500 mA/cm^2	1000 mA/cm^2
Stable cell V	3.0 V	2.5 V	2.0-2.2 V
Faradaic efficiency	95% for CO & formic acid 60-70% for ethylene	100% for CO and formic acid	Other products with reasonable FE
Single-pass efficiency	10-30%	40%	60%
Stability	>100 h	>1000 h	>10 000 h
Practical deliverables		EU test beds with realistic feedstocks, EU labs for testing & benchmarking 1 kW electrolyzers	Pilot plant industrial electrolyzers for CO, formic acid, and ethylene (10 000 h/year). Pilot scale plants for value-added products (halides, hydrogen peroxide, organics) & intermittent electricity supply

Regarding integrated CO_2 capture and electrosynthesis, where CO_2 is converted electrochemically directly from a capture solution, the maturity is still very low. Until recently, efficient procedures to directly reduce carbamate or bicarbonate solutions were “scarcely reported and experimentally unfeasible” (Gutiérrez-Sánchez et al., 2022). However, in the last couple of years, studies on such processes have started to emerge. While some promising results have been shown for CO_2 conversion from carbamates (result of amine capture) the CD is far too low for industrial applications (around 50 mA/cm^2), and extra heating is required, thus reducing overall energy efficiency. CO_2 conversion from bicarbonate solutions (result of using alkaline capture media), on the other hand, has shown more promising results in terms of CD (> 300 mA/cm^2), but this was achieved in cell setups with bipolar membranes, which are associated with high ohmic loss and thereby high electricity consumption for the electrolysis (Gutiérrez-Sánchez et al., 2022).

Other CO_2 capture media than amine and alkaline solutions have also been investigated for CO_2 capture followed by electrosynthesis. One such option is to use ionic liquids. Ionic liquids are non-aqueous solutions, which makes them interesting electrolytes for the electrochemical CO_2 reduction because the competition with the hydrogen evolution reaction is reduced. The electroconversion of CO_2 from ionic liquids also has the potential to be performed at lower cell voltages (Gutiérrez-Sánchez et al., 2022). Using ionic liquids for CO_2 capture is still in the conceptual phase of technology readiness.

4 What is needed to scale-up the technology?

Commercialization of CO_2 electrolysis for larger-scale applications faces several challenges related to achieving relevant performance levels as well as scaling up the technology. The emergence of flow cells using gas diffusion electrodes (GDEs) and zero-gap configurations has demonstrated a potential to reach industrially relevant Current Densities (CDs) (Kibria et al., 2019). However, for most products, performance improvements are needed in terms of selectivity (Faradaic efficiency, FE) and energy efficiency (Nørskov et al., 2019; Stephens et al., 2022, chap. 1). Achieving long-term stability is another important target.

The key performance metrics of CO_2 electrolysis need to be comparable to those of water electrolysis, and in the long term, to those of thermocatalytic processes, if the CO_2 electrolysis route should become competitive. This will require "the development of novel catalysts, suitable and stable membranes, electrolytes, gas-diffusion layers, and electrolysis cell architectures" (Nørskov et al., 2019). Nørskov et al. (2019) list the following critical research areas for further development of the technology:

1. Improving catalyst activity, selectivity, and stability
2. Advancing fundamental understanding of CO_2RR
3. Optimizing device performance and scale-up
4. Exploring novel systems and reaction conditions

Successful development and scale-up of CO_2 electrolyzers will require "effective cooperation among catalysis design, interfacial electrochemistry, materials science, and chemical engineering, and thorough consideration and integration of upstream (CO_2 capture) and downstream processes (product separation and conversion of e.g. CO or formic acid by thermal catalysis or microbial electrochemistry to higher-value products)" (Nørskov et al., 2019).

4.1 Improvements in selectivity

Mass transport limitation of CO_2 and competition with the hydrogen evolution reaction are limiting factors in reaching higher FEs. However, catalyst design is central to product selectivity (Stephens et al., 2022, chap. 3).

So far, high FEs have been achieved towards CO, formic acid (above 95%) and ethylene (ca 70%). However, for ethanol, and higher order alcohols, the selectivity is still too low (Kibria et al., 2019), especially considering the difficulty of downstream separation and purification of alcohols. Kibria et al. (2019) list the following approaches to improve selectivity: “Nanostructuring the catalyst material, alloying, inducing surface strain, functionalizing the catalyst surface, or tuning the chemical environment”. In the end, the catalysts developed using these strategies, should also be possible to produce in sufficient scale at reasonable cost and with low environmental footprint (Kibria et al., 2019).

4.2 Lifetime and stability

Achieving sufficient operational stability and lifetime of the electrolyzer system will be a key to successfully commercializing the technology. Long lifetimes of the key components and materials such as the electrocatalysts, the polymer membranes, and the gas diffusion layers lead to lower operating costs (due to less maintenance and replacement of materials), as well as effective utilization of capital costs (less downtime). To prolong the stability and lifetime of these materials, it is necessary to understand the causes of degradation (Stephens et al., 2022, chap. 1) and the failure mechanisms (Kibria et al., 2019).

According to Stephens et al. (2022, chap. 3) loss in catalyst activity that affects product selectivity can be caused by “(a) surface poisoning from electrolytes impurities and/or reaction intermediates, (b) surface restructuring under operating conditions, and/or (c) pore blockage through bubble formation or salt deposition.” These mechanisms are illustrated in Figure 9.

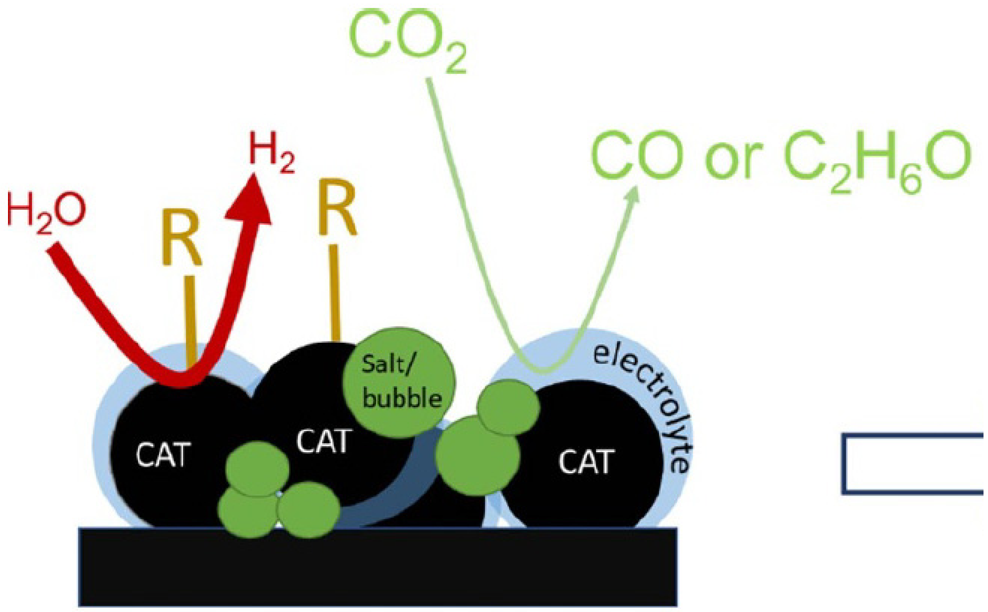


Figure 9. Mechanisms that affect the selectivity of the CO_2RR. Source: (Stephens et al., 2022) (The original figure has been cropped)

Although electrochemical conversion of CO_2 to CO has been achieved with 1000 h of stable operation (Stephens et al., 2022, chap. 23), for most products, long-term stability needs to be significantly improved. For example, for copper-based heterogeneous catalysts, which are used for conversion of CO_2 to C2 hydrocarbons and oxygenates, the catalyst surface restructures with resulting worsening of the performance over time (Nørskov et al., 2019).

4.3 Overall system efficiency

Further developments of electrolyzer setups to reduce overpotentials are needed to increase the energy efficiency of the CO_2RR. However, the energy efficiency of a production process using CO_2 electrolysis as the main reaction step is not only dependent on the cell voltage required for the CO_2RR.

Full cell performance also depends on the product generated at the anode. Consequently, the resistances (and thereby the required overpotential) need to be reduced across the whole cell, including both the cathode and anode half-cells. One important challenge is to identify a valuable product that can be produced at the anode in similar market volumes as the CO_2 reduction product (Nørskov et al., 2019). While oxygen is the most common, and most developed anode product, the performance and economics of the overall electrolyzer system may be improved if considering other products (Kibria et al., 2019).

The selectivity obtained for the desired product is also a key parameter for the overall efficiency of the system since low selectivity will lead to higher downstream separation costs.

Another key parameter for the overall efficiency of the full production route is the CO_2 utilization, i.e., to avoid losses of unconverted CO_2. High CO_2 utilization reduces the demand for CO_2 feedstock as well as downstream purifications costs. If high single-pass CO_2 conversion can be achieved, this will also reduce the capital and operating cost of the electrolyzer itself by avoiding recovery and recirculation of unconverted CO_2.

4.4 Scale up to larger capacities

The challenges of scaling up of the technology, even when lab-scale performance metrics have reached industrially relevant levels, should not be neglected. The width of the challenge can be intuitively realized by comparing the scale of current plants and demonstrators (kW or ton per year scale), with the scale needed for production of commodity chemicals (several hundred MW or thousands of tons per year) (Nørskov et al., 2019).

To reach industrially relevant capacities for the technology, the electrochemical reactor (the electrolyzer), as well as all components and materials must be scaled up to larger amounts and dimensions. The catalysts are new and typically not available off-the-shelf, which means that also their manufacturing needs to be scaled up (Stephens et al., 2022, chap. 1).

For both fuel cells and water electrolyzers it is common practice to construct multi-cell stacks as a way to reach larger capacities. Also for CO_2 electrolyzers, multi-cell stacks will most likely be used if the technology should reach industrial scale. The scale-up from individual cells to multi-cell stacks is, however, associated with new challenges, especially related to flow (of CO_2 and water) and heat management (Stephens et al., 2022, chap. 21).

In electrolyzer stacks, temperature control is provided by the electrolyte. This implies that the electrolyte should be evenly distributed within the stack and cells. Also the CO_2 reactant gas must be evenly distributed between the individual cells in the stack. However, with larger flows through the system and larger volumes within the individual cells, the heat transfer and distribution within the cells are affected. With larger electrolyzers, there will also be larger concentration gradients (of CO_2) between the point where CO_2 is introduced and the active cathode site. Uneven distribution of electrolyte and CO_2 flows, leading to differences in concentrations, might in turn lead to poorer condition for the CO_2RR in certain areas (Stephens et al., 2022, chap. 21). With regards to flow management, water removal is also a key to obtaining efficient mass transport. Water must be removed from each cell within the stack. Concentration and heat gradients, as well as bubble formation (from the oxygen generated at the anode), is also likely to negatively affect durability by, amongst other, locally favoring precipitate formate and flooding (Stephens et al., 2022, chap. 21).

Scaling up the electrolyzers looks especially challenging when considering higher-order products (i.e., beyond CO and formic acid), where selectivity towards either gas or liquid phase products is not as high. This will lead to product mixtures, which makes the design of the electrodes and membranes even more challenging (Stephens et al., 2022, chap. 21).

Eventually, promising CO_2 electrolyzer concepts (such as the membrane-electrode assembly) need to be demonstrated and systematically evaluated at larger scales (e.g., 1 kW). Their reliability must be tested under industrial conditions, and with stack sizes of 100-200 cells (to make the tests statistically relevant) (Nørskov et al., 2019).

An important step towards larger-scale testing was taken when the ZEUS demonstration facility for CO_2 electrolysis was installed in the Netherlands (VoltaChem, 2023). The installed reactor is a 15-cell, 10 kW CO_2 electrolyzer stack, which is designed for continuous operation and production of up to 1 kg/h of formate. The TRL 6 facility was made possible through the VoltaChem's E2C (Electrons-2-Chemicals) project and is available for public research and open to other organizations.

Part II.

Economics and Integration

5 Method and assumptions

The main assumptions for the techno-economic assessment (TEA) were discussed and agreed on in an internal project workshop. This led to the identification of three target chemicals for the analysis: ethanol, carbon monoxide and ethylene (see Section 5.2). During the workshop, it was also agreed to consider a plant scale of 100 000 ton CO_2 per year.

The objective of the TEA was to estimate potential future production costs for the target chemicals. The model used to calculate the costs is presented in Section 5.3. The production costs were then compared to current market prices and cost of alternative production routes to evaluate the economic feasibility of the electrochemical CO_2 reduction pathway. Input data and assumptions for the TEA were defined for two different scenarios, which are introduced in Section 5.1, and defined in more detail in Section 5.4 and 5.5.

5.1 Scenarios

Electrochemical reduction of CO_2 is a long-term technology option, and commercial production cannot be expected until at least 2040, and maybe even later. Consequently, a techno-economic evaluation of production costs should consider expected future performance levels and market conditions. To represent the large uncertainty in technology development and future conditions, two scenarios were defined according to Table 2. While Scenario B is more optimistic for most parameters, also Scenario A is optimistic in the sense that it assumes that state-of-the-art performances that so far has only been demonstrated in lab-scale experiments will also be achievable at reasonable costs in large-scale operation, and that remaining technological challenges will be resolved.

Table 2. Definition of the two scenarios used for the TEA.

	Scenario A	**Scenario B**
Technical performance	Based on current state-of-the-art for individual performance indicators	Optimistic assumptions assuming improvements beyond current state-of-the-art
Electricity price	Historical electricity price	Representing prices in low-price periods in a future scenario with significant price variations over the year.
Operational strategy	Stable operation over the year	Flexible operation, leading to fewer days of operation
CO_2 costs	CO_2 capture cost representing a value in the lower range of current capture costs	CO_2 capture cost representing optimistic targets for future capture costs

5.2 Target products

The products chosen for the techno-economic evaluation are listed below, together with the main arguments for the selection.

Ethanol

- Liquid product, which is assumed to make it easier to transport and store.
- Compared to other possible liquid products, literature suggests better potential economic margin than methanol, and significantly larger market than formic acid or propanol.
- Potential feedstock for ethylene production, and interesting potential synergies with ethylene production from bio-ethanol.

Carbon monoxide

- Important building block in Stenungsund (syngas).
- Product with the highest maturity and most promising performance in terms of selectivity and conversion efficiencies. Literature also indicates a potential economic margin (depending on pricing of carbon monoxide).
- Studies indicate it is more cost-efficient to optimize for CO rather than syngas ($CO+H_2$) and produce H_2 separately to control composition.

Ethylene

- Important building block in Stenungsund.
- Better performance than ethanol as an alternative C2 molecule.
- Interesting to compare with bio-ethylene production.

5.3 Techno-economic model

We used a model published by Shin et al. (2021) to estimate mass and energy balances and equipment costs for the electrolyzer, CO_2 separation and recycling and product separation.

An overview of the modelled system is shown in Figure 10.

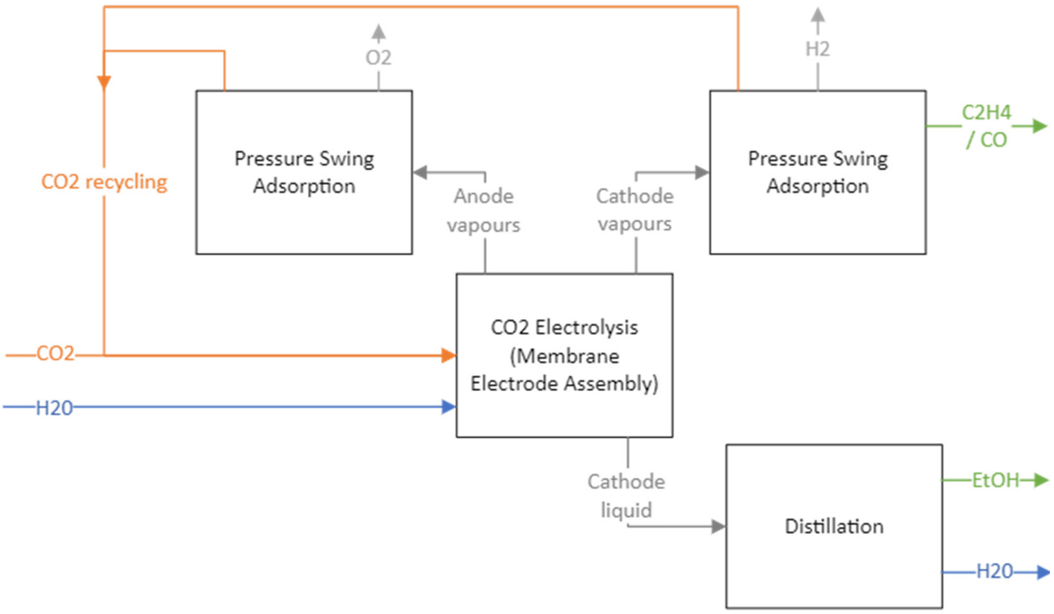


Figure 10. Simplified flow diagram for the modelled system. Pressure Swing Adsorption is assumed for the separation of CO_2 from O_2, as well as for separation of gas products from H_2. Distillation is assumed for separation of liquid products from water.

Key model assumptions are listed below:

- The electrochemical reactor is assumed to be a Membrane Electrode Assembly (MEA) with an Anion-Exchange Membrane (AEM).
- Some of the CO_2 fed to the electrolyzer at the cathode side will inevitably form carbonates when CO_2 reacts with OH^- ions. The carbonates pass through the membrane and reacts back to CO_2 at the anode. Separation of CO_2 from O_2 is assumed to be performed using Pressures Swing Adsorption (PSA).
- PSA is also assumed for the separation of unreacted CO_2, H_2 and gas products. If liquid products are targeted, distillation is assumed to be used to separate the product from water.
- CO_2 separated from the anode and cathode vapors is assumed to be recycled back to the electrolyzer.
- The modelling of by-products is simplified. In particular, H_2 is the only considered by-product from the electrochemical reactions at the cathode. At the anode, O_2 is assumed to be the only product, but without any value.

The majority of the input data regarding electrolyzer performance is taken from the study from which the model was provided (Shin et al., 2021). However, some adjustments have been made after comparison with a recent study from VoltaChem (Detz et al., 2023). The technical performance data is presented in Section 5.4. The economic data and assumptions are mostly our own, and have been discussed within the project group, see Section 5.5.

5.4 Electrolyzer performance data

Table 3 presents the input data used to represent the performance of the electrolyzer in terms of conversion efficiencies and durability. The majority of these values are taken from Shin et al. (2021), with Scenario A corresponding to their base case scenario, and Scenario B corresponding to their more optimistic scenario. Shin et al. (2021) base their base case on best reported values from a recent literature study, which means Scenario A represent current state-of-the-art. According to Shin et al. (2021), this means that production costs estimated using these values should represent “the near-term economic viability of the current technology”. However, it is worth noting that the technology has never been demonstrated on a scale comparable to the scale assumed for this TEA. Significant further development is necessary to reach the state-of-the-art performances shown for individual parameters, for all parameters at the same time, in a cost-effective way on a large scale. Consequently, Scenario A may rather be seen as a realistic target for future full-scale performance based on current state-of-the-art, while Scenario B represents more optimistic targets.

Table 3. Assumed input data for the performance of the CO_2 electrolyzer. All values taken from Shin et al. (2021) except the current density for ethylene (marked with *), which is based on other literature (Sisler et al., 2021; Klüh et al., 2023).

	Scenario A			**Scenario B**		
	Ethanol	Carbon monoxide	Ethylene	Ethanol	Carbon monoxide	Ethylene
Current Density (mA/cm²)	500	500	500*	700	700	1000*
Faradaic Efficiency (%)	60	95	70	80	100	90
Single-pass Conv (%)	15	30	15	25	50	25
MEA replacement (yr)	1.0			1.5		

The assumed single-pass conversion in Scenario B represents a theoretical maximum for Anion-Exchange Membranes (AEMs). Since each electron transfer means that one OH^- ion is formed, it is unavoidable that the OH^- reacts with CO_2 to form (bi)carbonates that are passed through the membrane to the anode, where it reacts back to CO_2. This CO_2 is ”lost” and will not be converted in the single reaction pass. However, the model considers recycling of CO_2, so the overall system (in Scenario B) is assumed to have 100% conversion.

The Current Density (CD) of a future, full-scale plant is especially difficult to predict based on available lab-scale data. One reason for this is that high CDs require other type of equipment than the H-cell reactors that are normally used in lab-scale experiments. In particular, we noted that the CD assumed by Shin et al. (2021) in their base case for ethylene (1000 mA/cm^2) seemed to be significantly higher than that used in many other studies. For example, Klüh et al. (2023) presented an overview of assumptions in TEAs of electrochemical production of ethylene, where the CD varied between 110 mA/cm^2 and 1000 mA/cm^2 between different studies. Notably, the value used in the VoltaChem study (Detz et al., 2023), is as low as 120 mA/cm^2. Furthermore, while Shin et al. (2021) claim that their data is based on current state-of-the-art, their listed literature does not include any example of such high CD. To be more in line with other TEA studies, we therefore chose a more modest value for our Scenario A (500 mA/cm^2), which is in the mid-range of the assumptions reported by others.

On the other hand, a catalyst for electroreduction of CO_2 to ethylene developed in a collaboration between Total Energies and the University of Toronto (Nevicato and Schreiber, 2019) has been demonstrated to achieve a 63% Faradaic efficiency at a total CD of 750 mA/cm^2 (Dinh et al., 2018). This shows that high CDs can be reached, also in combination with high selectivities. Furthermore, Sisler et al. (2021), while reporting a CD of 120 mA/cm^2 as the best demonstrated performance, also provides a motivation and reasoning for assuming 1000 mA/cm^2 as a realistic future target. We therefore kept the value of 1000 mA/cm^2 for Scenario B.

The MEA replacement time represents the need for component replacements due to limited durability of the electrode and membrane materials.

5.5 Economic data

Table 4 presents the cost of the cell stack, and the prices of CO_2 and electricity assumed in the two scenarios. The electricity price is also associated with an annual operating time during which this price level is assumed to be available. The annual operating time affects the utilization of the equipment and the required capacity to be able to reach an annual throughput of 100 000 ton of CO_2 per year. However, additional costs for storage in the case of intermittent operation have not been considered.

Table 4. Costs and prices assumed for the techno-economic model in the two investigated scenarios.

	Scenario A	**Scenario B**
Stack cost (SEK/cm^2)	13	4
CO_2 price (SEK/ton CO_2)	1000	500
Electricity price (SEK/MWh)	500	200
Operating time (days/yr)	350	200

Motivation for these assumptions, as well as assumptions about equipment for downstream separation, market prices for products, and other economic parameters are further detailed below.

Equipment costs

The stack cost is based on costs reported for PEM H_2 electrolyzers (in USD/kW_{el} or EUR/kW_{el}). Similar stack costs per kW were used by Shin et al. (2021) and VoltaChem (Detz et al., 2023): 550 USD/kW and 60% of 667-1450 EUR/kW, respectively. However, these costs referred to PEM electrolyzers with very different Current Densities (CDs of 400 mA/cm^2 and 1700 mA/cm^2 respectively). Together with data on reported cell voltages and CDs, the reported costs per kW have been recalculated to costs per cm^2.

The converted stack cost from Shin et al. (2021), ca 4 SEK/cm^2, was used in the more optimistic Scenario B. The more modest assumption in Scenario A is instead based on the VoltaChem study, taking an average of the range they provide. Based on their assumptions about cost reductions due to technological learning, we also assume that the cost in 2040 is approximately 60% of the current cost level. This leads to an assumed stack cost of 13 SEK/cm^2.

Stack costs are assumed to be 61% of total electrolyzer cost, where Balance of Plant is the rest of the cost (39%) and consist of power electronics, gas conditioning and other auxiliaries.

To find the total electrolyzer cost using the cost per cm^2, the required electrode area must be calculated. This is primarily determined by the CD. Since CD is one of the most uncertain performance parameters and has a huge influence on the required size of the electrolyzer and thereby the costs, a sensitivity analysis investigating the dependence of CD on product costs was performed, see Section 6.2.3.

Equipment costs for downstream separation units were taken to be the same as in the original model by Shin et al. (2021).

CO_2 price

The cost of CO_2 to be used as a feedstock for the CO_2 reduction process is based on an assumed cost of capturing CO_2 from flue gases. Even if CO_2 capture is more mature than CO_2 electrolysis, capture technologies are expected to be further developed and reduced in costs over time. Capture costs are also dependent on the scale of capture (as well as on other characteristics of the flue gas source). However, in this study, a fixed price of 1000 SEK/ton CO_2 was assumed in Scenario A, and 500 SEK/ton in the more optimistic Scenario B.

If the CO_2 is not captured on the same site as the CO_2 electrolyzer, costs for transporting the CO_2 from the source site to the utilization site need to be considered as well. The cost for transporting CO_2 from Gothenburg to Stenungsund has been estimated to approximately 60 SEK/ton based on data and assumption from a study on CO_2 transport infrastructure in Sweden (Karlsson et al., 2023). Since this is within the general range of uncertainty and variations in capture costs, it was not explicitly included in our analysis.

ETS allowances (EUAs) will need to be surrendered for fossil CO_2 even if it is used for electrochemical conversion, as long as permanent storage cannot be shown. Consequently, no adjustments in the CO_2 price were made for cost savings related to EU ETS (in the case of fossil CO_2). Furthermore, no alternative cost savings or revenues for the competing use of CO_2 for CCS was considered (sales of carbon removal credits (CRCs) in the case of biogenic CO_2). However, if the price of EUAs or CRCs becomes higher than the cost for full-chain CCS, the price for CO_2 can be expected to be even higher due to competition for CO_2 with the storage application.

Electricity price

In Scenario A, an electricity price of 500 SEK/MWh is assumed. This represents historical (pre-2021) prices in Southern Sweden, which were relatively stable over the year. Consequently, this price level is combined with an assumption of the plant being operated during 350 days per year.

The electricity price in Scenario B is set to 200 SEK/MWh to represent low-price periods in a future energy market scenario with a high degree of intermittent power generation. The value is based on results from energy market scenario models for Southern Sweden indicating that electricity prices around or below this level can be possible approximately 200 days/year (Göransson et al., 2019; Svensson et al., 2020).

Since the results are strongly dependent on the assumptions about electricity price and operating time, a sensitivity analysis has been performed for these parameters, see Section 6.2.2.

Market prices for products

In the results (Section 6.2), the estimated production costs are compared to market prices for the respective products. Here, we have considered both the current market price and a potential optimistic price level, which includes an assumed price premium on top of the basic price.

For carbon monoxide the current market price was set in discussion with project partners to represent a value of carbon monoxide in on-site syngas applications. The "premium price" is instead set based on the market price for pure carbon monoxide (Gawel et al., 2022).

The current market price for ethylene is taken from another study performed within Klimatledande Processindustri, "the Bio-olefins project" (Heyne et al., 2021). The "premium price" is taken from the same study and represents the estimated cost for production of bio-ethylene from ethanol. It can be considered an estimate of the willingness to pay for a "green", "premium" product, based on alternative costs.

For ethanol, current markets are dominated by bio-ethanol and market prices are consequently referring to an, at least partly, green/renewable product. It was therefore considered unrealistic to assume an additional price premium for the product from the CO_2 electrolyzer being "green and renewable". The market price of ethanol is taken from the same study as the ethylene price (Heyne et al., 2021).

Other economic assumptions

The model by Shin et al. (2021) did not include any installation factor to convert equipment costs to capital costs. Therefore, an installation factor with a value of 1.8 has been added for our analysis. The value of 1.8 is low compared to general chemical engineering processes. However, this value was used in the VoltaChem study (Detz et al., 2023), where the low value is chosen to reflect the benefits of the technology being modular.

To annualize the capital cost, a project lifetime of 20 years and a discount rate of 10% were chosen. This is also in line with the VoltaChem study (Detz et al., 2023).

6 Results and discussion

6.1 Annual production and electricity demand

The estimated mass and energy balances of the electrolyzer plant are presented in Table 5.

Table 5. Mass and energy balances of the electrolyzer plant, assuming an annual CO_2 throughput of 100 000 ton per year, and an annual operating time of 350 days per year in Scenario A and 200 days per year in Scenario B.

		Scenario A			**Scenario B**		
		Ethanol	Carbon monoxide	Ethylene	Ethanol	Carbon monoxide	Ethylene
Production	kton/yr	31	60	22	42	64	29
Production capacity	ton/d	90	173	64	209	318	143
Electricity demand	GWh/yr	898	312	1060	898	312	1060
Electric power demand	MW	107	37	126	187	65	221

The estimated production of ethylene (between 22 000 and 29 000 ton per year depending on the scenario) can be compared to current ethylene use in the Stenungsund cluster, which is approximately 700 000 ton per year (Heyne et al., 2021). However, as the results show, even a plant with this small production capacity would require more than one TWh of electricity per year and the power demand would be substantial. For comparison, the total industrial electricity use in Västra Götaland in 2022 was 6.2 TWh (SCB, 2022).

The power demand is clearly larger for production of ethanol and ethylene compared to carbon monoxide, since the electrochemical reduction of CO_2 to these products require more electron transfers. Considering that access to power capacity is likely to be limited in West Sweden in the future, this may well be a barrier to employment of this technology for large-scale production of higher-order products such as ethanol and ethylene.

6.2 Economic performance

The results from the TEA are presented in Figure 11. In the figure, the stacked columns show the cost components of the production cost for the three evaluated target products in the two scenarios. These estimated production costs are also compared to current market prices (black, dotted lines) and potential premium price levels (green, dashed lines).

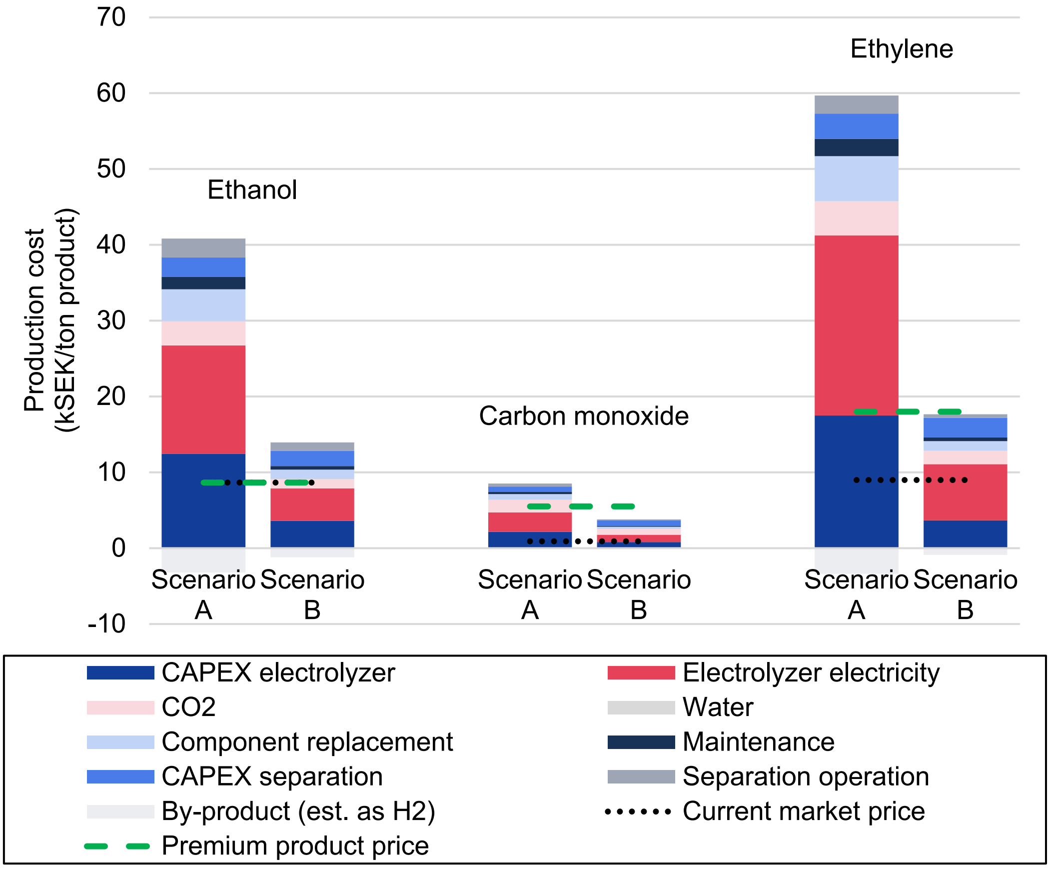


Figure 11. Estimated production cost compared to current market prices and prices including a premium.

The results from the TEA clearly show the major contribution of electricity to total production costs. Even in Scenario B, where the price of electricity is assumed to be much lower (200 SEK/MWh compared to 500 SEK/MWh in Scenario A), the relative cost share of electricity remains significant, since other cost contributions are also assumed to be reduced in this, generally more favorable, scenario. A sensitivity analysis that further investigated the effect of different electricity prices, their annual duration, is presented in Section 6.2.2.

CAPEX, especially for the electrolyzer, is also a major cost component. In Scenario B, both the specific stack cost and the Current Density (CD), which affects the required size of the electrolyzer, are improved compared to Scenario A. On the other hand, the lower electricity price assumed in Scenario B is associated with lower utilization of the electrolyzer (fewer operating hours per year), which leads to higher capacity requirement during the hours in operation. The combined effect of the changed assumptions is, however, a significant reduction in electrolyzer CAPEX. However, since electricity and other costs are also reduced, the relative contribution of CAPEX to total production costs remains high. Due to the large uncertainty in both future stack cost and CD, and their significant contribution to total production costs, a sensitivity analysis on these parameters has been performed for the case of ethylene, and the results are presented in Section 6.2.3.

The cost of CO_2 constitutes a small share of the total production costs for ethanol and ethylene, while for carbon monoxide, it constitutes a larger share.

Costs for separation are also a relatively small share of total costs. Furthermore, since standard separation technologies are assumed, the capital costs for separation could potentially be reduced further if the electrolyzer system is integrated into an existing site where it is possible to utilize existing separation capacity.

The results also show that the production cost is quite far from competing with current market prices (for all products in both scenarios), and that some kind of price premium above current price levels will be needed to make the electrochemical production route economically feasible. Current market prices for carbon monoxide (syngas) and ethylene refer to these products produced from conventional, fossil-based production routes. In a future where such fossil-based production cannot be accepted, a more relevant comparison is against production costs for alternative bio-based, circular, and renewable production routes (while the price will also be determined by the willingness to pay for such products).

In the case of ethylene, the above reasoning makes it relevant to compare the estimated production costs against production costs for bio-ethylene. The results indicate that under optimistic assumptions, these technologies could potentially have similar costs.

For carbon monoxide the premium price product is assumed to be pure carbon monoxide sold to small-volume special applications (rather than CO used in bulk syngas applications). This application seems to have a promising economic potential under favorable conditions (Scenario B).

6.2.1 Comparison with VoltaChem study

While we were working on our TEA, a similar study was released by VoltaChem (Detz et al., 2023). Compared to our results, they arrive at significantly higher cost estimates. For example, their estimated costs for carbon monoxide and ethylene (in 2050) are around twice as high as our estimates for Scenario A. They also conclude that capital costs dominate production costs while electricity costs only make up a minor share. This is not in line with our results, which indicate that capital costs and electricity are both major cost components. A more in-depth analysis into assumptions and input data points to two major differences between our study and the VoltaChem study: 1) the assumed CD, and 2) the scale.

Most notably, the VoltaChem study assumes a CD of 120 mA/cm^2. As discussed in Section 5.4, the CD of a future, full-scale plant is especially difficult to predict and as presented by Klüh et al (2023), TEAs reported in literature use a wide range of different values (110 – 1000 mA/cm^2). The value used by VoltaChem is clearly in the lower end of this range, while we have chosen higher values (500 and 1000 mA/cm^2 in Scenario A and B respectively). Since CD has a significant influence on the required size of the electrolyzer, this assumption strongly influences the capital costs. The difference in CD is the sole main explanation for the different results and conclusions from our study and VoltaChem's. Due to the sensitivity of the results to the assumption about CD, we performed a sensitivity analysis where this value was varied, see Section 6.2.3.

It is also worth noting that the scale assumed for the plant differs substantially between our study and VoltaChem's. We assumed a scale of 100 000 ton CO_2 per year, corresponding to 126 MW electricity in the case of ethylene in Scenario A (see Table 5). VoltaChem assumed a scale corresponding to 1 MW electricity. While this huge difference does not affect the cost of the electrolyzer considering this is assumed to scale linearly with size due to the modularity of the technology, it does affect costs for downstream separation.

6.2.2 Sensitivity analysis with respect to the electricity price

As shown in Figure 11 the cost of electricity has a considerable influence on the estimated cost of electrochemical production. One way to ensure a lower electricity cost is to operate the electrolyzer with flexibility towards varying prices (or towards availability of renewable, but intermittent, electricity generation). However, this will lead to fewer hours of operation, and poorer utilization of the investment. Consequently, there is a trade-off between ensuring low electricity costs and low CAPEX.

This was further investigated in a sensitivity analysis where the price paid for electricity (during time of operation) was varied for two different levels of assumed annual operating time. Since the annual throughput of CO_2 is given (100 000 ton per year), changing the operating time implies that the capacity and thereby the investment cost of the electrolyzer plant are changed accordingly. All other parameters were set as in Scenario B (see Table 3 and Table 4). In particular, no additional cost for storage to handle varying production has been considered, and the durability of components is not assumed to be affected (i.e. the component replacement interval is assumed constant). Furthermore, the potential influence of the electricity price on the cost of captured CO_2 has not been considered. The results are shown in Figure 12.

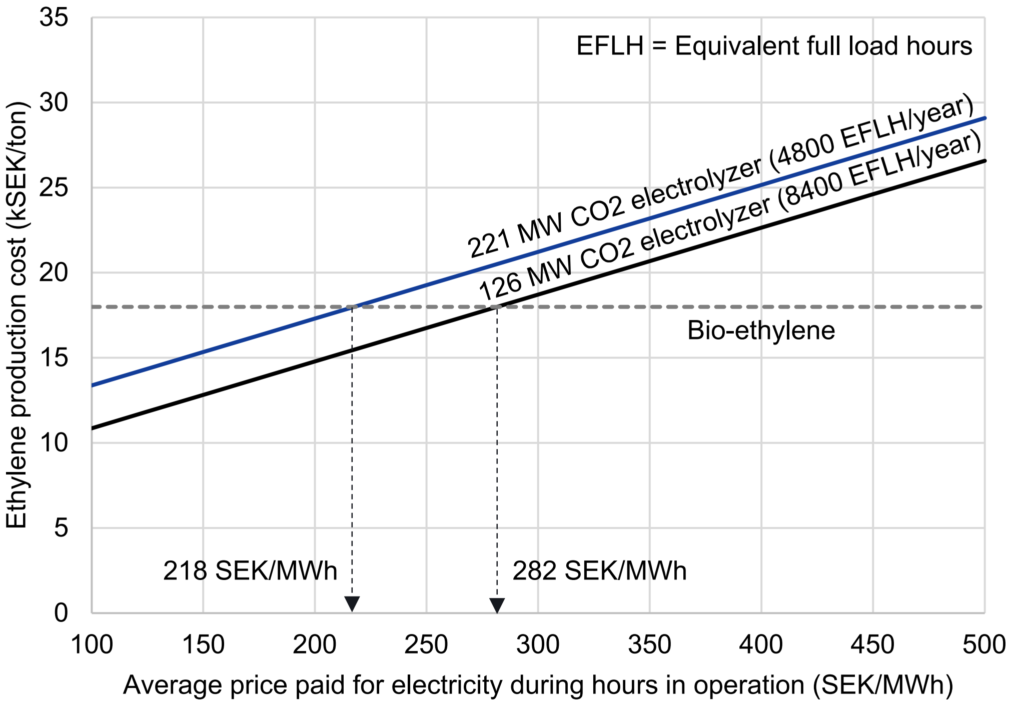


Figure 12. Influence of electricity price on the production cost of ethylene for different sizing of the CO_2 electrolyzer plant and given an annual throughput of 100 000 ton CO_2. Technical performance parameters, specific stack cost and CO_2 price are set as in Scenario B. Arrows indicate the average electricity price that must be secured when the electrolyzer is operated to make production costs for electrochemically produced ethylene equal to assumed production cost for bio-ethylene. Note that oversizing the electrolyzer (blue line) allows for flexible operation in response to electricity price variations and thereby provides better opportunities for obtaining low-cost electricity supply during operation (i.e. utilizing electricity prices in the lower end of the scale).

As shown in Figure 12 the price paid for electricity has a strong influence on the production cost and will be a determining factor for the cost competitiveness of the technology.

Perhaps less apparent from the chart is the influence of designing for flexible operation (higher capacity, but fewer operating hours). Such design not only affects the required investment, but also the electricity price that can be achieved during operation. For example, results generated using the energy systems model presented by Göransson et al. (2019) indicate that, in a future scenario for Southern Sweden with strategic sector collaboration, the short-term marginal electricity generation cost for the cheapest 4800 hours could well be below 100 SEK/MWh while the corresponding cost over the entire year would be 400–500 SEK/MWh.

Consequently, the overdesign represented by the blue line may in fact be a better option even though the blue line is above the black line. The reason for this is that this design also provides better opportunities to operate with lower-cost electricity, i.e., going lower on the x-axis in the chart (see also Example on next page).

Example: Consider a future energy market scenario with an annual average price of electricity of 500 SEK/MWh. In such a scenario, designing for continuous operation would result in a production cost of 27 kSEK/ton (see Figure 12, black line, 500 SEK/MWh). However, with large shares of intermittent power generation in the grid, there may still be periods with a significantly lower price. Assume for example that prices around 200 SEK/MWh could be obtained during 4800 hours. If the CO_2 electrolysis plant is designed with overcapacity to allow for flexible operation, a production cost of 17 kSEK/ton could be achieved (see Figure 12, blue line, 200 SEK/ton). Under these assumptions, the more flexible design would clearly be more beneficial.

It is, however, worth noting that no negative effects on performance or component wear of part-load or on/off operation and no additional costs for storage due to varying production have been considered (see Section 2.4 for further discussion on the potential for flexible operation).

The results in Figure 12 seems to indicate that the extra cost for additional capacity (difference between blue and black line) is relatively small. However, this is because the low specific stack cost and high CD assumed in Scenario B result in low capital costs for the electrolyzer, and consequently, the over-dimensioning required to allow for flexible operation is not so expensive. If considering less favorable assumptions (e.g., as in Scenario A), the overcapacity will cost significantly more. On the other hand, in that scenario, not even a combination of a very low electricity price and stable operation would allow for competitive production costs.

6.2.3 Sensitivity analysis with respect to electrolyzer cost

Since the potential CD achievable in future electrolyzers turns out to be one of the more uncertain parameters, as well as one of the most influential parameters on total production costs, a sensitivity analysis was performed also for this parameter. The CD not only determines the required electrode area and thereby the cost of the stack, but indirectly also costs for balance of plant, component replacements and maintenance, which are all calculated by applying cost factors to the total stack cost.

The specific stack cost for a future full-scale CO_2 electrolyzer is also highly uncertain since there are no costs for comparable type of plants in a relevant scale. Our cost estimates are based on costs reported for H_2 electrolyzer, but the cell architecture and materials used in CO_2 electrolyzers will differ in many important regards, for example, in the application of gas diffusion electrodes, membrane electrode assemblies, flow arrangements, types of membranes and catalysts. Furthermore, it can be expected that future costs and performance of CO_2 electrolyzers will be connected. For example, it might well be possible that higher CDs can be reached if also allowing for higher equipment costs. Because of this, the sensitivity analysis also includes analysis of different assumptions about the specific stack cost. The results of the sensitivity analysis on estimated production costs for ethylene are shown in Figure 13.

The results in Figure 13 clearly show the importance of improving the CD for electrochemical production of ethylene. In particular, it is clear that commercial production of ethylene at current state-of-the-art CDs (around 100-150 mA/cm^2), is not realistic independently of the specific stack cost. On the other hand, further improvements in CD above ca 600 mA/cm^2 makes less of a difference.

The results also show that even at very high CDs, it is also important to achieve low specific stack costs.

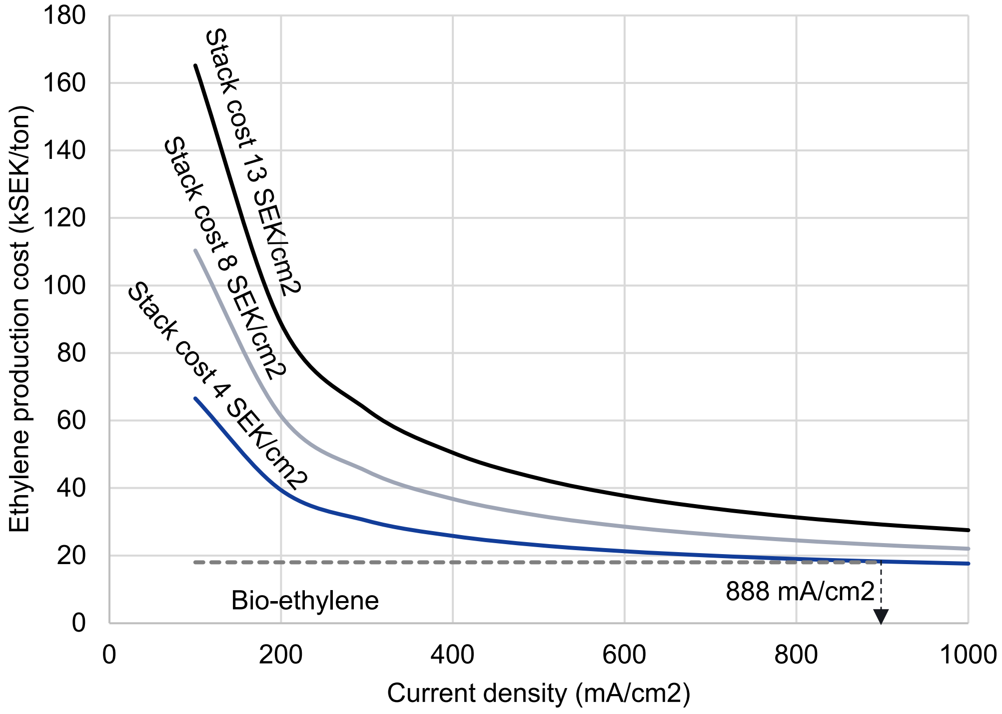
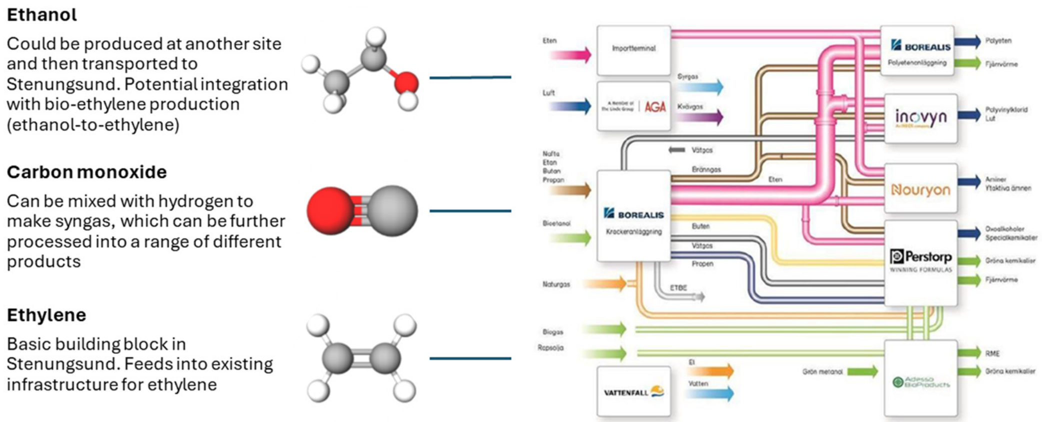


Figure 13. Sensitivity analysis showing the influence of CD and specific stack cost on the production cost of ethylene. All other parameter values are set according to Scenario B. Stack cost as in Scenario A (black line), Scenario B (blue line), and an intermediate level (grey line). Arrows indicate the breakpoint for the CD at which production costs for electrochemically produced ethylene becomes equal to assumed production cost for bio-ethylene assuming a stack cost of 4 SEK/cm^2.

6.3 Integration opportunities

The three products evaluated in the TEA were chosen for different reasons, but they could all provide interesting opportunities for integration in Stenungsund’s chemical cluster. Figure 14 gives an overview of the main opportunities related to each of the products.



Ethanol

Could be produced at another site and then transported to Stenungsund. Potential integration with bio-ethylene production (ethanol-to-ethylene)

Carbon monoxide

Can be mixed with hydrogen to make syngas, which can be further processed into a range of different products

Ethylene

Basic building block in Stenungsund. Feeds into existing infrastructure for ethylene

Figure 14. Overview of key integration possibilities for the three investigated target products from a future CO_2 electrolyzer.

Ethanol, as a liquid product, provide better opportunities for being transported. It could therefore, for example, be produced at a site with good opportunities for cost-efficient carbon capture from flue gases, and then transported to the Stenungsund site for further conversion to other chemicals. Alternatively, it could be sold to the market, for example, for use as a transportation fuel. In Stenungsund, ethanol from electrochemical reduction of CO_2 could potentially be integrated with a future ethanol-to-ethylene process, where ethylene is also produced from bio-ethanol. The lower selectivity of ethanol (low FE) implies that electrochemical CO_2 reduction to ethanol will lead to more by-products. One likely by-product is ethylene, which would favor integration of the CO_2 electrolyzer with the ethylene production process. With regards to separation and purification of the ethanol from the CO_2 electrolyzer, there are limited opportunities for integration with existing infrastructure, although heat integration to recover heat to drive the distillation process could always be a possibility.

Carbon monoxide can be mixed with hydrogen to make syngas, which is well-known in Stenungsund and can be further processed into a range of different products. For example, syngas from a CO_2 electrolyzer could potentially be integrated with Project Air to produce methanol. The high selectivity of carbon monoxide/syngas production in CO_2 electrolysis implies that mostly hydrogen will be obtained as a by-product. Hydrogen is needed together with the carbon monoxide in the syngas and does not need to be separated. Product separation from unreacted CO_2 is based on well-known and cost-efficient PSA.

Ethylene is a basic building block in Stenungsund, and ethylene from electrochemical CO_2 reduction could feed into existing infrastructure for ethylene. Downstream processes could potentially be integrated with bio-ethylene production. As for carbon monoxide/syngas product separation from unreacted CO_2 is based on well-known and cost-efficient PSA.

Other by-products than hydrogen will also be obtained from the process, both from competing reaction pathways for the electrochemical reduction of CO_2 and from the reactions at the anode. In the model we used, oxygen is assumed to be the main product at the anode, but other anode reactions could also be possible and could improve the business case for integration of the technology in Stenungsund. For example, literature mentions opportunities to use the anode reaction for waste-water treatment. Which, and how much, by-products that could be obtained from the cathode reactions depends to a large extent on the development of catalysts.

The temperature of the CO_2 electrolysis process will most likely be too low to leave any opportunities for *excess heat recovery*. The range of operating temperature reported from lab-scale experiments of electrochemical CO_2 reduction is commonly between 20–40 °C. Although the optimum temperature may be slightly elevated for some products (e.g., around 60 °C), this depends on a number of factors, where some favor a lower temperature and some favor a higher, and the optimum will differ depending on catalysts and targeted products.

7 Conclusions

Electrochemical conversion of CO_2 could provide future opportunities for utilization of captured CO_2 and pathways for electrified production of chemicals. With direct conversion of CO_2 in one step at mild process conditions, CO_2 electrolysis could potentially also provide advantages compared to other carbon capture and utilization (CCU) options. However, the technology is still in a very early development phase and significant further development is needed to overcome the challenges associated with the technology. Techno-economic assessments to estimate potential future production costs are therefore inevitably subject to significant uncertainty. However, the results of our techno-economic evaluation point to a few key conclusions.

Price premium likely required for economic feasibility.

Some kind of price premium (compared to current fossil-based market prices) will most likely be required to make electrochemical production economically feasible. Not even in a scenario with optimistic assumptions about the future technical performance, low electricity prices and low CO_2 costs, electrochemical production can compete with current market prices for any of the large-volume, bulk products considered. Production costs for electrochemical CO_2 conversion to carbon monoxide could, however, potentially compete with current market prices for pure carbon monoxide (a specialty application with low market volumes). Electrochemically produced ethylene could potentially also compete with bio-ethylene (indicating competitiveness against green premium products), although the results are highly sensitive to assumptions about the electricity price (and uncertainties in future costs for bio-ethylene have not been considered).

Development of low-cost electrolyzers with high current density is critical.

The equipment cost for the electrolyzer depends on the specific stack cost and the required size, and the size in turn depends on the current density. With both specific stack cost and current density being highly uncertain parameters (little knowledge about these parameters can be obtained by lab-scale experiments), and both of them having a significant influence on equipment costs, the range of potential future capital costs for a full-scale plant is enormous. Our results show that even with optimistic assumptions, capital costs make up a large share of total production costs. With less optimistic assumptions, electrochemical reduction of CO_2 is not realistic from an economic perspective. Cost reductions will be driven by improvements in current density in particular, and by technological learning in general. The latter should be favored by the modularity of the technology but is dependent on the technology actually being adopted.

Low-price electricity will be a determining factor for cost competitiveness.

Assuming a successful development in terms of equipment costs, the price of electricity will be a determining factor for the economic feasibility of the technology. For example, our results indicate that electricity prices need to be below 300 SEK/MWh for electrochemically produced ethylene to be competitive with bio-ethylene (under otherwise favorable assumptions). Flexible operation in response to electricity price variations may be required to reach these price levels. However, since this will lead to lower utilization of equipment, the relative importance of low capital costs becomes even stronger.

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Appendix A – Companies

Companies and start-ups active in the field of Electrochemical CO_2 reduction, either as their core business, or as part of their R&D project portfolio.

Company	Technology brand for CO_2 electrolysis	Core business	Comment	Link
Haldor Topsoe	eCOs	Chemistry: Catalysts, equipment, licensing, project development etc	SOEC for CO2-to-CO. Commercial but small scale	https://www.topsoe.com/processes/carbon-monoxide
Twelve	CO2Made	CO_2 electrolyzer	Formerly known as Opus 12	https://www.twelve.co/
Coval Energy	Colyser	CO_2 electrolyzer		https://www.covalenergy.com/
CERT Systems		CO_2 electrolyzer	CERT= Carbon Electrocatalytic Recycling Toronto	https://co2cert.com/
Dioxide Materials		CO_2 electrolyzer		https://dioxidematerials.com/
Mantra Energy Alternatives Ltd		CO_2 electrolyzer & fuel cell	CO_2 electrolyzer pilot plant, 100 kg/h CO2, in Richmond, B.C. Company seems to have disappeared since 2017.	?
Prometheus Fuels		CO_2-to-fuel	Integrated DAC and electrochemical conversion	https://prometheusfuels.com/technology
De Nora		Electrochemical components		http://denora.com/
Gaskatel		Electrochemical components		https://gaskatel.de/en/
Sunfire	SynLink	Electrolyzers	Syngas production in 1-step SOEC	https://www.sunfire.de/en/syngas
Skyre	CO2Renew	Electrolyzers	Formerly known as Sustainable Innovations	https://www.skyre-inc.com/
IRD Fuel cells		Fuel cells		https://irdfuelcells.com/
Advent		Fuel cells and components		https://www.advent.energy/

Company	Technology brand for CO_2 electrolysis	Core business	Comment	Link
Avantium	Volta	Innovative technologies within polyester value chain		https://www.avantium.com/
Siemens Energy		Energy technology	Pilot CO_2 electrolyzer within the Rheticus I and II projects (collaboration with Evonik)	www.wko.at/site/OEGEW/Veranstaltungen/co-electrolysis-and-synthesis.pdf
Total Energies		Production and distribution of energy carriers	Collaboration with academic partners and start-ups like OPUS12 and CO2 Solutions. Sponsors University of Toronto's competition entry for the Carbon X-prize. Ambition to develop CO2 reduction technology to demonstration scale (TRL 5) by 2035.	https://www.innovationnewsnetwork.com/co2-electroreduction-energy-sector/761/

Appendix B – Projects

European projects aiming at evaluation and further development of electrochemical CO_2 reduction technologies, in full or in parts.

Project	Lead partner	Full project title	Target CO2R molecule(s)	Target end product	TRL target	Funding	Time period	Link
A-LEAF	Institut Catala d'Investigacio Quimica (ICIQ)	Artificial Leaf	not specified	chemicals and fuels	?	H2020 RIA	2017-2020	http://www.a-leaf.eu/
CELBICON	Politecnico di Torino	Cost-effective carbon dioxide conversion into chemicals	formic acid	lactic acid, isoprene, terpenes (via fermentation)	5	H2020 RIA	2016-2019	https://www.igb.fraunhofer.de/en/reference-projects/celbicon.html
CLUE	VITO	Clusters for CO2 electrolyzers to ethylene	ethylene		?	VLAIO / Catalisti, BE	2022-2026	https://clue-project.be/en
CO2EXIDE	Fraunhofer IGB	CO2-based electrosynthesis of ethylene oxide	ethylene	ethylene oxide	6	H2020 RIA	2018-2021	http://www.co2exide.eu/
CO2PERATE	Ghent University	All Renewable CCU Based on Formic Acid Integrated in an Industrial Microgrid	formic acid		NA	VLAIO / Catalisti, BE	2018-2022	https://catalisti.be/project/co2perate/
D2M	Catalisti	Dioxide to Monoxide	CO		3-4	VLAIO / Catalisti, BE	2020-2022	https://vito.be/en/d2m-dioxide-monoxide
E2C	TNO (Voltachem)	Electrons to High Value Chemical Products	formic acid, etc		4 / 6	Interreg 2 Seas region	2018-2022	https://www.voltachem.com/e2c

Project	Lead partner	Full project title	Target CO2R molecule(s)	Target end product	TRL target	Funding	Time period	Link
ECO2Fuel	Deutches Zentrum fuer Luft und Raumfahrt (DLR)	Large-Scale Low-Temperature Electrochemical CO2 Conversion to Sustainable and Climate-Neutral E-Fuels & Chemicals	C1-C4 alcohols		7	H2020 IA	2021-2026	https://eco2fuel-project.eu/
eCOCO2	Consejo Superior de Investigaciones Científicas (CSIC)	Direct electrocatalytic conversion of CO2 into chemical energy carriers in a co-ionic membrane reactor	synthetic jet fuels		5	H2020 RIA	2019-2023	https://ecocoo.eu/
EcoFuel	AVL LIST GMBH		gaseous C2/C3 hydrocarbons	Fuels	5	H2020 RIA	2021-2023	https://www.ecofuel-horizon.eu/
ECOMATES	Politecnico di Torino	Electrochemical conversion of CO2 into added value products via highly selective bimetallic MATerial and innovative process dESign	CO, formic acid, ethylene		?	H2020 Marie Sklodowska-Curie Action	2023-2027	https://www.msca-dn-ecomates.eu/
eForFuel	IN SRL	Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons	formic acid	Hydrocarbons (via bioreactors)	4	H2020 RIA	2018-2022	https://www.eforfuel.eu/
EleReCEt	TNO (Voltachem)	Electrochemical reduction of CO2 to ethylene	ethylene		?	NOW, NL	2017-2021	https://www.voltachem.com/news/new-project-on-electrochemical-ethylene-production-from-co2
LOTER.CO2M	Deutches Zentrum fuer Luft und Raumfahrt (DLR)	Critical Raw Material Free Low Temperature Electrochemical Reduction of CO2 to Methanol	methanol		5	H2020 RIA	2018-2022	https://www.loterco2m.eu/

Project	Lead partner	Full project title	Target CO2R molecule(s)	Target end product	TRL target	Funding	Time period	Link
MoReCCU	UP Catalyst	Molten Salt Regeneration for Carbon Capture and Utilization	not specified		4	EIT Manufacturing	2023-2024	https://moreccu.eu/
OCEAN	Italian Institute of Technology (IIT)	Oxalic acid from CO2 using Electrochemistry At demonstratioN scale	formate/oxalate -> formic acid/oxalic acid -> glycolic acid etc		6	H2020 RIA	2017-2022	https://www.aspire2050.eu/ocean
P2X	DECHEMA	Kopernikus project P2X	syngas		NA	BMBF, DE	Phase 2: 2019-2022 Phase 3: 2022-2025	https://www.kopernikus-projekte.de/en/projects/p2x
Phaskat	Siemens Gas and Power	Phase-pure electrocatalysts and adjustment of conditions regarding the reduction of CO2	ethylene or ethanol		?	BMBF, DE	2020-2023	https://co2-utilization.net/en/projects/electro-and-photocatalysis/phaskat/
Power-2-FA	TNO (Voltachem)	Power-2-Formic Acid	formic acid		?	RVO, NL	2017-2019	https://www.voltachem.com/projects/co2-utilisation-power-2-formid-acid
ProMet	Covestro	CO2 to Propylene via eMethanol	methanol	propylene	?	BMBF, DE	2020-2023	https://co2-utilization.net/en/projects/electro-and-photocatalysis/promet/
RECODE	Italian Institute of Technology (IIT)	Recycling carbon dioxide in the cement industry to produce added-value additives: a step towards a CO2 circular economy	formate, oxalate and glyoxylic acid		6	H2020 RIA	2017-2022	https://recodeh2020.eu/
RELEASE	TU Delft	Reversible Large-scale Energy Storage	ethylene, ethanol		?	NWO, NL	2020-2025?	https://nwo-release.nl/

Project	Lead partner	Full project title	Target CO2R molecule(s)	Target end product	TRL target	Funding	Time period	Link
Rheticus I & II	Siemens Energy, Evonik	Artificial photosynthesis - a contribution to the energy transition	CO	hydrocarbons (via fermentation)	6	BMBF, DE	Phase II: 2019-2021	https://www.creavis.com/en/success-stories/current-projects/rheticus
SelectCO2	DTU	Selective Electrochemical Reduction of CO2 to High Value Platform Chemicals	CO, ethanol, ethylene		4	H2020 RIA	2020-2023	https://selectco2.eu/index.php/en/
SolDAC	COMET Global Innovation		ethylene		4	Horizon Europe	2022-2025	https://soldac-project.eu/
SynCat	Catalisti	Synergetic design of catalytic materials for photo- and electrochemical CO2 conversion processes	methanol and/or DME		?	VLAIO / Catalisti, BE	2021-2025	https://syncat.be/
TOeLS	TU Delft	Towards large-scale electroconversion systems	not specified		?	NWO, NL	2019-2024	https://www.tudelft.nl/e-refinery/research/our-flagships/toels
Transformate	b.fab	Combined process for production of the biopolymer PHB and crotonic acid	formic acid	biopolymers in bioreactor	?	BMBF, DE	2020-2023	https://co2-utilization.net/en/projects/chemical-and-biotechnological-reduction-of-co2/transformate/
Zenid	?	Sustainable Aviation Fuel from Air	syngas	SAF	6-7	?	2021-?	https://climeworks.com/news/christoph-gebald-co-ceo-and-co-founder-of-climeworks
	Siemens	Electrochemical CO2 reduction to Ethylene for industrial applications	ethylene		?	Energiforskning, DK	2018-2021	https://energiforskning.dk/en/node/15809

About CIT Renergy

CIT Renergy AB is a subsidiary of Chalmers Industriteknik. We specialize in analyses and inquiries. Our focus is on energy systems, energy technologies, indoor environments, and energy efficiency in industry and buildings. We have extensive practice in working with energy-intensive industries, small and medium-sized companies, real estate companies, entrepreneurs, and public actors. The majority of the company's employees have a Ph.D. in energy systems or technology. We are certified according to ISO 14001 (environment) and ISO 9001 (quality).