

Conclusion

Electrochemical CO₂ conversion is developing from scientific promise into an increasingly relevant industrial technology. Its strength lies in the direct coupling of captured CO₂, renewable electricity and chemical production, making it a promising route for replacing fossil carbon in the chemical industry.

Although significant challenges remain, especially in energy efficiency, long-term stability and industrial scale-up, current developments show that the field is moving steadily towards application. Projects such as WaterProof illustrate how electrochemical CO₂ conversion can be used not only to valorise CO₂, but also to connect carbon management with water treatment and resource recovery in a genuinely circular system.



Project Coordinator



Partners



Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Health and Digital Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.



Factsheet

Electrochemical CO₂ Conversion
Turning emissions into valuable chemicals and fuels

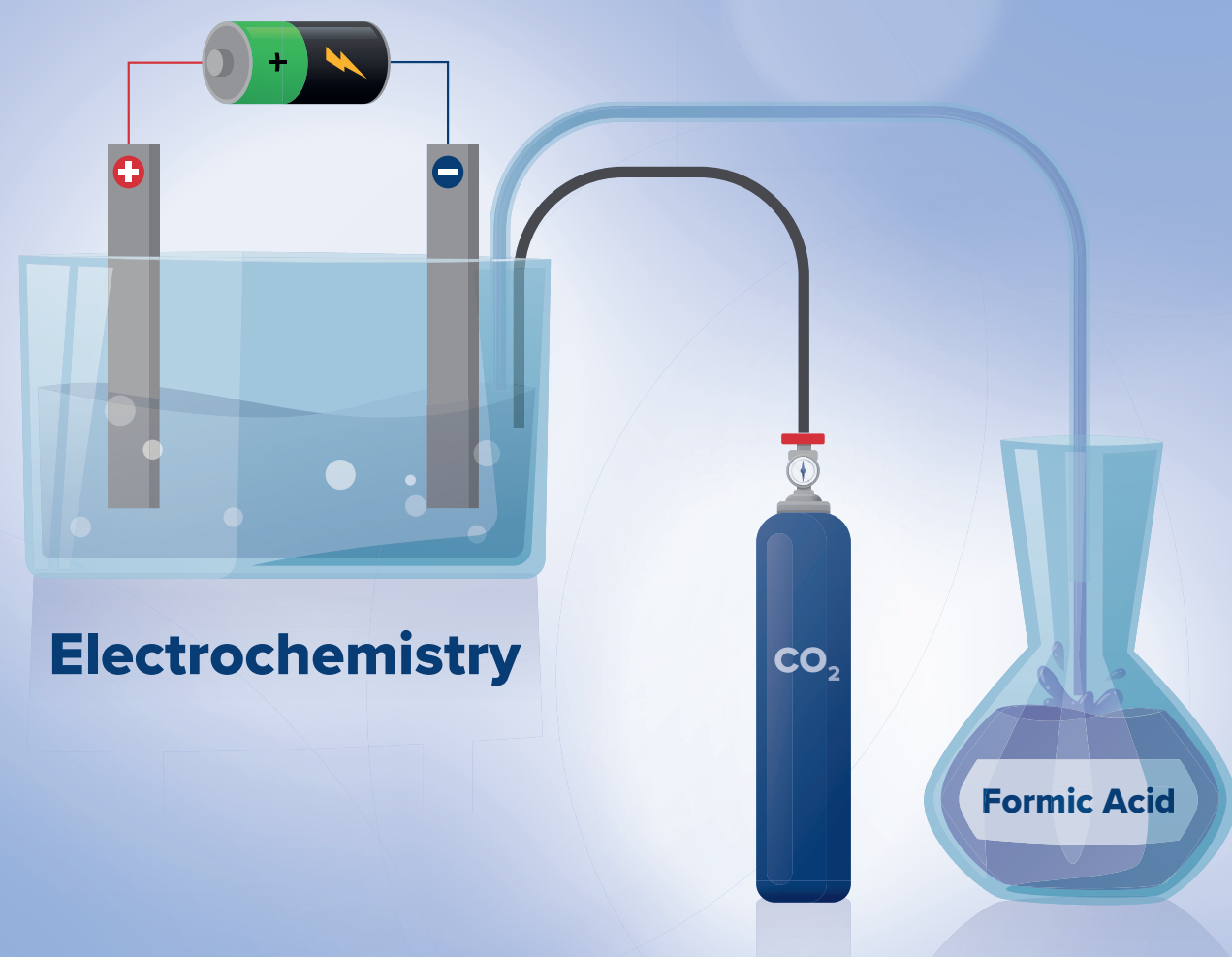


Lowering Greenhouse gas emissions by Electrochemical CO₂ Conversion

Electrochemical CO₂ conversion is an innovative approach that uses electrical energy to transform carbon dioxide (CO₂) into CO₂-based chemicals, fuels and materials. These include key platform molecules such as syngas, formic acid, methanol and ethylene, which are already widely used in the chemical and energy industries.

As part of Carbon Capture and Utilisation (CCU), this technology keeps carbon in the industrial cycle instead of releasing it into the atmosphere. By doing so, it contributes to reducing greenhouse gas emissions, lowering the demand for fossil resources, and enabling the transition towards a truly circular carbon economy.

When combined with renewable energy, electrochemical conversion can also support the mitigation of negative emissions, making it a key technology for achieving climate neutrality.



From captured CO₂ to new molecules

The CO₂ used in electrochemical conversion can come from industrial point sources such as waste incineration, wastewater treatment, cement, steel or chemical production, where it is captured before being released into the atmosphere. It can also be obtained through direct air capture (DAC), where CO₂ is removed directly from ambient air, or direct ocean capture (DOC) from seawater. The source of CO₂ is important because it shapes the climate impact of the overall process: high CO₂ concentration of point-source capture helps to reduce ongoing emissions, while DAC requires high energy supply and even with renewable energy struggles to be feasible.

The conversion itself takes place in an electrochemical cell. Here, electrical energy is used to drive chemical reactions that would not happen spontaneously. CO₂ is fed into the cell and reduced at the cathode, where it gains electrons and is transformed into new carbon-containing molecules. At the anode, a corresponding oxidation reaction takes place to complete the circuit. Which product is formed depends on the catalyst, the electrode material, the electrolyte, the membrane and the operating conditions. In this way, electrochemistry allows the targeted production of different molecules from the same carbon source.

This is what makes electrochemical CO₂ conversion especially attractive: it links carbon capture, renewable electricity and chemical production in one system. In contrast to conventional thermochemical processes, electrochemical systems can often operate under comparatively mild conditions and can be switched more flexibly in line with variable electricity supply from wind, solar or hydropower. In contrast to other CCU options it uses the electricity directly and hydrogen production for the process is not needed.

Why electrochemistry matters for CCU

The importance of electrochemistry lies not only in the fact that it can convert CO₂, but in how it does so. Because electricity directly drives the reaction, electrochemical processes can be integrated into a future energy system based on renewable power. This creates the possibility of producing chemicals with a significantly lower fossil footprint and of coupling chemical manufacturing more closely to the expansion of renewable electricity.

Another important feature is product flexibility. Depending on how the system is designed, electrochemical conversion can deliver different outputs with different industrial functions. For example formic acid can be used in cleaning products, leather tanning and as a precursor for green solvents. Carbon monoxide and syngas are key intermediates for established synthesis routes such as Fischer–Tropsch or methanol production. Methanol is an important platform molecule for fuels, chemicals and materials. Ethylene, one of the most important petrochemical building blocks, is especially relevant because it is used to produce plastics such as polyethylene for packaging and consumer goods.

In this way, electrochemical CO₂ conversion does not create an isolated niche technology. It connects directly to existing industrial infrastructures and can therefore support the gradual



defossilisation of chemical value chains. For example, syngas from CO₂ electroreduction can already function as a drop-in intermediate in established downstream processes, while ethylene production shows particular promise for reducing fossil input in the petrochemical sector. Future applications extend further to aviation fuels via Fischer–Tropsch synthesis and to sustainable polymers derived from e-methanol via Methanol-to-Olefin (MTO) processes.

The challenge of scale-up

For many years, the discussion around electrochemical CO₂ conversion focused mainly on catalyst performance in the laboratory. Today, the main question is broader: can the technology deliver the required performance under real industrial conditions?

The decisive issues now include selectivity, long-term stability, energy efficiency and product separation at scale. In other words, it is no longer enough to show that a catalyst works in a small lab cell for a limited period. Industrial systems must run continuously, tolerate impurities in CO₂ streams, deliver reliable product quality and operate efficiently enough to become technically and economically viable.

This is why integrated system design has become so important. Electrodes, membranes, catalysts and cell architecture must work together as one coherent unit. Pilot and demonstration plants play a crucial role because they generate the practical data needed to evaluate performance beyond the laboratory. Modular plant concepts combine elements such as direct air capture, multi-cell electrochemical stacks and downstream separation systems as examples of how the field is moving towards industrial relevance

Current opportunities and remaining bottlenecks

Electrochemical CO₂ conversion offers major opportunities, but several bottlenecks still need to be addressed before large-scale deployment becomes common. A central challenge is the high demand for renewable electricity. The process can only deliver strong climate benefits if the electricity input is low-carbon and available in sufficient quantities. Closely linked to this is the question of overall energy efficiency, which remains a key development target.

Another challenge is product selectivity and durability. Target molecules must be produced in sufficiently high yields and purity, while catalysts and cell components must remain stable over long periods of operation. In parallel, downstream processing becomes increasingly important: once a product has been formed, it still has to be separated and purified efficiently enough for industrial use. Industrial viability depends not only on electrochemistry itself, but on the optimisation of the entire process chain.

At the same time, the opportunities are considerable. Highlights include the electrified reverse water–gas shift systems for syngas production from CO₂ and green hydrogen, as well as advances in air-to-ethylene process development, as examples of how different electrochemical and electrified CCU routes are progressing towards practical application.

Electrochemistry in the WaterProof project

The EU-funded research project WaterProof demonstrates how electrochemical CO₂ conversion can be embedded in a broader circular economy approach.

In WaterProof, CO₂ captured from waste incineration and wastewater treatment plants is converted into formic acid using electrochemical processes. This formic acid is then used as a renewable building block for various applications. It can be utilised in cleaning products and for (fish)leather tanning, replacing fossil-based chemicals. In addition, it serves as a precursor for acidic deep eutectic solvents (ADES), which enable the recovery of valuable metals from wastewater sludge and incineration ash.

A further benefit is the generation of peroxides as by-products, which can be applied to remove pharmaceuticals and pesticides from wastewater.

By linking CO₂ utilisation, water treatment and resource recovery, WaterProof creates an integrated system that reduces emissions, replaces fossil resources and closes material cycles.

