Whitepaper

Harnessing Power-to-X for a sustainable carbon future

Prospects for the ARRRA cluster

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Executive summary

Power-to-X-CCU technologies enable the substitution of fossil carbon by circular carbon. This *defossilisation* is crucial to rendering the chemicals and fuels industries more sustainable when *decarbonisation* (in particular electrification and the use of hydrogen) is not feasible. The majority of chemicals will continue to be carbon-based, and carbon-based fuels offer the high energy density that is required for many heavy-duty transport modes.

Power-to-X-CCU technologies utilize captured CO_2 (CCU) to produce carbon-based products in processes powered by renewable energy (Power-to-X), thus ensuring a sustainable future for industry sectors that are key to the Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA). Also known as the 'Trilateral Chemical Region', it is Europe's most important chemical region, accounting for approximately 40% of petrochemical production in the EU.

This whitepaper explores how Power-to-X-CCU technologies can contribute to a sustainable, circular and competitive chemicals and fuels industry in the ARRRA cluster. It identifies technological developments, analyses strengths and weaknesses, and presents strategic directions for the ARRRA cluster to leverage its integrated industrial networks and support Europe's strategic autonomy in the production of sustainable chemicals and fuels.

Power-to-X-CCU technologies

Three Power-to-X-CCU technologies pathways are in scope of this whitepaper: thermochemical, electrochemical and plasma CO_2 conversion. These are described in terms of their technological maturity, economic viabililty and potential climate impact. While conventional thermochemical CO_2 conversions are the most mature (TRL 6-9), the other technologies still need significant development towards scale-up and ultimately commercial operation. It is clear that, due to high investment and operational costs, CO_2-based products do not currently provide a cost-competitive alternative to fossil-fuel-based products. For thermochemical CO_2 conversion, electricity is the largest cost driver. For electrochemical and plasma conversion, capital expenditure currently is dominant, followed by electricity cost. Learning effects, economies of scale, and improved designs are expected to reduce costs significantly over the next 15–20 years.

The potential climate impact of the technologies hinges on the availability of renewable energy and the extent of carbon circularity in the product lifecycle. With abundantly available renewable electricity and sustained recycling (which results in long-term CO_2 storage in a product), Power-to-X-CCU pathways can lead to significantly reduced—potentially even net-negative—emissions.

SWOT analysis

A SWOT analysis of the development and utilization of Power-to-X-CCU technologies in the ARRRA cluster forms the basis for a strategic evaluation. The presence of integrated industry clusters, the strong technology position in Power-to-X-CCU development and the large market reach for fuels and chemicals are considerable strengths of the ARRRA cluster. On the downside, the high cost and limited availability of renewable electricity, the lack of available industrial space, and the high labour cost constitute its weaknesses. Opportunities lie in favourable European policies and market support mechanisms, the rising European desire towards strategic autonomy, and the potential synergies with existing and future biogenic and waste-based processes. Finally, the trend of industries closing down and moving away from ARRRA poses a threat, as do the risk-averse investment culture, and the limited availability of critical raw materials.

Strategic directions

A confrontation matrix containing the key SWOT elements guides the determination of two strategic directions for Power-to-X in the ARRRA cluster. On the one hand these use ARRRA's strengths to take advantage of the opportunities and fend off the threats, and on the other hand these directions help overcome the weaknesses of the ARRRA cluster so that they do not become constraints in exploiting the opportunities or fending off the threats. These two strategic directions are:

Build strategic production capacity

Building strategic production capacity will reduce dependence on suppliers from outside Europe, stimulate innovation and drive further deployment of Power-to-X-CCU in ARRRA.
This can be made a success by boosting the competitiveness of the chemical industry, targeting of specific product-market combinations (such as sustainable aviation fuels) and harnessing synergies with other sustainable production pathways.

Become a global technology provider

Leveraging its strong position in technology development, the ARRRA cluster can gain a competitive edge in the global market by exporting Power-to-X-CCU technologies or components.
This can be made a reality by consolidating and protecting the Power-to-X-CCU technology position, addressing technical challenges, proving the technology, and strengthening the ecosystem. It also requires reducing the dependency on critical raw materials.

Translate ambition into action

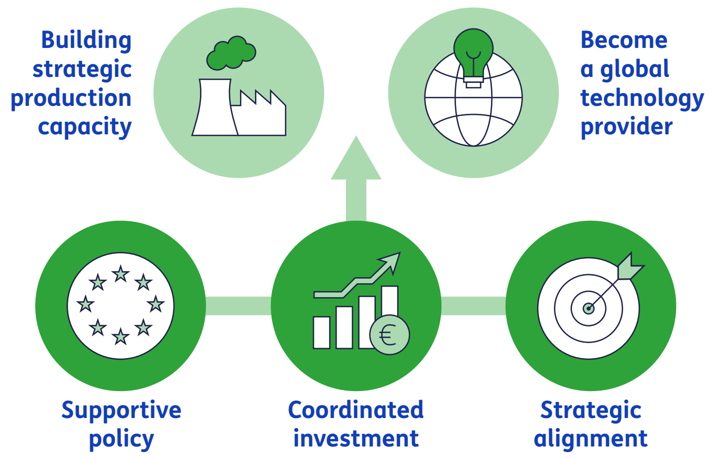
To secure a leading role for the ARRRA cluster and the broader EU in developing a Power-to-X-CCU based economy, all stakeholders need to act collectively and decisively. It is imperative to convert the ambitions of the EU Clean Industrial Deal into tangible measures by means of supportive policy, coordinated investment and strategic alignment throughout the value chain.

Supportive policy will have to aim at accelerating market demand for chemical products based on circular carbon (similar to existing fuels mandates); developing consistent and transparent carbon accounting rules; enabling the reuse of captured carbon as a feedstock for chemicals; and creating an EU strategic production capacity.

Coordinated investment is required in renewable electricity generation, upgrading and expanding the electricity grid, and creating cross-border interconnection; in infrastructure for CO_2 capture, storage, and transportation; and in hydrogen production capacity and distribution networks.

Strategic alignment is needed to create a coordinated ecosystem that spans technology development, industrial scale-up, financing, policy, and global supply chains. Such an ecosystem includes technology providers, chemicals and fuels producers, energy suppliers, investors, governments, and civil society. An important aspect of this strategic alignment is to unlock synergies with bio- and waste-based pathways to accelerate scale-up and sustainability.

By acting decisively on these matters, Power-to-X-CCU technologies can contribute to a sustainable, competitive, and circular chemicals and fuels industry in the ARRRA cluster. Aligning innovation, infrastructure, and policy will not only unlock the potential of Power-to-X-CCU, but also redefine its role in the global energy and materials transition.



Contents

Defining Power-to-X-CCU

This whitepaper presents Power-to-X-CCU as an overarching concept to describe the sustainable conversion of CO_2 into valuable chemicals and fuels. It combines two commonly known concepts:

Power-to-X, which refers to a large number of pathways and technologies designed to use renewable energy for the production of useful goods and services. The 'X' in Power-to-X denotes a diverse set of end products, with common applications under development including Power-to-Ammonia, Power-to-Chemicals, Power-to-Fuels, Power-to-Gas (Power-to-Hydrogen, Power-to-Methane) and Power-to-Liquid (synthetic fuel).

CCU, or carbon capture and utilization. This is a set of pathways and technologies that 1) capture CO_2 from the atmosphere or point sources and 2) convert the CO_2 into useful materials, including chemicals such as carbon monoxide, syngas, methanol and formic acid, which can serve as intermediates for producing value-added products such as plastics and synthetic fuels. CO_2 capture and purification systems have already been developed on an industrial scale, while conversion technologies are still at various stages of development. Figure 1 provides an overview of the leading CO_2 conversion technologies, categorised according to their core conversion principle.

Because of its thermodynamic stability and low reactivity, the conversion of CO_2 requires a significant amount of energy. Power-to-X technologies provide this energy in the form of renewable electricity or green hydrogen, enabling the sustainable production of carbon-based fuels and chemicals [1]. This focus on **Power-to-X-CCU** technologies implies that other CCU technologies such as chemo-enzymatic mineralisation, photocatalytic, and biological conversion, as well as mineralisation, fall outside the scope of this paper.

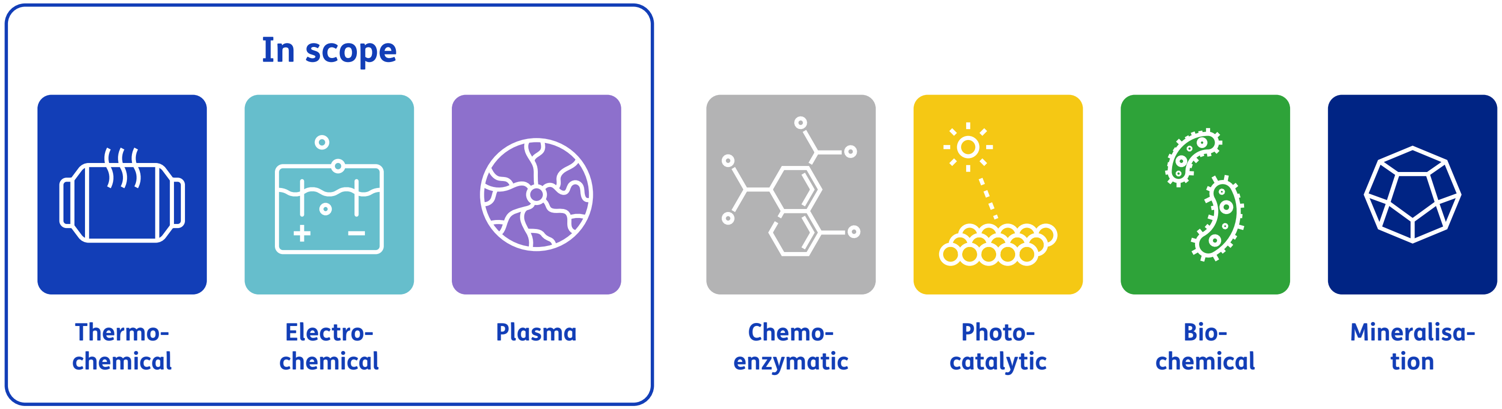


Figure 1. Overview of CO_2 conversion technologies. This whitepaper focuses on thermochemical, electrochemical and plasma conversion technologies.

1 The need for Power-to-X-CCU in the carbon transition

This whitepaper explores how Power-to-X-CCU technologies can contribute to a sustainable, circular and competitive chemicals and fuels industry in the ARRRA cluster. It identifies technological developments, analyses strengths and weaknesses, and presents strategic directions.

1.1 Challenges of Europe's chemical industry today

Europe's chemical industry, once a global leader, is now facing a slow but steady decline. Its competitive position has weakened significantly over the past 10-15 years, due to several factors, such as high energy prices, regulatory pressure, scarcity of critical raw material, limited investments and high labour cost [3] [4]. The share of the European chemical sector in global chemicals sales decreased from 23% in 2008 to 13% in 2023 [4]. In that year, the sector ranked as the third-largest chemicals producer worldwide (behind China, and the rest of Asia), generating €665 billion in sales [2].

The Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA), also known as the 'Trilateral Chemical Region', remains Europe's most important chemical region, accounting for approximately 40% of petrochemical production in the EU [5]. This region benefits from an extensive infrastructure network, connecting the industrial clusters in Germany, the Netherlands and Belgium by road, rail, waterways and pipelines [6]. Nevertheless, the declining competitiveness has led to the shutdown of chemical production facilities over the past two years [4]. This not only weakens the ARRRA cluster but also undermines Europe's strategic autonomy ambitions.

Responding to rising geopolitical tensions, reduced economic growth and increasing technological competition, the European Commission published the Clean Industrial Deal (CID) in early 2025 [7]. The objective of this strategy is to boost the competitiveness of the energy intensive industries, including chemicals, as well as supporting Europe's clean tech sector. Through the CID, Europe reaffirms its commitment to climate targets, while acknowledging the concerns of declining competitiveness. Ensuring both sustainability and competitiveness requires a fundamental shift in how Europe's chemical industry sources its carbon and energy. The CID specifically calls for the use of captured carbon in a wider range of products, signalling the need for Carbon Capture and Utilization (CCU) technologies, which can convert CO_2 into valuable chemical feedstocks and fuels.

1.2 The need for Power-to-X-CCU technologies

Reducing CO_2 emissions and reliance on fossil carbon sources can be achieved through two main strategies: **decarbonisation** (reducing the use of carbon) or **defossilisation** (substituting fossil carbon by alternative sources of carbon such as biomass, waste and CO_2). While many sectors can be decarbonised through electrification and the use of hydrogen, hard-to-abate sectors - specifically heavy-duty transport sectors and the chemical industry - will continue to require carbon-based feedstocks and fuels. The chemical industry, in particular, depends on carbon as an essential building block for materials and chemicals. Furthermore, global demand for these products is expected to double by 2050, driven by the increasing demand for chemicals from emerging markets, such as Asia-Pacific and Africa [2]. To meet this demand in a sustainable manner, carbon must be sourced from renewable and circular alternatives. These include:

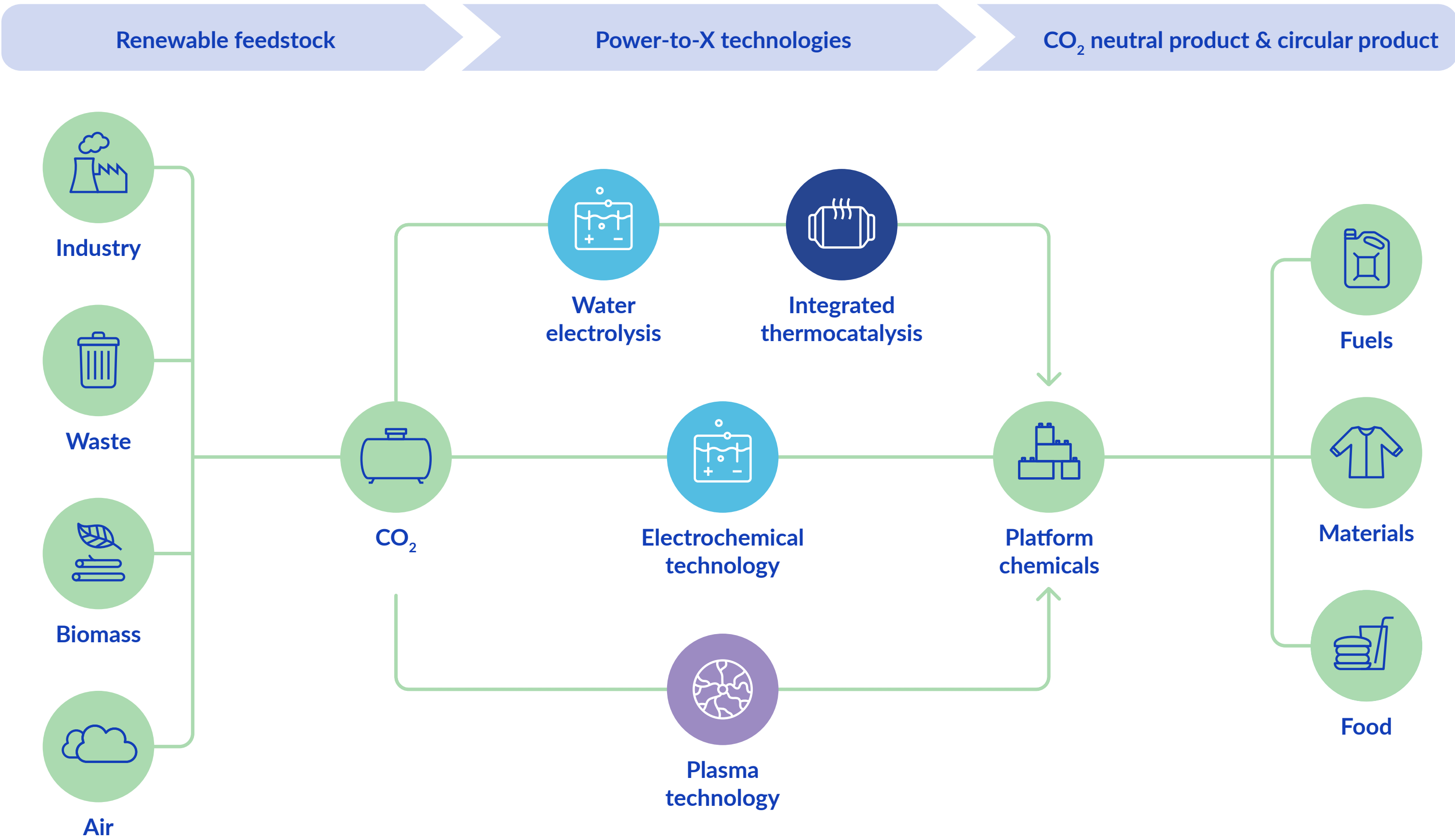


Figure 2. Overview of key Power-to-X-CCU technology value chains based on CO_2 captured from various sources.

- **Waste**: This source refers to plastic waste. Mechanical and chemical recycling play an important role in reducing the chemical industry's reliance on virgin fossil-based carbon. However, even if global recycling rates reach their theoretical potential, only 60-70% of plastic volumes can be produced from recycled feedstock due to losses along the supply chain [8].
- **Biomass**: The use of bio-feedstocks, after processing by, for instance, gasification or pyrolysis, offers a circular alternative for producing chemical building blocks. Their future availability, however, is uncertain. The extent to which biomass can contribute to the production of sustainable chemicals and fuels depends heavily on policy frameworks, such as agricultural policies, sustainability standards and sector-specific regulations [9] [10].
- **CO_2**: Given the constraints on biomass and recycling, carbon (dioxide) capture and utilization (CCU) represents a valuable supplementary route to closing the carbon loop. However, converting CO_2 into useful products is challenging due to its thermodynamic stability and low reactivity, requiring significant energy input to build hydrocarbon molecules. Additionally, specific CO_2 conversion routes require a substantial amount of green hydrogen, produced via energy-intensive water electrolysis using renewable electricity. It should also be noted that compared to other routes, CCU technologies have a stronger reliance on critical raw materials, for which the EU is heavily reliant on imports.

Figure 2 presents an overview of Power-to-X-CCU value chains that are based on CO_2 captured from four major sources: industrial emissions, plastic waste and biomass (after processing), or the atmosphere (air capture).

For the ARRRA cluster, Power-to-X-CCU technologies can offer a long-term opportunity to leverage its integrated industrial networks and support Europe's strategic autonomy in the production of sustainable chemicals and fuels.

1.3 Motivation and structure of this whitepaper

This whitepaper aligns with VoltaChem's recognition of the urgent need to transition Europe's chemical industry towards a more sustainable, competitive, and circular future. The ARRRA cluster, as Europe's largest chemical cluster, is at the heart of this transformation.

The whitepaper builds upon previous VoltaChem publications, including Enabling Power-to-X & CCU in the Chemicals Industry [11] and E-Fuels: Towards a More Sustainable Future for Truck Transport, Shipping, and Aviation [12]. By further exploring technological pathways, strengths and weaknesses, and strategic directions, it aims to inform stakeholders, support decision-making, and drive collaboration in scaling up Power-to-X-CCU solutions for the ARRRA cluster.

The structure of this whitepaper is as follows:

- Chapter 2 compares Power-to-X-CCU technologies, including thermochemical, electrochemical, and plasma-based approaches. A more detailed description of the technologies is included in the Annex.
- Chapter 3 presents a SWOT analysis and suggests strategic directions of Power-to-X-CCU development in the chemical cluster of ARRRA.
- Chapter 4 outlines a high-level roadmap for Power-to-X-CCU implementation in the ARRRA cluster.

2 Power-to-X based CO_2 conversion technologies

This white paper covers three Power-to-X-CCU pathways: thermochemical, electrochemical, and plasma CO_2 conversion. In this chapter the technologies involved are evaluated on maturity, economic and environmental performance. The Annex provides a closer look at these Power-to-X-CCU technologies.

Figure 3 shows an overview of the three identified pathways. It is important to note that the thermochemical conversion pathway relies on green hydrogen, produced via water or steam electrolysis, which is then used to convert CO_2 into valuable chemical building blocks. In contrast, the electrochemical and plasma-based pathways utilise electricity directly in the CO_2 conversion process, avoiding the need for intermediate hydrogen production.

The different Power-to-X-CCU technologies have different product portfolios, although there is some overlap. For example, syngas can be produced through multiple pathways and can be further processed into other valuable products, such as methanol, dimethyl ether (DME), sustainable aviation fuel (SAF) and ethylene (see Figure 3).

This chapter first provides an overview of the technological readiness levels (TRL) and advantages and disadvantages for the various technologies (2.1). Then, the economic viability (2.2) and the global warming potential of the value chains (2.3) are discussed. The chapter ends with a summary of key takeaways (2.4).

2.1 Status of technology development and industrial application

Power-to-X-CCU technologies are at various stages of technological maturity, which also depends on the product they address. The same type of technology may need component modifications (other catalyst, cell configuration, separation steps, etc.) to produce a different product. As a result, the maturity of technology development varies per product. This is reflected in their Technology Readiness Level (TRL) which is expressed on a scale from 1 to 9 with 9 being the most mature technology.

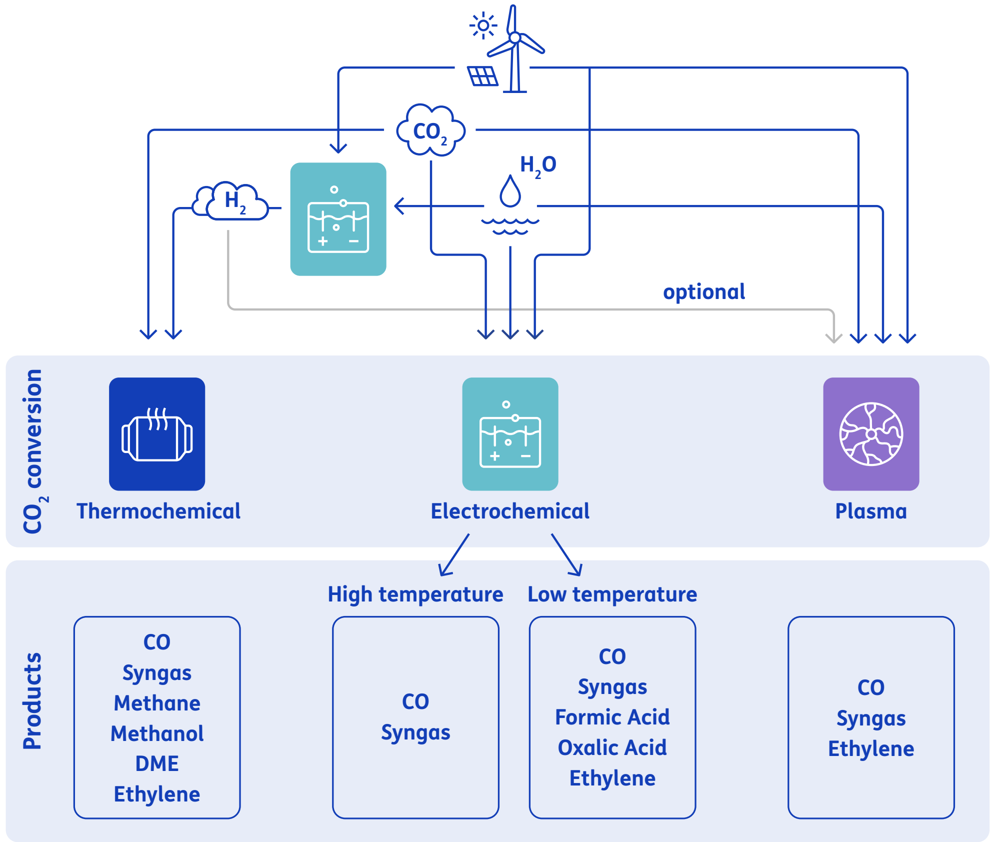


Figure 3. Three CO_2 conversion technologies and their main products: thermochemical, (high and low temperature) electrochemical and plasma.

Every technology offers distinct advantages and disadvantages that come into play when choosing a CO_2 conversion technology for a certain industrial use case. Table 1 shows a (non-exhaustive) list of advantages and disadvantages for multiple technologies and their applications, arranged by type.

Table 1. Comparison of various CO_2 conversion technologies. Advantages and disadvantages are summarised under the assumption that technology-specific development hurdles have been overcome.

Technology type	Product (TRL)	Advantages	Disadvantages
Thermochemical conversion	CO (6/7) syngas (6/7) methane (7/8) methanol (9) DME (7-8) ethylene (<4)	• **Highest technology readiness** and commercial industrial implementation • **Good fit with current industrial practices** as industry has operational and maintenance experience with thermochemical conversion processes	• **Two separate unit operations required**: 1) production of green H_2 2) CO_2 conversion • **Design of catalyst and plant need significant modifications** in case it needs to fit with flexible operation modus compared to steady state operation.
Separation enhanced conversion Conversion	methanol (5) DME (5-6)	• **Experience with scale up** of thermochemical conversion processes in industry helps derisking	• **Single pass CO_2 conversion** limited by reaction products -> removal in reactor necessary to increase conversion and prevent external recycle
High temperature electrochemical conversion	CO, syngas (4-6)	• **Highly efficient** CO_2 conversion due to combination of waste heat and electrical energy • **One step conversion** of steam and CO_2 with controllable H_2/CO ratio • **Modular scale up** possible to gradually grow capacity	• **New type of unit operation**, lack of knowledge and experience. • **Material degradation**, due to corrosive, high temperature operating conditions • **Complex and expensive system integration**: on a large scale, many modules need to be interconnected for electrical part, feed and product manifolds and heat integration
Low temperature electrochemical conversion	CO (4-5) formic acid (5-6) oxalic acid (<4) ethylene (<4)	• **Milder operating conditions**, material of construction less expensive than HT • **Various products** can be made with this technology at high selectivity • **No need for high temperature (waste) heat input**, so good combination with biotechnological processes	• **Slower reaction rates than HT electroconversion**, resulting in larger electrolysers • **More complex components compared to SOE**: gas diffusion electrodes, membranes • **On large scale more complex and expensive** system integration: many modules need to be interconnected for electrical part, feed and product manifolds and heat integration
Plasma conversion	CO (5-6) syngas (4) ethylene (<4)	• **Plasma reactors** can be turned on and off quickly • **Large scale operational experience with** plasma reactors • **No critical raw materials** needed	• **Control of selectivity** more challenging • **Expensive plasma reactor**, due to complexity • **CO_2 only conversion more challenging** than combination of CO_2 and CH_4 to produce syngas

In general, conventional thermochemical CO_2 conversion technologies are the most mature (TRL 6-9). For methanol, this pathway is already commercially applied at various locations in the world. Other technologies still require significant development to scale up to demonstration and ultimately commercial scale.

Technology selection for specific use cases will be based on selection criteria like technology readiness, process efficiency, commercial references, fit with operational and maintenance experience, availability of green hydrogen, etc. For example, at existing production sites thermochemical conversion will be easier to fit in for operational and maintenance reasons. In a greenfield situation, alternative technologies like electrochemical conversion might offer advantages, such as the possibility of modular scale-up. This offers a way to reduce risk: the technology can be proven for a single module, then scaled up.

Cost and environmental impact are two other important main technology selection criteria. These are discussed separately in the following paragraphs.

2.2 Economic viability

When selecting an emerging CO_2 conversion technology, it is crucial to understand the techno-economic landscape and the key factors influencing production costs. Comparing data reported in literature is challenging due to differences in scope boundaries, assumptions, and methodologies, as well as use cases, plant locations, and year of operation. Nevertheless, an order of magnitude can be derived for the cost per ton of product.

The techno economic evaluation presented below was carried out for a production pathway towards CO and syngas, including carbon capture, CO_2 conversion technology, separation and purification steps to meet the required product quality. The total production costs using the various CO_2 conversion technologies were analysed and compared.

Electrochemical CO production

Figure 4 shows the costs for electrochemical CO_2 conversion to CO at the current state of development [11] at low temperature (LT) and high temperature (HT) electrolysis.

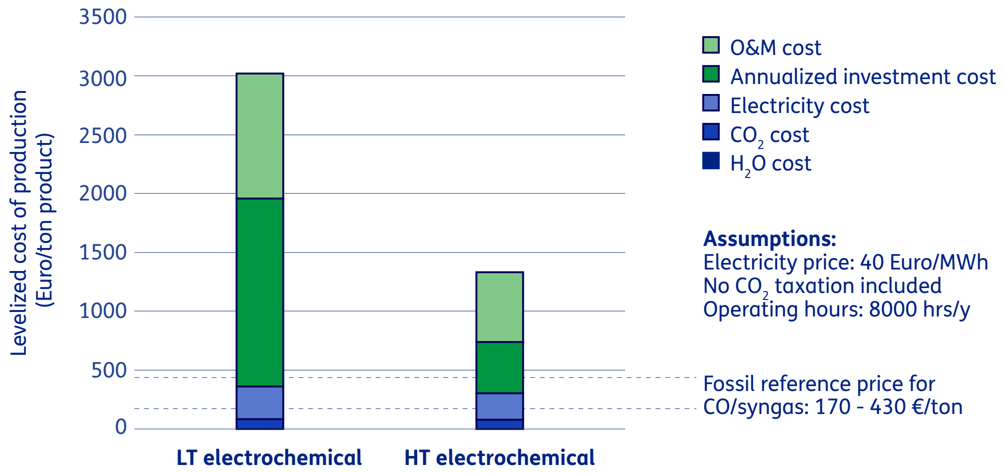


Figure 4. Costs of HT and LT CO_2 electro conversion pathways for CO. [11].

The main cost contributors for the HT electrochemical production pathway are the investment cost and the operating and maintenance (O&M) costs, due to a limited lifetime of the electrolyser cell and stack. Electricity costs rank as the third highest contributor. Also, for the LT electrochemical conversion pathway these three are the main cost contributors.

The total levelised cost for CO production by HT electrochemical pathway at the current state of technological development is more than twice as low compared to the LT pathway, making this the preferential pathway from a cost perspective.

Syngas production

Another interesting chemical building block is syngas, which consists of CO and H_2. Syngas can be produced using various CO_2 conversion routes; thermochemical, HT electrochemical and plasma. Table 2 summarises the levelised cost for electrochemical CO_2 conversion to syngas, as mentioned in various papers.

The **thermochemical CO_2 conversion route** to syngas has an estimated levelised cost in the order of ~1000 €/ton syngas at an electricity price of 40 €/MWh [12]. For this route the electricity price and consequently the green hydrogen production cost are the largest contributors to the levelised cost.

The levelised cost for syngas production using the current state of **HT electrochemical conversion** is calculated at ~1000 €/ton syngas at an electricity price of 40 €/MWh [13]. The main cost contributors for this pathway are investment costs, followed by electricity and operational cost.

Syngas production by **plasma technology** includes the production pathway of CO_2 capture, CO_2 conversion to CO using (microwave) plasma, water electrolysis to produce green hydrogen and mixing both gases to syngas. The cost of converting CO_2 to CO using (microwave) plasma technology via this pathway is estimated to be approximately 2200 €/ton of syngas, at an electricity price of €40 per MWh [13]. Green hydrogen cost, followed by investment and electricity cost are the largest cost contributors for this pathway.

Comparison to fossil-based production

With the current state of the art, CO_2 conversion pathways are not cost competitive compared to current fossil-based pathways. Given the nascent state of CO_2 conversion technologies, the initial investment costs are high and still uncertain for early commercial applications. However, as these technologies become commercially proven and more widely adopted, investment costs are anticipated to decrease, driven by economies of scale, manufacturing improvements, process optimization and gained experience and trust in the nascent pathways. Furthermore, the costs of fossil pathways are expected to increase due to regulation, market incentives and CO_2 pricing. Also, it can be expected that the willingness to pay for sustainable alternatives will increase over the years.

Forecast of future cost

As an example, Figure 5 illustrates the anticipated levelised cost development for syngas production via HT electrochemical conversion, using the Solid Oxide Electrolyser technology. Learning curves for related mature technologies, such as Solid Oxide Fuel Cells, can help to forecast future cost trends. For the high-temperature (HT) electrochemical CO_2 conversion pathway to syngas, a 20% learning rate was assumed based on the fuel cell learning curves. In the cost projections, the investment costs, OPEX and electricity cost will reduce significantly over time, while CO_2 cost will increase [13]. Ultimately, if learning progresses as expected, the cost will reduce with about a factor 2 in the coming 15-20 years and electricity and CO_2 costs will become the dominant factor in the levelised cost of syngas.

Table 2. Order of magnitude cost comparison for syngas production via different production pathways at the current state of the art.

Thermochemical conversion	High temperature electrochemical conversion	Plasma conversion
~1000 €/ton	~1000 €/ton	~2200 €/ton

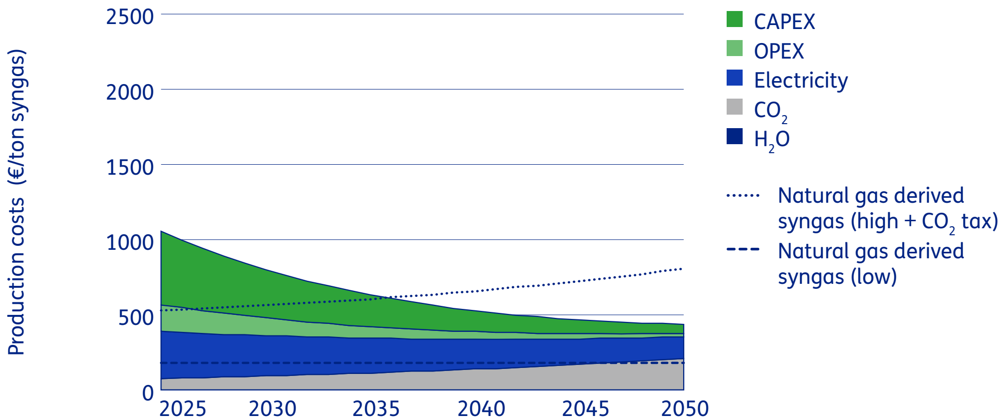


Figure 5. Projections of the levelised production costs for HT electrochemical CO_2 conversion to syngas (excl. ETS pricing).

As electricity price becomes the dominant cost factor in the future, one strategy to enhance competitiveness against fossil-based products is to operate the plant dynamically at various loads during times of abundant, cheap renewable energy supply. Investigating the feasibility of adapting technologies and production pathways for this purpose is an interesting area for further exploration.

ETS pricing for CO_2 emission and the currently active mandates for e-fuels will drive market demand and will help to create a momentum for the development and scale up of new technologies and their value chains to a mature level. Since Power-to-X-CCU technologies produce chemical building blocks, these developments are also valuable for e-chemical value chains.

2.3 Climate impact

The feasibility of Power-to-X-CCU technologies depends to a major part on their potential to drive industrial transformation toward net-zero emissions by 2050. This section compares the climate impact of CO_2-based chemicals to their fossil-derived counterparts using a screening Life Cycle Assessment (LCA). This simplified LCA estimates global warming potential (GWP, in CO_2-equivalent emissions) of a product or process throughout its lifecycle. Two Power-to-X-CCU pathways are assessed:

- **Methanol** via thermochemical CO_2 conversion
- **Ethylene** via low temperature electrochemical conversion

The system boundaries of the screening LCA are shown in Figure 6. It includes the carbon source, processing steps to make the carbon available for conversion, the production process, and end-of-life processing of the product (burning, recycling, landfill) [14].

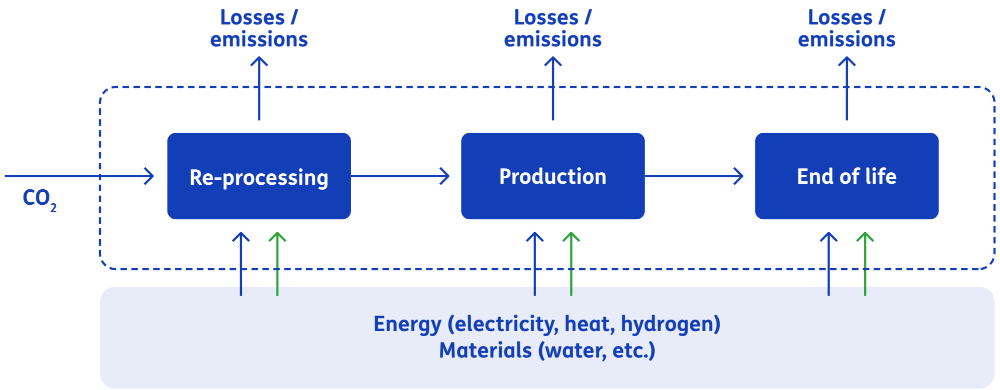


Figure 6. System boundary definition of the screening life cycle assessment.

Two scenarios were defined to illustrate a bandwidth of the climate impact of the energy source and end-of-life processing of the product:

1. **Current scenario**: represents the current electricity mix, natural gas for heat and incineration at the end-of-life;
2. **Future scenario**: represents the use of renewable electricity, biomass for heat and recycling at the end-of-life.

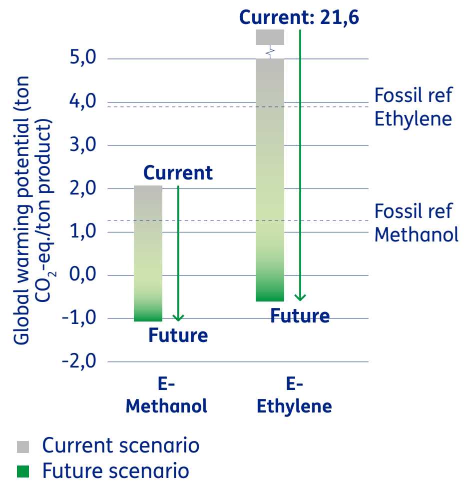


Figure 7. Global warming potential (ton CO_2-eq. emissions/ ton product) of value chains for the chemicals methanol and ethylene.

The two scenarios were used in screening life cycle assessments of two value chains that use carbon dioxide as feedstock: the production of methanol and ethylene. This led to the determination of the bandwidth of the global warming potential of the two value chains, depicted in Figure 7. The fossil reference in the graph is the conventional fossil-based production route for methanol and ethylene.

Under current conditions, the Power-to-X-CCU pathways have relatively high global warming potentials, due to their energy intensive nature, combined with the use of fossil-based energy and incineration at the end-of-life (which releases CO_2 to the atmosphere). However, following the future scenario in which these processes are powered by renewable energy and the products are part of a circular economy, the carbon footprint drops significantly and could even become negative. This illustrates that although Power-to-X-CCU concepts have great potential, their viability to help meet net zero ambitions hinges on the availability of abundant renewable energy.

It must be noted that the simplified LCA approach presented here only provides an outlook on the global warming potential of Power-to-X-CCU value chains. There are, however, many other factors that are relevant in the broader sense of the full environmental impact. Think, for instance, of land use, use of critical raw materials and the recycling of components like waste catalyst, electrodes or membranes. All these require thorough investigation to provide insights into the full environmental impact.

Table 3. Overview of key technology development efforts per CO_2 conversion technology.

	Thermochemical conversion	**High temperature electro conversion**	**Low temperature electro conversion**	**Plasma conversion**
Performance	**Increase lifetime**: Increase efficiency, improve catalyst stability, also for variable load-production.	**Increase lifetime cell/stack**: improve catalyst stability, develop advanced cell/ stack materials to reduce degradation	**Increase lifetime cell**: improve catalyst stability, increase lifetime and robustness of electrodes and membranes	**Increase product yield**: improved understanding and control of reactions in reactor
Cost reduction	In situ water and/or side products removal from reactor to enhance efficiency	Optimization of cell/ stack design and scale up of cell dimensions	Improve single-pass conversion rate, increase reaction rates and selectivity	Improve process and conversion efficiency, optimise reactor design

2.4 Key takeaways

Drawing from the analysis presented in the previous sections and the Annex, the following key takeaways summarise the current state of progress, challenges, and opportunities for Power-to-X-CCU pathways.

- **Key technology development efforts**: Significant R&D efforts are being invested in Power-to-X-CCU and other CO_2 conversion technologies, recognizing the future need for CO_2 as a feedstock. Table 3 outlines the key focus areas for the development of each technology. A detailed analysis is provided in the Annex.
- **Technological maturity**: Conventional thermochemical CO_2 conversions (TRL 6-9) are the most mature technologies. Other technologies still need significant development to scale up to demonstration scale and ultimately commercial production scale.
- **Dominant cost drivers**: Currently, CO_2-based products are not cost-competitive with fossil-based alternatives due to high investment and operational costs. Investment cost is the dominant cost driver for electrochemical and plasma conversion, followed by electricity. For conventional thermochemical CO_2 conversions, electricity is the largest cost driver. Learning effects, economies of scale, and improved designs are expected to reduce costs significantly over the next 15–20 years. The dynamic operation of plants to take advantage of low electricity prices needs further investigation, as this may have many consequences for the catalyst stability and process design, as well as operational and investment cost.
- **Climate impact**: Reducing global warming potential hinges on the abundant availability of renewable energy, and the circularity of the product lifecycle. Under current fossil-based energy conditions, CO_2 conversion technologies offer limited climate benefit. However, these pathways can lead to significantly reduced—potentially even net-negative—emissions through the use of renewable electricity, recycling, or long-term CO_2 storage in a product.
- **Relevance of location**: CO_2 conversion pathways to produce commercial scale sustainable chemicals and fuels will in particular provide opportunities for regions with abundant availability of low-carbon energy and CO_2.

3 Unlocking Power-to-X-CCU potential in the ARRRA cluster

The Power-to-X-CCU technologies described in Chapter 2 offer opportunities to shape the carbon transition for the chemical and fuels industry. This chapter explores those opportunities for the ARRRA (Antwerp-Rotterdam-Rhine-Ruhr Area) cluster by means of a SWOT analysis of the development and utilization of Power-to-X-CCU technologies. The SWOT elements are then incorporated in a confrontation matrix which leads to the identification of two major strategic directions for the ARRRA cluster. The SWOT analysis was performed in collaboration with industrial companies from the VoltaChem community and experts from TNO through workshops and interviews.

Section 3.1 explores the strengths and weaknesses of the ARRRA chemicals and fuels clusters, assessing their capacity to develop and implement Power-to-X-CCU technologies compared to global competitors. The opportunities and challenges shaping the potential market demand for CO_2-based fuels and chemicals are described in 3.2. The two strategic directions for the ARRRA cluster derived from this SWOT analysis are elaborated in 3.3.

3.1 Strengths and weaknesses of ARRRA's industrial system regarding the development and application of Power-to-X-CCU

The Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA) is the most important chemical region in Europe. The region's unique strengths, as well as weaknesses, affect its competitive position to develop and commercialise Power-to-X-CCU technologies.

Strengths
- Presence of integrated clusters
- Strong position in P2X-CCU technology development
- Large market reach for fuels and chemicals

Weaknesses
- High cost and limited availability of renewable electricity
- Scarcity of physical space
- High labour costs

Strengths

- **Presence of integrated clusters**
  The ARRRA cluster is in fact a supercluster of multiple regional industry clusters spanning the Netherlands, Germany and Belgium. These extensive integrated industrial infrastructure networks, which enable efficient resource sharing and optimization of supply chains, constitute the main strength of the ARRRA cluster for the development of Power-to-X -CCU technologies. The geographical location at two large seaports in Antwerpen and Rotterdam provides opportunities for the import of feedstocks (such as hydrogen and hydrogen carriers) and the landing of large amounts of electricity from offshore wind farms. Key investments in hydrogen and CO_2 transport infrastructure, such as the Rotterdam hydrogen network, the Dutch hydrogen backbone, and the Delta Rhein Corridor enhance resource efficiency.

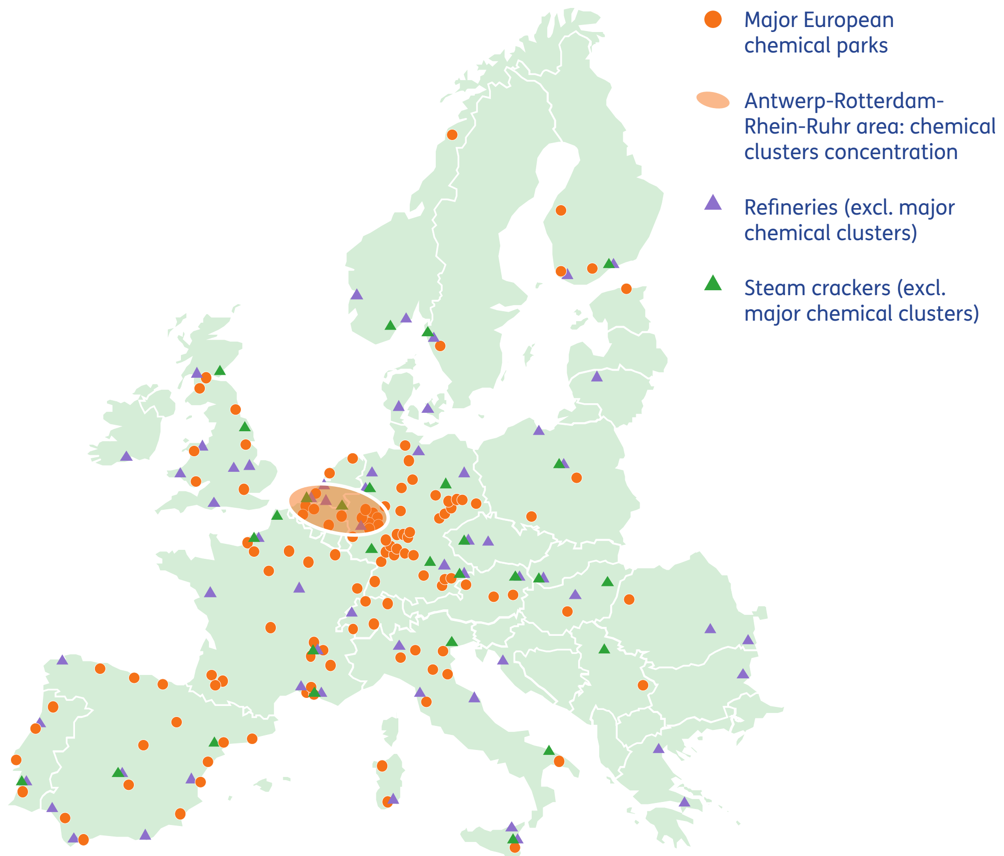


Figure 8. The ARRRA is a supercluster of multiple regional industry clusters in the Netherlands, Germany and Belgium, which are connected through extensive infrastructure networks. Source: [4].

- **Strong position in Power-to-X-CCU technology development**
  The ARRRA cluster is home to many innovative and leading companies spanning the entire value chain of CO_2 utilization: from R&D organizations and technology developers to technology manufacturers, EPC (Engineering, Procurement, and Construction) contractors, and large-scale chemicals and fuels producers. Table 4 provides a (non-exhaustive) list of companies that are already active in the technology value chain. The ARRRA cluster has a particularly strong position in catalyst development, process development and separation technology, as well as in high-tech manufacturing [15].

- **Large market reach for fuels and chemicals**
  Although Europe's global market share is falling, the ARRRA chemical and fuels cluster still benefits from a significant market share within and outside Europe. In 2023, the chemical industry in Germany, Belgium and the Netherlands represented 48% of EU27 chemical sales and 6% of global chemical sales [2]. Rotterdam is home to one of the largest fuels producing clusters worldwide. Existing customer relations can be leveraged to create a market share in CO_2-based chemicals and fuels. The strategic geographic location and logistical infrastructure facilitate access both to European markets and markets outside Europe through the major ports. This ensures that CO_2-based fuels and chemicals produced within the cluster can quickly reach high-demand regions. The region's well-developed transport networks (rail, road, waterways, and pipelines) enable the efficient trade of intermediate products, and final goods, reducing logistical bottlenecks within and outside of the EU.

Table 4. Steps in the Power-to-X-CCU technology value chain, as well as examples of companies within ARRRA, which are already active or could potentially play a role.

Step in CCU technology value chain	Outputs	Active and potential players in the ARRRA (not exhaustive)
Research & Development (R&D)	Scientific papers, patents, prototype systems, pilot projects, demo projects (first-of-a-kind plants)	• TNO VoltaChem (NL) • VITO (BE) • Fraunhofer UMSICHT (DE)
Technology Development and Component Design	Pre-commercial systems, scaled prototypes, validated materials, ready-to-manufacture components	• Avantium (NL) • BSE Methanol (DE)
Manufacturing and Component Supply	Capture units, catalytic converters, CO_2 -to-product reactors, integrated components	• Thyssenkrupp Industrial Solutions (DE) • Bosch • Johnson Matthey (Toshiba) • Topsoe (DK)
Engineering, Procurement, and Construction (EPC)	Fully installed and operational CCU facilities capable of capturing and converting CO_2 at scale	• Fluor (NL) • Technip Energies (DE/NL) • Bilfinger (DE/NL) • Jacobs Engineering (DE/NL) • MAN Energy solutions (DE)
Operation, Maintenance, and Service Providers	Optimally functioning CCU plants, high capture rates, efficient CO_2 conversion, reduced operational costs	• ENGIE (NL/BE) • Air Liquide (NL) • Sitech (NL)
End Product Utilization and Market Integration	Commercial products (fuels, chemicals, materials) with reduced carbon footprints integrated into markets	• Neste (NL) • ArcelorMittal (BE) • BASF (DE) • OMV (Austria, with ARRRA operations) • Covestro (DE) • P-2-X (NL) • Evonik (DE)

Weaknesses

- **High cost and limited availability of renewable electricity**
  Electricity and natural gas prices in Europe spiked in the period of 2021-2023 as a result of the gas crisis and the war in Ukraine. Although energy prices have declined towards 2024, the European electricity and gas prices have significantly weakened its competitive position compared to other regions such as China and the US. This price gap is expected to remain both for natural gas (2-3 times higher compared to the US) and electricity (1.5-2 times higher than in the US) [4]. In addition, the electricity cost of energy intensive industries in ARRRA is higher than the European average. In the Netherlands (€95/MWh on average, in 2024) it is even higher than in Germany (€45/MWh) and Belgium (€56/MWh) [16], as a result of higher network charges and a lack of exemptions on taxes and levies [17]. In comparison, the electricity cost in France is €32/MWh. In the long term, the limited availability of renewable energy sources in the ARRRA region could lead to even higher electricity prices. Although the ARRRA-cluster can tap into vast amounts of electricity from offshore wind, this is likely not enough to fulfil demand for renewable electricity in all sectors [18] (see Figure 9).

Power-to-X-CCU technologies are particularly sensitive to electricity costs, as they require more electricity than biobased and waste-based processes. In case of thermochemical CO_2 conversion, hydrogen could be imported to reduce electricity demand in ARRRA. However, electrochemical and plasma CO_2 conversion rely on local power sources. Besides the expected scarcity of electricity, network congestion and long lead times for (capacity extensions of) grid connections are already urgent problems for the industry in the Netherlands. This may also become the case for the Belgian and German parts of ARRRA.

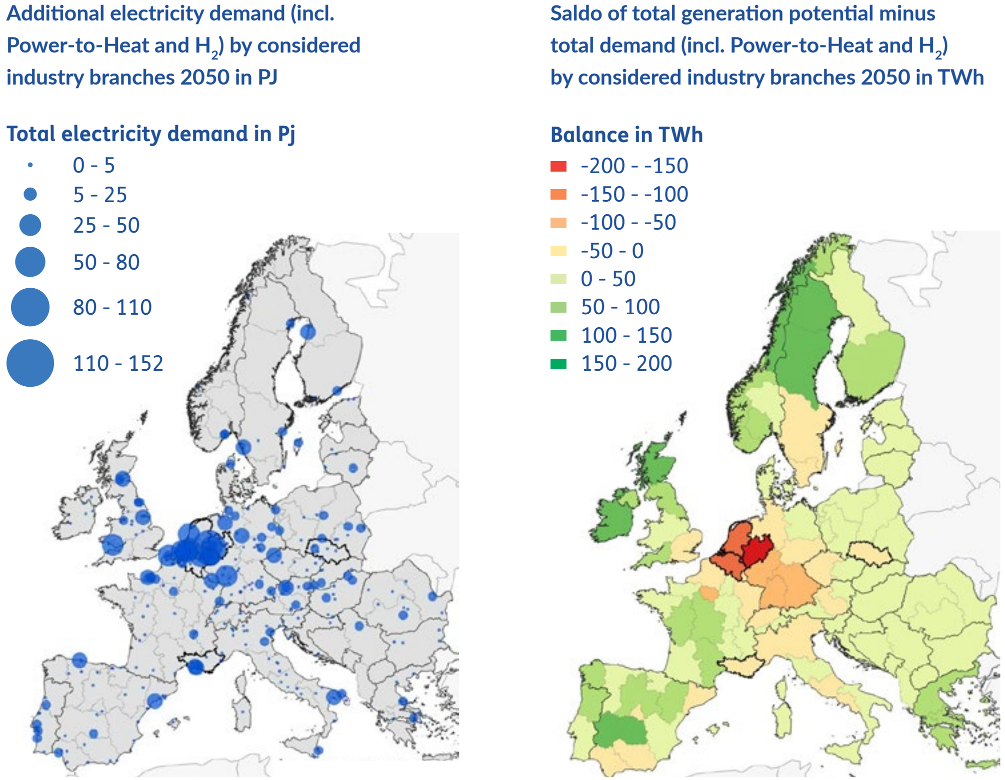


Figure 9. Left: Regional distribution of electricity demand in 2050 (including Power-to-Heat and H_2 for decarbonising steel, basic chemicals and cement, and electrification of other sectors). Right: Balance of total electricity generation potential minus total demand. Source: [18].

- **Scarcity of physical space**
The establishment of Power-to-X-CCU plants and the necessary infrastructure will require physical space. In some parts of the ARRRA-cluster, especially in the harbour industrial cluster in Rotterdam, physical space is so limited that thorough planning will be needed to make room for new industrial initiatives for the energy and materials transition. A complicating factor is that existing fossil production capacity must remain operational until sustainable alternatives have taken over. This means that during the transition even more space is needed [19]. In particular Direct Air Capture is known to be space-intensive, and since it is also energy-intensive, DAC is unlikely to be deployed within the ARRRA cluster.
- **High labour cost**
Labour costs in Belgium, the Netherlands and Germany are among the highest in Europe [20]. Although comparable to the US they are much higher than in many other countries. Often these countries already have a cost advantage for Power-to-X-CCU due to low costs for electricity from renewable energy sources. This is for instance the case in Chile, Brazil, Morocco, the Middle East and Australia. This makes it difficult for the ARRRA cluster to become cost competitive when operating Power-to-X-CCU plants.

3.2 Opportunities and threats for Power-to-X-CCU in the ARRRA cluster

The market for CO_2-based chemical building blocks is shaped by a mix of external factors, presenting both opportunities and threats to the development of Power-to-X-CCU technologies in the ARRRA cluster.

Opportunities
- Mandates for CO_2-based fuels
- Drive towards strategic autonomy
- Potential synergies with biogenic and waste-based processes

Threats
- Industries moving away from ARRRA
- Risk-averse investment climate
- Limited availability of critical raw materials

Opportunities

- **Mandates for CO_2-based fuels**
The EU stimulates the adoption of CO_2-based fuels through a combination of policy mandates and market support mechanisms, notably REDIII, FuelEU Maritime and RefuelEU Aviation. All three incentivise or mandate the use of Renewable Fuels of Non-Biological Origin (RFNBOs) for the transport sector, including fuels produced by Power-to-X-CCU technologies. As an example, the RefuelEU Aviation policy creates a market demand for sustainable aviation fuel based on CO_2 (e-SAF) via a particularly clear and legally binding blending requirement. The policy will be enforced through a financial penalty to fuel suppliers, which is larger than the price difference between fossil kerosene and e-SAF [21]. This creates a willingness to pay for e-SAFs and provides a clear opportunity for the scale up of e-SAF production plants based on Power-to-X-CCU technology.
- **Drive towards strategic autonomy**
Recent geopolitical developments have intensified the EU's focus on reducing dependence on foreign suppliers and developing resilient supply chains for energy and materials. The recently published Clean Industrial Deal emphasises circularity and regional resource use, reinforcing Europe's push for open strategic autonomy. This presents a major opportunity for Power-to-X-CCU technology. Using CO_2 as a feedstock can reduce reliance on imported sources of carbon and strengthen industrial resilience in Europe.
- **Potential synergies with biogenic and waste-based processes**
Power-to-X-CCU is not just an alternative to biomass and waste-based routes for sustainable fuels and chemicals – it is a complementary pathway that could enhance overall system efficiency. As biobased production of fuels and chemicals grows, it generates biogenic CO_2 emissions which can serve as a feedstock for Power-to-X-CCU processes. This synergy can be useful in the ARRRA cluster, maximizing the use of available carbon streams.

Threats

- **Industries moving away from ARRRA**
  High costs for energy, stringent regulations and a lack of regulatory clarity are prompting some industries to relocate outside of Europe. Competitiveness of the European chemical industry has weakened and plant closures have been announced, of which many are located in the ARRRA cluster (see Figure 10).This trend weakens its highly-integrated industrial systems, threatening competitive advantages necessary for scaling-up Power-to-X-CCU technologies.

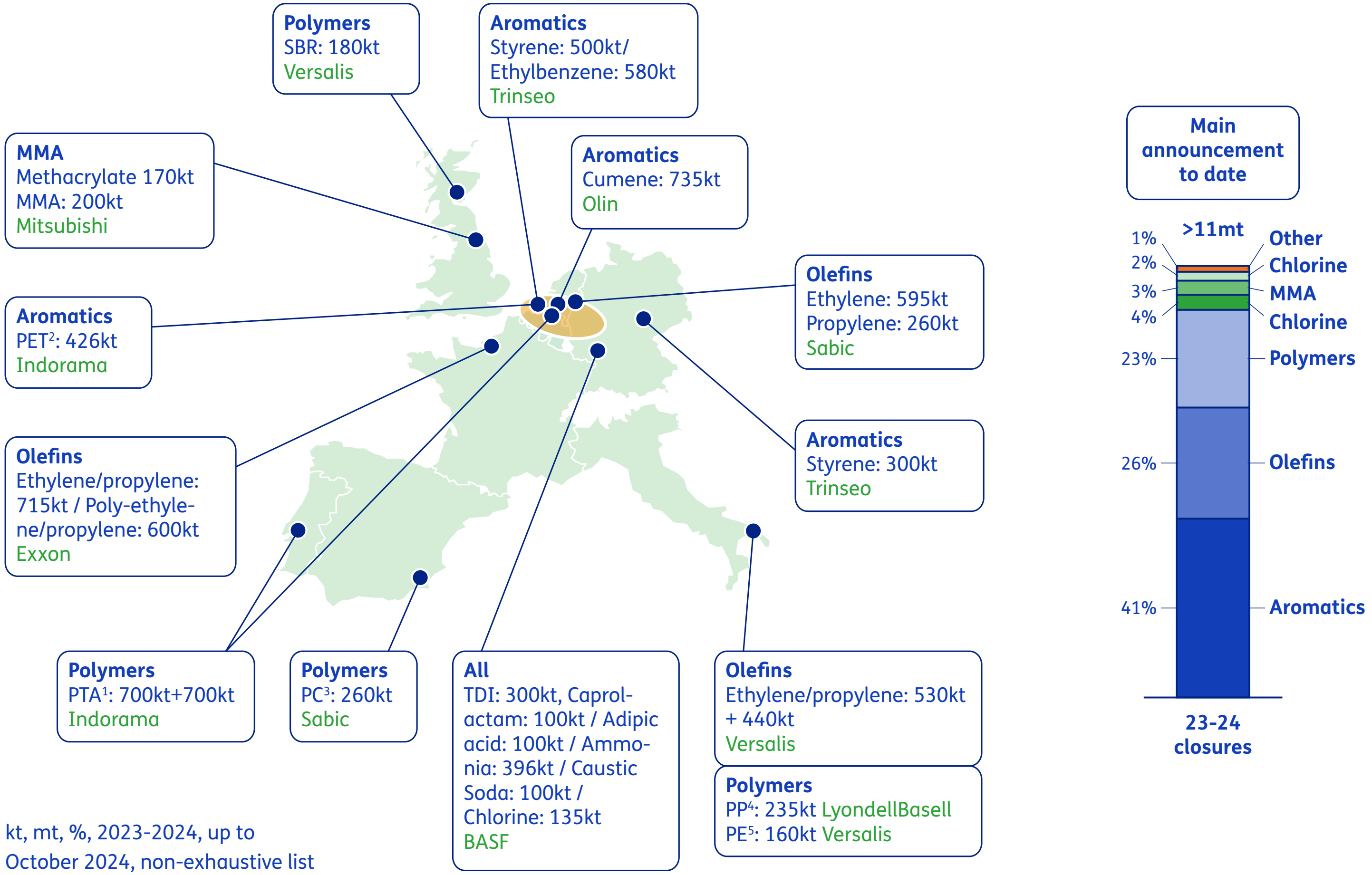


Figure 10. Main European capacity closure announcements. Source: Advancy [4].

- **Risk-averse investment climate**
  Investment in Power-to-X-CCU technology in Europe faces multiple challenges, including decreasing R&D spending and lack of high-risk funding. While European chemical companies invest heavily in R&D, their spending as a percentage of sales remains lower than in the U.S [4]. In addition, industries leaving Europe also transfer their R&D activities outside the ARRRA cluster. European venture capital investors are also more risk-averse than their US counterparts, limiting funding for emerging technologies like Power-to-X-CCU [22]. Fortunately, the recently published Clean Industrial Deal (CID) aims to create a more favourable investment climate by providing long-term regulatory clarity on the use of captured carbon, expanding funding opportunities, and leveraging private investment.
- **Limited availability of critical raw materials**
  Dependence on critical materials is an important concern for the further development of Power-to-X-CCU technologies, also in the light of the EU's goal of strategic autonomy. Alkaline electrolysers rely on platinum and nickel, PEM electrolysers on iridium and platinum catalysts, and solid oxide electrolysers (SOE) on rare earth elements (such as yttrium and lanthanum) and cobalt. However, the related risks differ strongly per technology. For instance, the nickel demand resulting from projected electrolyser capacity scale-up in the EU[1] is negligible compared to current global production, while the iridium demand is estimated at 7% to 22% of the current global production [23]. The metals and rare earth elements have strong supply chain vulnerabilities and technology suppliers in the ARRRA cluster are dependent on a limited number of supply countries. Also, economic and socio-environmental aspects have to be addressed. For instance, the mining of these metals is often associated with large amounts of greenhouse gas emissions, water pollution, and soil contamination. These concerns underline the need for regulations (e.g. the European Critical Raw Materials Act) to mitigate supply chain risks and reduce environmental impacts.

3.3 Strategic directions for Power-to-X-CCU in the ARRRA cluster

Based on the SWOT analysis above, strategic directions for the ARRRA cluster can be derived by answering the following questions:

- How can the **strengths** be used to take advantage of the **opportunities** or to fend off the **threats**?
- How can the **weaknesses** of the ARRRA cluster be overcome so that they do not become constraints in exploiting the **opportunities** or in fending off the **threats**?

The SWOT confrontation matrix as depicted in Figure 11 is instrumental in the sound determination of strategic directions. These follow from the circled green and red cells, which provide clues to addressing the growing demand for CO_2-based chemical building blocks:

1. **Build strategic production capacity for Power-to-X-CCU in the ARRRA cluster**
   Building strategic production capacity will reduce dependence on suppliers from outside Europe and drive innovation and deployment of Power-to-X-CCU in ARRRA. However, due to high costs of electricity, labour and land, the ARRRA cluster will not become cost-competitive regarding Power-to-X-CCU. Production capacity will therefore not evolve based on commercial drivers alone, but will require strong governmental support in the form of mandates, market protection, subsidies and other measures. The future scale of this strategic production capacity is therefore at least partially dependent on political choices. A minimum scenario would be to establish a large demonstration-scale plant, to validate technological maturity and to ensure scalability for potential future deployments.

1 To meet EU hydrogen demand in accordance with IEA Net Zero Emissions by 2050 scenario.

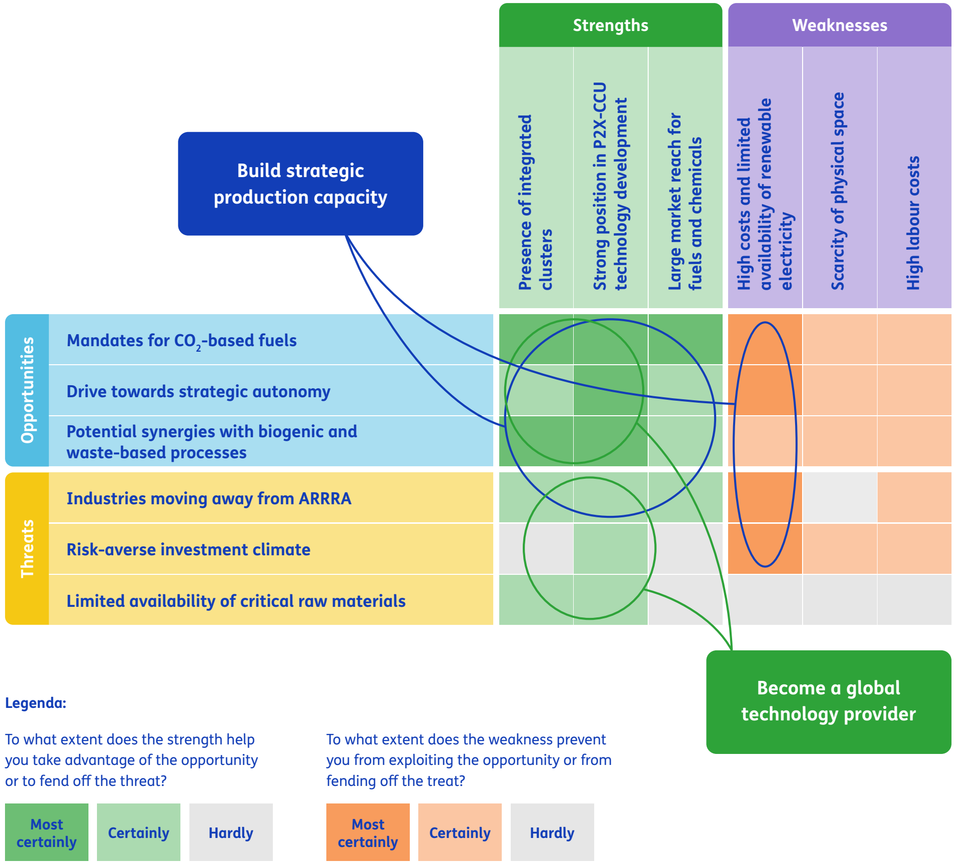


Figure 11. SWOT confrontation matrix leading to two strategic directions for development and utilization of Power-to-X -CCU technologies in the ARRRA cluster.

To counterbalance the weaknesses, scalable technologies should feature high energy and feedstock efficiency and low dependence on critical raw materials. These strategic production facilities could produce essential building blocks like syngas, methanol, DME, and ethylene (as outlined in Chapter 2) and could also further process these into high-value chemicals. This strategy aligns with the EU's policy emphasis on CO_2-based fuels (and potentially CO_2-based chemicals) and its push for strategic autonomy. Developing strategic production capacity for CO_2-based chemicals and fuels within the ARRRA cluster builds upon the existing industry clusters and infrastructure and the region's large market reach for fuels and chemicals.

2. **Become a global technology provider**
   The ARRRA cluster has a strong position in technology development. Leveraging this position, technology providers in the ARRRA cluster can export proven technologies globally to locations where Power-to-X-CCU production facilities are likely to be established, featuring abundant, low-cost renewable energy sources (RES) and cheap biogenic and atmospheric CO_2 feedstocks. Even in a scenario where many industries move away from Europe, companies along the Power-to-X-CCU technology value chain can still gain a competitive edge in the global market. These technologies can enable the cost-effective production of chemical building blocks abroad, which could then be imported into the EU, and potentially further processed into high-value chemicals. The technologies can be developed, piloted and implemented in the commercial plants that will be developed in the ARRRA cluster, though the scale of these plants is still uncertain

The next chapter presents a roadmap for pursuing both these strategic directions.

4 Making Power-to-X-CCU a reality in the ARRRA cluster

The two strategies presented in the previous chapter allow ARRRA-based companies to capitalise on emerging markets: by expanding domestic production and/or by exporting cutting-edge technologies. Pursuing these approaches simultaneously will ensure that the ARRRA cluster can remain a leader in the transition toward CO_2-based fuels and chemicals, fostering both regional growth and global impact. This chapter describes the steps needed to realise both strategies (4.1 and 4.2) and presents a call to action (4.3).

4.1 Build strategic production capacity for Power-to-X-CCU in the ARRRA cluster

To build strategic production capacity, proposed actions are structured along the following lines of action: (1) Boost competitiveness of the chemical industry in the ARRRA cluster; (2) Target specific product-market-combinations; (3) Harness potential synergies with alternative sustainable production pathways, like biobased routes.

Build strategic production capacity

- Boost competitiveness of the chemical industry in ARRRA
- Target specific product-market-combinations
- Harness synergies with alternative sustainable production pathways

Boost competitiveness of the chemical industry

To enable the chemical industry in the ARRRA cluster to realise the desired production capacity for Power-to-X-CCU based chemicals, it is urgently needed to boost the competitiveness of the chemical industry, in the ARRRA cluster and the EU. The recently published Clean Industrial Deal offers a strong foundation for the EU plans for affordable renewable electricity, stronger market demand for clean products, financial support for clean manufacturing, and access to critical raw materials. To turn these ambitions into reality, the following concrete actions are needed:

- **Stimulate market demand for clean products through regulation**
  To stimulate the market for sustainable chemicals, the EU regulatory framework should include demand-side targets for chemicals containing circular carbon, similar to the fuel targets from RefuelEU and REDIII. Furthermore, governments could support the use of CCU products through green public procurement mechanisms [24].
- **Strengthen availability and affordability of electricity**
  The scale-up of renewable electricity generation and expansion of grid capacity should be accelerated. EU-wide interconnection should be expanded, and intensified cross-border collaboration between countries bordering the North Sea can turn the North Sea into an energy hub[25]. Countries in North Western Europe (like Sweden and Norway), and in Southern Europe (like Spain and Greece), could supply renewable electricity or hydrogen based molecules to the ARRRA cluster and other regions with a forecasted shortage (see Figure 9).

Target specific product-market combinations

The first commercial plants needed to demonstrate viability and facilitate technology scale-up can target specific product-market combinations that address a need for autonomy and reflect a high willingness-to-pay. Some potential examples are:

- **Production of e-SAF**
  The regulatory framework in RefuelEU Aviation mandates the use of Renewable Fuels of Non-Biological Origin (RFNBOs) from 2030 onwards, increasing the mandatory share in the fuel mix from 1.2% in 2030 to 35% in 2050. This will result in a willingness-to-pay by fuel suppliers in Europe. As an example, Advario and Power2X have the ambition to build an e-SAF production plant in Rotterdam with a capacity of 250 kt/year [26]. Though the e-methanol feedstock will be imported, the plant will make use of locally produced green hydrogen. To reduce dependence on e-methanol suppliers from outside Europe, feedstock can be imported from multiple countries that have a stable political, economic and social profile.

- **The military as launching customer**
  Governments can act as early adopters for CO_2-based products and fuels, driving initial demand. For the military sector, production of e-fuels may be useful to enhance operational autonomy. An interesting concept is being developed by US Army researchers, allowing production of biobased fuels in remote locations [27], which could also be applicable for e-fuels.
- **Local production of gases**
  Since gases are more difficult and expensive to safely transport compared to liquids, local production of e-gases, CO, syngas and methane, could provide a competitive advantage. This might sometimes also be preferable from a safety perspective.
- **High-value niche products**
  E-molecules that currently have niche markets may find significant markets in the future. For example, Avantium converts CO_2 into formic acid and oxalic acid, serving as a feedstock for sustainable polymers production. [28]

Harness synergies with alternative sustainable production pathways:
The transition to Power-to-X-CCU based chemicals cannot be viewed in isolation and has many connections with other areas in the transition. These connections offer many opportunities to harness synergies with alternative sustainable production pathways:

- **Use of captured CO_2 from bio- or waste-base point sources**
  Many synergies are possible between Power-to-X-CCU, biobased and waste-based routes. For example, Power-to-X-CCU processes can make use of captured CO_2 from bio- or waste-base point sources. When using biogenic CO_2, the overall process can even result in negative emissions, while also being more energy efficient than Direct Air Capture. Another potential synergy lies in the use of Power-to-X-based hydrogen to optimise biobased routes. To fully unlock these synergies, stronger collaboration is needed between stakeholders working on biobased and waste-based routes, and those focused on Power-to-X-CCU based routes. This will help identify concrete opportunities for integration. Besides that, a regulatory framework is needed with clear carbon accounting rules that supports the use of bio- and waste-based CO_2 [28].
- **Synergies between chemicals and fuels**
  While nowadays the chemical and fuels are already closely related, especially through the use of fossil naphtha from refineries for chemicals production, the future production of sustainable chemicals and fuels will have even more overlap. Both sectors will rely on the same feedstocks (bio, waste and CO_2) and the same building blocks like methanol, ethanol, hydrogen and syngas. These building blocks will be produced using the same technologies, creating a strong basis for cross-sector collaboration [29]. Regarding Power-to-X-CCU, methanol stands out as an important platform molecule for both sustainable fuels and chemicals. Notably, the market for sustainable aviation fuels is developing more rapidly than the market for sustainable chemicals, driven by policy and regulations. This creates a strategic opportunity for the chemical sector to piggyback on the aspects of scale, technology advancements, emerging infrastructure and supply chains for sustainable fuels.

4.2 Become a global technology provider

For the ARRRA cluster to become a global technology provider for Power-to-X-CCU, proposed actions are structured along the following action lines: (1) Consolidate the technology position in Power-to-X-CCU; and (2) Reduce dependency on critical raw materials.

Become a global technology provider

- Consolidate ARRRA's technology position
- Reduce dependency on critical raw materials

Consolidate the technology position
To establish companies within the ARRRA cluster as global frontrunners in Power-to-X-CCU technology development, and consolidate ARRRA's technology position, the following actions are required:

- **Gain insight**
  It is crucial to gain better insight into the global market of Power-to-X-CCU based fuels and chemicals production as well as the competitiveness of technology companies in the ARRRA cluster. These insights can be used to refine the strategic positioning of Power-to-X-CCU technology suppliers in the ARRRA cluster.
- **Address technical challenges**
  A number of technical challenges should be addressed to improve the performance, efficiency and lifetime of the Power-to-X-CCU technologies and to make upscaling of the technologies possible. Also, the development of dynamic operation strategies to leverage lower electricity prices needs to be investigated. These technical challenges have been discussed in Chapter 2 (see Table 3). When technology suppliers from the ARRRA cluster develop and implement these technical advancements in their product, it will give them a competitive advantage.
- **Prove technology**
  The first Power-to-X-CCU applications (mentioned under the first strategy) can be utilised to prove the technology from providers in the ARRRA cluster at scale. This will not only de-risk these technologies but will also attract global interest.
- **Strengthen ecosystems**
  Existing Power-to-X-CCU ecosystems in the ARRRA cluster should be strengthened and cover the full technology value chain, including EPC contractors and component manufacturers who can provide access to global markets.
- **Allocate funds**
  The allocation of funds both by governments and investors for research into technologies along the TRL scale, in particular for development of pilot projects and first commercial plants, is key to success. Also creating a workforce skilled in Power-to-X-CCU is of vital importance. Both financing and establishing a union of skills are already included in EU's Clean Industrial Deal. It is now important to make these ambition a reality.
- **Protect technology**
  Protecting technologies by patenting is crucial, especially for application in countries where Power-to-X-CCU is expected to be utilised.

Reduce dependency on critical raw materials
An important aspect in technology development for electrolysers is the reduction of dependency on critical raw materials (CRM). Besides attracting virgin CRMs at an early stage, both *reduction* of the use of CRMs in electrolysers and *recycling* of CRMs can significantly impact virgin CRM demand.

- **Deploy high-tech manufacturing techniques**
  High-tech manufacturing techniques such as ultrasonic spray coating and spatial atomic layer deposition can help producing thin catalyst layers that are uniform and stable, while reducing the use of CRMs in electrolysers. Besides that, technologies to optimise the structure of the cell components can help minimise the use of CRMs as catalyst[30]. High-tech equipment companies and research institutions in the ARRRA cluster, especially in the Brainport region, have a strong position in thin film technology [30]. Stimulated by governments, electrolyser component developers, high-tech equipment companies and research institutions in the EU should join forces to accelerate the application of thin film technology in next generation electrolyser technology. In addition, setting standards with performance criteria regarding CRMs can safeguard the reduction of CRM use in electrolysers. However, before implementing these innovations, commercial systems should be launched first, so that essential data can be gathered about the trade-offs between material loading, lifetime extension and operational performance.
- **Recycle critical raw materials**
  The recycling of CRMs will be important on the longer term. It will hardly relieve the peak demand for iridium for electrolysers in the EU, which is already expected in 2035 due to upscaling of the electrolyser capacity required to meet climate goals. However, from 2040 onwards, substantial amounts of iridium

and other materials can be recovered from electrolysers through recycling [23]. A circular value chain should be implemented by stakeholders [31], supported by development of recycling technologies to separate CRMs from electrolysers at their end-of-life.

4.3 Let's make Power-to-X-CCU a reality

To secure a leading role for the ARRA cluster and the broader EU in developing a Power-to-X-CCU based economy, all stakeholders need to act collectively and decisively. And the time to act is now.

Yes, there are still many uncertainties in the development and scaling-up of Power-to-X-CCU technology. And yes, large-scale commercial deployment of Power-to-X-CCU may take the better part of the coming decade. But the opportunities to shape the foundations of this emerging market are already upon us.

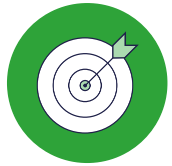
Seizing these opportunities requires more than technological innovation—it calls for supportive policy, coordinated investment and strategic alignment across the entire value chain:

Supportive policy
It is crucial to convert the ambitions of the EU Clean Industrial Deal into tangible measures that turn policy into progress. This includes:

- Accelerating market demand for chemical products based on circular carbon, similar to existing fuels mandates;
- Developing consistent and transparent carbon accounting rules;
- Enabling the reuse of captured carbon as a feedstock for chemicals;
- Creating an EU strategic production capacity.

Coordinated investment
It is imperative to expand the infrastructure and production capacity for clean electricity, CO_2, and hydrogen, to enable the production of Power-to-X-CCU based chemicals and fuels. Investments are urgently needed in:

- Renewable electricity generation, upgrading and expanding the electricity grid, and creating cross-border interconnection, to make renewable electricity available and affordable;
- Infrastructure for CO_2 capture, storage, and transportation;
- Hydrogen production capacity and distribution networks.



Strategic alignment
It is essential to build coalitions across the value chain and establish a coordinated ecosystem

- That spans technology development, industrial scale-up, financing, policy, and global supply chains;
- That includes technology providers, chemicals and fuels producers, energy suppliers, investors, governments, and civil society;
- Moreover, integrating Power-to-X-CCU with bio- and waste-based pathways will unlock synergies that accelerate scale-up and sustainability.

By acting decisively on these matters, Power-to-X-CCU technologies can contribute to a sustainable, competitive, and circular chemicals and fuels industry in the ARRRA cluster. Aligning innovation, infrastructure, and policy will not only unlock the potential of Power-to-X-CCU, but also redefine its role in the global energy and materials transition.

Annex: Pathways for CO_2 conversion

This annex provides a deeper dive into three types of Power-to-X-CCU technologies: thermochemical, electrochemical and plasma CO_2 conversion.

Thermochemical CO_2 conversion

Thermochemical CO_2 conversion makes use of a combination of catalysts, elevated temperature and pressure to convert CO_2 into valuable products using green hydrogen. The latter is produced through water or steam electrolysis (Power-to-H_2). The CO_2 and H_2 can be converted to chemical building blocks via processes such as reverse water gas shift (r-WGS, 650-900 °C, < 20-70 bar) to produce syngas; hydrogenation (200-300 °C, 50-100 bar) to produce methanol or DME; and Sabatier synthesis (200-400 °C, 1-30 bar) to produce methane. Syngas and methanol are chemical building blocks from which hydrocarbons (such as SAF and ethylene) can be synthesised. Although these conversion reactions differ in temperature, pressure, and applied catalyst, the processes follow roughly the same steps, shown in Figure 12.

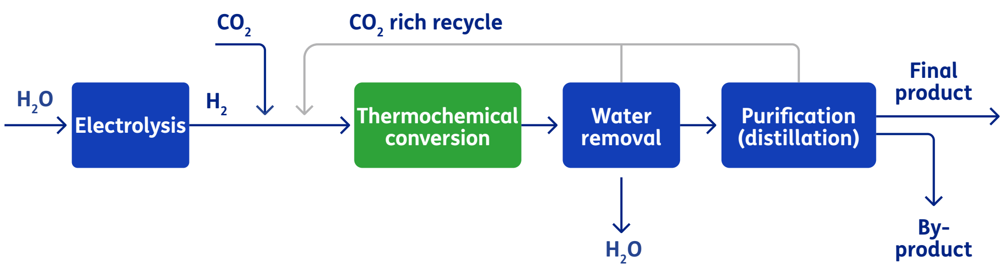


Figure 12. Simplified block flow diagram of the thermochemical CO_2 conversion process.

The thermochemical route is the most technologically mature CO_2 conversion route. Most implementations of this route have reached a Technology Readiness Level (TRL) between 6 and 9, and several commercial scale plants are already in operation. However, large-scale industrial adoption remains limited due to an unfavourable business case compared to fossil-based alternatives.

A key challenge lies in the high energy demand for producing the green H_2 that is needed to convert CO_2 into hydrocarbons. To optimise the thermochemical conversion process, catalysts are being used to facilitate an efficient and selective reaction towards the desired products. Also heat transfer and integration can further be optimised e.g. by use of molten salts to maximise heat recovery and reuse within the chemical process. [32] The reaction generates water as a by-product, limiting the CO_2 conversion and necessitating downstream water separation processes, which further increase the cost of the overall process. To address this challenge, multiple research groups explore process intensification methods such as reactor integrated water separation enhancement or in situ methanol-water condensing. The objective of such separation enhanced technologies is to separate water from the product in the reactor to reduce a process step and move the reaction equilibrium towards a higher conversion to the desired product. An example of a separation enhancement technology is described in Box 1. Reactor integrated condensing separates methanol and water from unconverted CO_2 and H_2 within the reactor. The unconverted gases are recycled internally in the reactor to achieve a high CO_2 conversion and to prevent an external recycle loop, thereby reducing cost. [33]

One thermochemical CO_2 conversion pathway that has gained major traction is hydrogenation towards methanol. Multiple synthetic methanol plants are currently commercially operational or under construction [34]. The largest CO_2 to methanol plant is based in China (see Box 2), which utilises Carbon Recycling International (CRI) technology. Commercial-scale CCU-based methanol plant solutions are also provided by Engineering, Procurement and

Construction companies such as KAPSOM Engineering. As of May 2025, the Kassø I E-methanol facility in Denmark, developed by European Energy and Mitsui, is fully operational. It is designed to produce 42,000 tonnes of e-methanol annually, using only renewable energy, green hydrogen, and biogenic CO_2 as feedstock.

Box 1. Bench Scale unit of Sorption Enhanced Reverse Water Gas Shift technology

The COMAX sorption enhanced reverse water gas shift (rWGS) technology, developed by TNO, provides a more sustainable alternative to conventional rWGS systems. It enables selective (>98%) CO_2 to CO conversion at moderate temperatures of 300-400°C, which is 40% more energy efficient than the state-of-art technology operating at 900°C. The patented bifunctional reactive sorbent materials for in-situ water sorption shift the reaction equilibrium towards a higher CO yield and reduce the energy requirement. The COMAX technology has been validated at bench scale and process development has been targeted to supply CO for the production of renewable fuels and chemicals, as a reducing agent for the steel industry, and as an industrial bulk gas.

Reactive Water Sorbents for the Sorption Enhanced Reverse Water–Gas Shift

Box 2. First commercial synthetic methanol plant from lime production emissions

The first commercial-scale synthetic methanol from CO_2 plant in the world (Anyang, China) produces 110,000 tonnes of methanol per year, operated by Shunli. The methanol is produced using CO_2 recovered from lime production emissions and hydrogen recovered from coke-oven gas. CO_2 and H_2 are converted in a thermochemical Emissions-to-Liquid (ETL) reactor complemented by a specialised gas compressor and a distillation unit. The plant converts 160,000 tonnes of captured CO_2 per year, an amount equal to the emissions of 60,000 cars.

[The Shunli CO_2-to-Methanol Production Plant]

Electrochemical CO_2 conversion

In electrochemical CO_2 conversion, carbon dioxide is converted into chemical building blocks using electricity directly in an electrochemical cell. Although many technologies are under development, all electrochemical cells share a fundamental structure; two electrodes in contact with an electrolyte. An external power source generates a potential difference across the two electrodes that drives the reaction at the interface of the electrodes and the electrolytes.

A wide variety of electrochemical CO_2 conversion technologies utilise various types of electrodes, membranes, electrolyte materials, cell architectures and operating conditions. Two important types of electrolyser are the high temperature solid oxide electrolyser and the low temperature electrolyser. Their general cell configurations are shown in Figure 13.

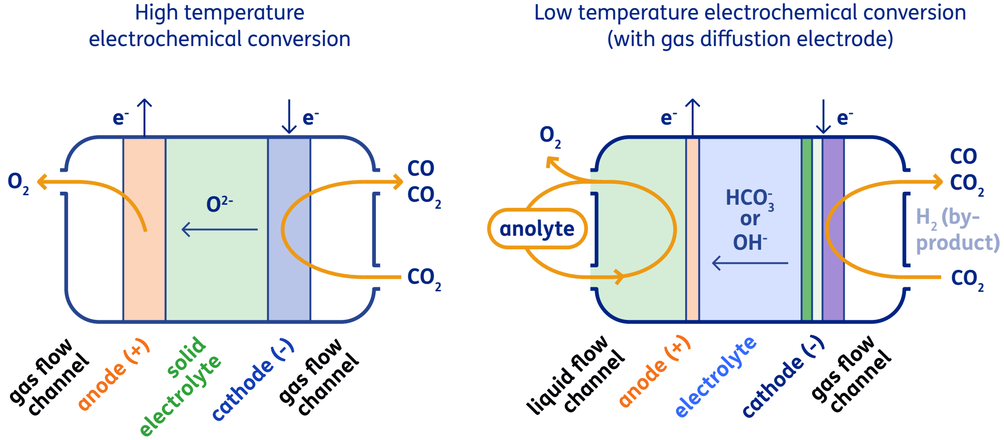


Figure 13. Simple schematic of HT solid oxide electrolyser cell and LT electrochemical cell with gas diffusion electrode configurations. [38].

High-temperature (HT) electrochemical CO_2 conversion
A high-temperature (HT) CO_2 conversion electrolyser uses a combination of electricity and heat to drive the conversion of CO_2. The high temperature operation improves thermodynamic efficiency and increases the reaction kinetics. An important type of HT electrolyser is the Solid Oxide Electrolyser (SOE). This consists of a porous cathode and anode separated by a solid ceramic electrolyte. These electrolysers typically operate at temperatures between 750-900°C, which allows the solid electrolyte to sufficiently conduct oxide ions.

SOECs can process either pure CO_2 to produce CO, or a mixture of CO_2 and steam to produce syngas (referred to as co-solid oxide electrolysis or co-SOE). The H_2:CO ratio in syngas can be tuned to match the requirements of the downstream processes, such as the production of synthetic chemicals and fuels, like methanol, ethylene and sustainable aviation fuel. For commercial use, the electrolyser needs to be integrated into a production pathway that includes CO_2 capture, conversion and separation, as shown in the block flow diagrams in Figure 14.

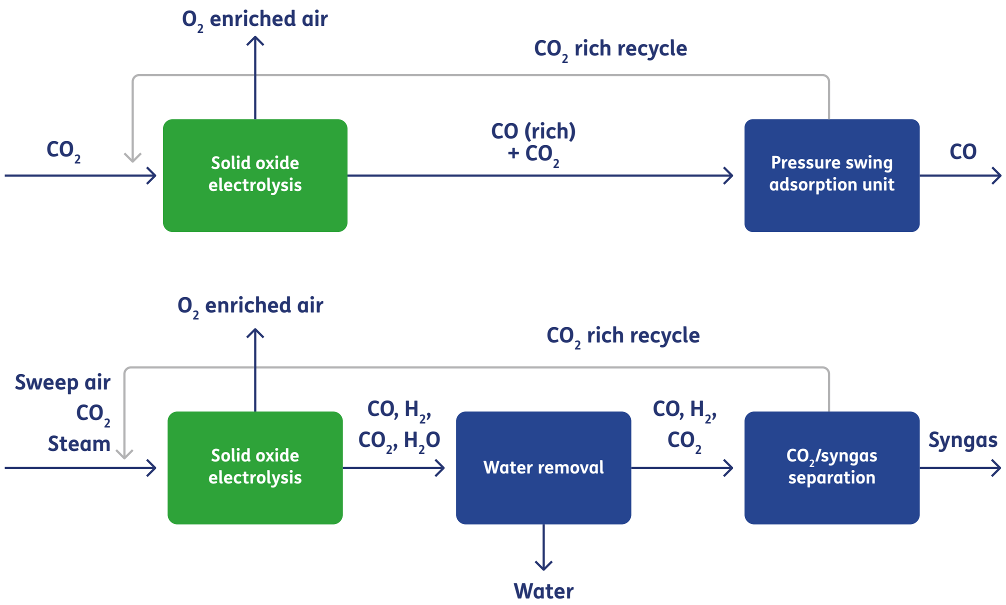


Figure 14. Conceptual block flow diagram for the HT CO_2 electrolysis process for CO and syngas production [13].

Currently, the technology is at a TRL of 4-6 and efforts are underway to improve and scale up the electrolyser technology and to optimise the integration of SOEs into industrial processes. Leading players for SOE systems include Topsøe and Sunfire. Several other companies are actively developing and offering SOE technology solutions at the cell and stack level, like SolydEra and Elcogen.

The high operating temperatures and the use of syngas and steam as feedstock necessitate the use of expensive materials, resulting in high investment costs (CAPEX). Key areas for further technological advancement to reduce these costs include improving cell performance (increasing current density and enhancing cell longevity), producing larger cell areas, increasing the number of cells in the stack, and optimization of balance of plant design and operational strategies. Technological advancements, upscaling, and mass production, can lead to significant future reductions in investment cost. [36]

Box 3. TNO Faraday Lab Testing Facilities – SOE towards upscaling

The TNO Faraday lab testing facilities include a single cell testing station for 3.5 kW electrolysis and reversible-SOC operation. Single cell testing is conducted for cells with a 30 x 30 cm² area, with automated operation of r-SOEC and co-SOE tests. These testing capabilities provide valuable insights and data, paving the way for potential commercial stack testing.

[Faraday lab: optimising and scaling up electrolysis]

Low-temperature electrochemical CO_2 conversion routes

A low-temperature (LT) CO_2 conversion electrolyser operates by using electrical energy to drive the electrochemical conversion of CO_2 at low temperatures (<100°C) and low to moderate pressures (<10 bar). CO_2 is reduced at the cathode, while water molecules are oxidised at the anode to produce oxygen. The electrolyte, which can be a solid polymer membrane or a liquid solution, conducts ions between the electrodes, enabling the overall reaction to proceed efficiently. For LT CO_2 electrolysers various configurations can be used with a variety in electrodes, membranes and feedstock phases, such as aqueous-fed and gas-fed electrolysers.

This technology – currently at TRL 4-6 – can produce carbon monoxide, oxalic acid and formate (as pre-cursor of formic acid) with relatively high efficiency and selectivity. CO is a chemical building block that can be used for downstream processes, together with hydrogen, to produce chemicals and fuels, like methanol, ethylene and sustainable aviation fuel. Oxalic acid has applications in cleaning, pharmaceuticals, tanning, and the extraction and purification of rare earth elements. It could also be used as a chemical building block in plastics production. Formic acid has major applications as a preservative in livestock feed and as an additive for cleaning products. It also has some minor applications in textile dying, pharmaceuticals and pesticides. In the future, new use cases for formic acid could emerge, such as a fuel for fuel cells, as a liquid storage medium for H_2 and CO [37], or as feedstock for biological processes producing microbial oils for fuels, chemicals and beauty care products. In the production pathway, both conversion and downstream separation steps are important to meet the required final product quality. Ethylene is another attractive product, since it can be produced by a one-step process in the electrolyser. However, this conversion is more complex and still at lab scale.

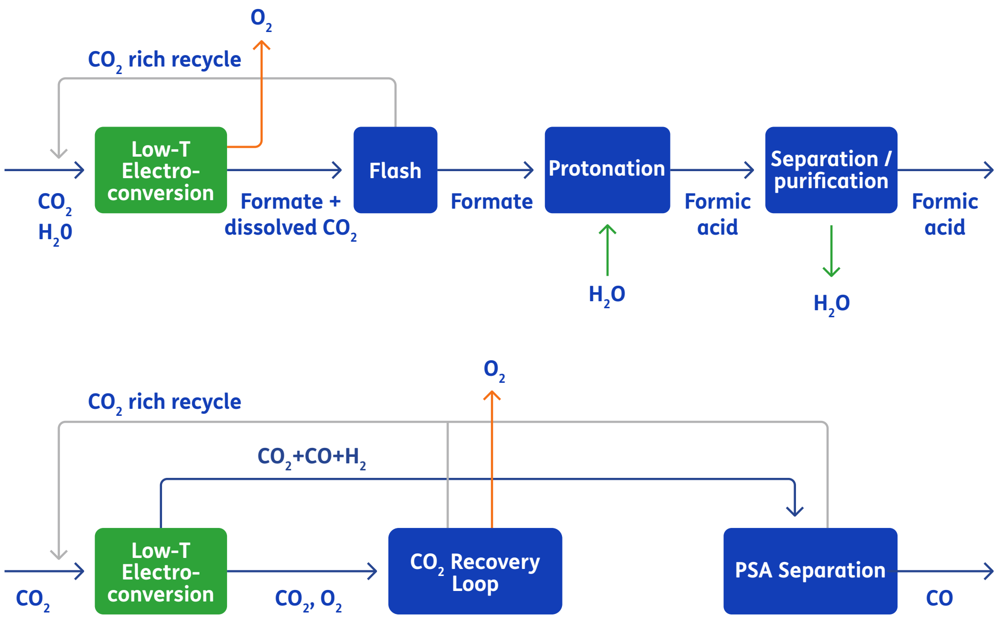


Figure 15. Block flow diagram of CO_2 conversion by LT electroconversion to formic acid and CO.

Several projects and companies are driving the development of LT CO_2 electrolysis, building pilot or demo plants. For example, the European collaboration project Interreg 2 Seas resulted in a pilot installation with multiple stacked electrochemical cells. Companies like Avantium (Volta program), Twelve (developing an e-SAF facility in Washington), Dioxycle (focused on CO_2 to ethylene) and eChemicles (working on CO and ethylene pathways) are accelerating technological progress in this field.

Despite its potential, LT CO_2 electrolysis still faces multiple challenges – particularly in enhancing product selectivity, increasing conversion rates and extending catalyst lifetime [38]. This requires optimising the catalyst, improving the cell configuration and establishing optimal process control. Ongoing R&D efforts are targeted at improving these crucial aspects to enable future industrial-scale applications.

Box 4. E2C Project: LT electrochemical conversion of CO_2 to formic acid

The interregional project "Electrons to high-value chemical products (E2C project)" (2018-2022) aimed to showcase two pilot installations demonstrating the possibilities of Power-to-X technologies. A pilot demonstration system called ZEUS was constructed and installed at the TNO facility in Rijswijk, Netherlands. The demonstrator (TRL 6) consists of multiple stacked electrochemical cells that can convert 1 kg of CO_2 per hour into platform chemicals such as formic acid.

[Electrons to High-Value Chemical Products - E2C - VoltaChem]

Box 5. Avantium: LT electrochemical conversion of CO_2 to formic and oxalic acid
Avantium, a company committed to de-fossilization of the chemical industry, develops innovative electrochemical technologies to convert CO_2 into valuable chemicals. Their Volta Technology platform converts CO_2 into formic acid, oxalic acid, and glycolic acid. These chemicals have various applications, including the production of the carbon-negative polymer PLGA (polylactic-co-glycolic acid). This approach not only reduces CO_2 emissions but also replaces fossil carbon, supporting a circular and sustainable future.

[CO_2-based Chemicals & Materials - Avantium Corporate]

Plasma CO_2 conversion

A plasma is an ionised gas produced by applying a high-voltage to the process gas. At a sufficiently high voltage the gas breaks down and an ionised, conductive channel is formed, to which the applied electrical power is transferred [39]. This highly localised power deposition induces extreme temperatures (>3000K) very quickly, while keeping the reactor wall comparatively cool (<500K). The highly reactive plasma can convert CO_2 (and H_2O) into products like CO, syngas, or when fed with methane, as feedstock into hydrocarbons such as ethylene and acetylene. Because power must be actively provided to sustain the plasma, the conversion can be easily switched on and off, allowing integration with an intermittent renewable energy supply. Moreover, the technology does not use critical and rare earth metals, reducing technology supply chain risks.

Presently, the technology for CO_2 to CO conversion is at TRL 4-5. Further development requires a better understanding of plasma chemistry, reaction products, and interactions between plasma and catalyst. Key challenges are: 1. Understanding and controlling the chemical kinetics, 2. Optimizing the quenching of reaction products, in order to stop unwanted back-reactions, and 3. Handling the inherently large thermal gradients around the plasma. Research is needed to improve process efficiency (energy and conversion efficiency, selectivity towards value-added chemicals), reactor design, develop modular equipment to facilitate scale-up, and realise technology integration into an industrial production pathway.

Several start-up companies are working on various plasma technology applications for CO_2 conversion. EnaDyne, a Leipzig-based startup, specialises in plasma-based CO_2 conversion through non-thermal plasma catalysis. Products are chemical building blocks for valuable chemicals and fuels like methanol, ethylene, and formaldehyde. D-CBRN, a spin-off company of the University of Antwerp, has developed plasma technology that enables the conversion of CO_2 to CO. Together with ArcelorMittal Ghent and Mitsubishi Heavy Industries (MHI) D-CRBN trialled its plasma unit with actual industry off gasses. CAPHENIA is a German company that develops plasma technology for CO_2 and biomethane conversion (box 6). In the Netherlands, plasma technology is being developed at the Plasmalab at Brightsite (box 7).

Box 6. CAPHENIA pilot for conversion of biomethane and CO_2 into SAF

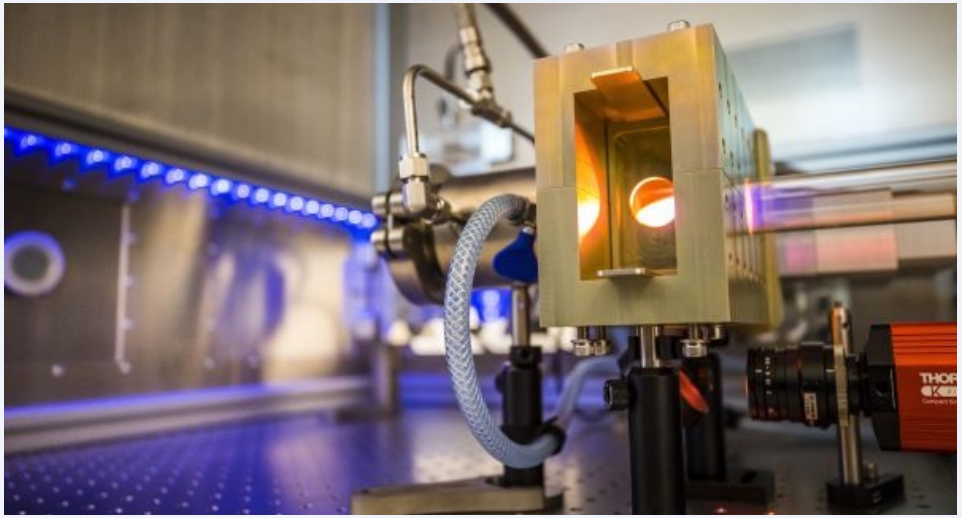
German clean-tech company CAPHENIA installed a custom-built Plasma-Boudouard Reactor (PBR) at its production site in Frankfurt-Höchst, Germany. This reactor is at the heart of a pilot plant that converts electricity, biomethane and CO_2 into sustainable aviation fuel (SAF) and other renewable fuels. Production is planned for the first half of 2025. The pilot plant is projected to produce approximately 500 tons of these fuels, which will provide valuable data for optimizing production processes and scaling up operations.

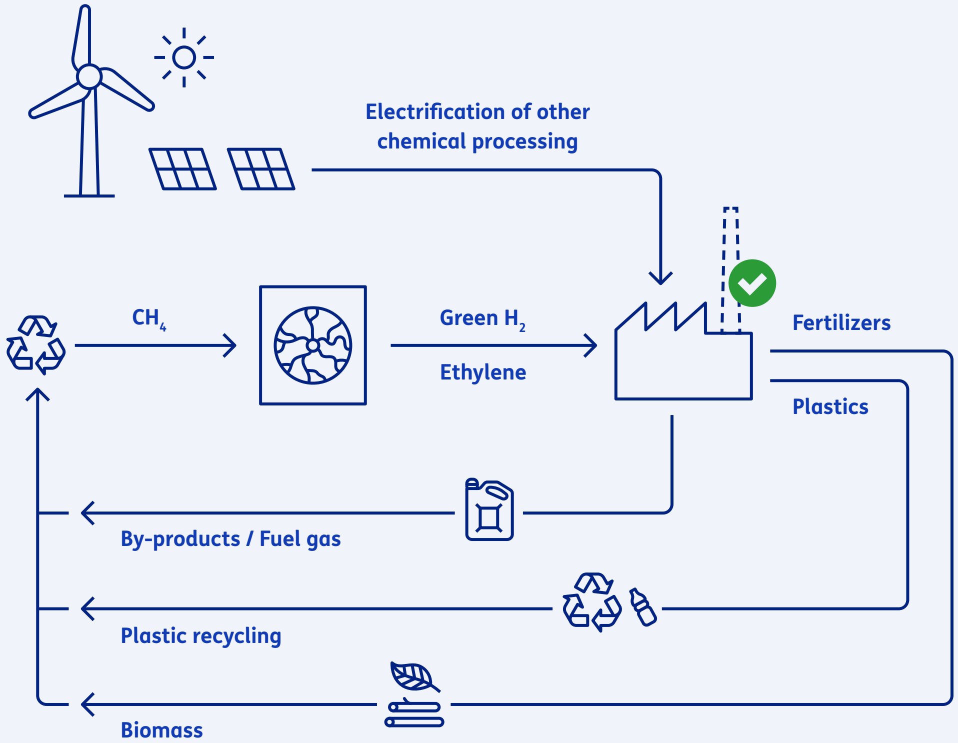
News & Presse | CAPHENIA

Box 7. Plasmalab at Brightsite

The Brightsite Plasmalab is a collaboration between Maastricht University, TNO, and Sitech Services at the Brightlands Chemelot Campus in the Netherlands. It develops plasma technology for application in the chemical industry and has already successfully tested the conversion of methane to hydrogen and high-quality hydrocarbons like acetylene and ethylene. A pilot plant (TRL 6) is under construction for the hydrogen and acetylene formation via the Hüls process. Construction of a demonstration plant (TRL 7-8) with a capacity of 10 kta H_2 is expected for 2027-2029.

Plasmalab - Brightsite





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TNO innovation for life

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The chemical and process industries face enormous challenges. The pressure to reduce CO_2 emissions, embrace circular economy and stay competitive at the same time is increasing. Companies are looking for ways to make their processes more sustainable without sacrificing efficiency and profitability.

At TNO, we understand these challenges. We research, develop and orchestrate breakthrough innovations that enable the transition to a carbon-neutral industry and society.

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