ENABLING POWER-TO-X & CCU IN THE CHEMICALS INDUSTRY

PERSPECTIVES AND KEY RESULTS FROM THE INTERREG 2 SEAS ELECTRONS TO HIGH VALUE CHEMICAL PRODUCTS (E2C) PROJECT

PROJECT PARTNERS

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This whitepaper outlines the opportunities and challenges identified within the E2C project concerning the development of Power-to-X and Carbon Capture & Utlization (CCU) technologies in Europe's chemical sector. The paper highlights the key enablers for accelerating the roll-out of Power-to-X applications and provides examples of the technical advancements made within the E2C project, combined with an economic analysis comparing production costs of Power-to-X and CCU processes with conventional production routes. A set of policy recommendations are provided.

TABLE OF CONTENTS

INTRODUCTION

ADVANCING TOWARDS CIRCULARITY AND NET-ZERO FOR THE EU'S CHEMICAL SECTOR

The chemical sector contributes greatly to Europe's welfare and economic output and is a crucial element in all value chains. The sector generates approximately €500 billion through annual chemical sales, and directly employs 3.4 million people (CEFIC, 2022). At the same time the sector faces challenges from strong international competition and high energy prices, as well as growing pressure to identify sustainable pathways to reduce greenhouse gas emissions in line with Europe's climate targets. In 2021, the enactment of the EU Climate Law committed the Union to achieve climate neutrality by 2050. Climate neutrality, often referred to as 'net-zero', means that the emissions of carbon dioxide (CO_2) into the atmosphere and removal by sinks the take up CO_2 are in balance. In practice, this will require a significant reduction of CO_2 emissions from all facets of society, while maintaining and enhancing natural CO_2 sinks, combined with the use of CO_2 removal technologies.

However, carbon is the primary building block for the organic chemicals sector. Whereas the use of renewable power and heat can provide the energy to operate chemical processes, carbon will still be needed as feedstock to produce the fuels and chemicals needed in everyday life. Therefore, in a net-zero future, it will be necessary to fundamentally alter how everyday fuels and chemicals are produced. To achieve this, the chemical sector will need to transform from one based on fossil carbon to one focused on innovative production routes, renewable energy and the use of bio-based or recycled carbon. However, with global demand for chemicals and derived products expected to more than double by 2050, and with 85% of carbon used for chemical production currently fossil-based, the challenge is considerable. This challenge is depicted in Figure 1.

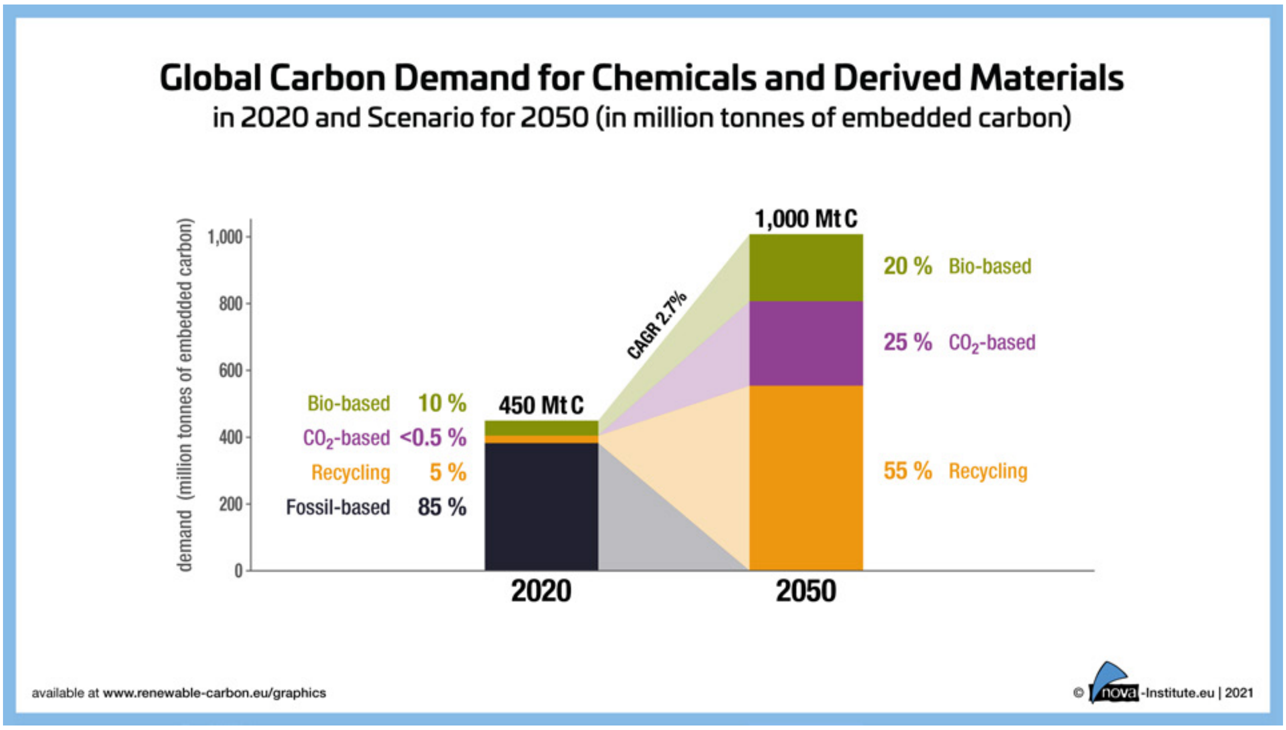

Figure 1: Global Carbon demand for chemicals and derived materials (Carus et al., 2021))

Another important building block for the chemical industry is hydrogen (H_2). In the chemical sector, hydrogen is used for the production of fertilizers (ammonia), petrochemicals and methanol. In Europe, hydrogen is mainly produced through the reforming of natural gas (methane – CH_4), or as a byproduct from oil refining activities. However, the production of H_2 is very carbon intensive, with approximately 9 kgs of CO_2 released for each kg of H_2 produced. The global production of ammonia and methanol generates emissions of approximately 630 megatons per year, around 1% of total global emissions (IEA, 2022a). Carbon-free or 'green' hydrogen production is possible by using renewable electricity (or nuclear power) to split water into H_2 and oxygen in an electrolyser. Within the chemical industry, green hydrogen can replace fossil fuel-based hydrogen and is considered an important pathway for decarbonizing the chemical sector, if sufficient low-carbon power becomes available. Electrolysis currently only accounts for 2% of global hydrogen production; however, a major ramp-up of electrolysis projects is currently underway across Europe in line with the acceleration of renewable power installations.

With the prospect of rapidly growing supplies of the renewable energy in the EU, combined with the emergence of CO_2 capture projects able to deliver abundant supplies of recycled carbon in the future, the chemical sector has the opportunity to shift away from a fossil-dominated economy and unlock enormous environmental and business potential. Power-to-X defines a group of technologies able to turn electricity into carbon-neutral synthetic fuels and chemicals. These technologies have the capability to revolutionize how Europe's chemical sector operates, firmly embedding the sector into the green transition.

POWER-TO-X

Power-to-X technologies cover a large number of pathways and technologies designed to use renewable energy for the production of useful goods and services. Surplus electric power can be converted into other forms of energy for storage and reconversion. The 'X' is a term used to denote various end products, with common applications under development including Power-to-Ammonia, Power-to-Chemicals, Power-to-Fuel, Power-to-Gas (Power-to-Hydrogen, Power-to-Methane) and Power-to-Liquid (synthetic fuel). By using excess renewable power, opportunities exist to develop new production processes for several everyday products, such as plastics, textiles and fuels, which are currently provided from fossil fuels. However, to achieve this, a sustainable supply of carbon molecules will also be necessary.

In this context, the ***Electrons to High Value Chemical Products*** ("E2C") project is focused on the development of Power-to-X technologies, that are capable of utilising excess renewable energy, thus balancing intermittent energy supply and demand, to convert waste CO_2 streams into valuable fuels and chemicals, while reducing greenhouse gas emissions.

Electrons to High Value Chemical Products – the E2C project

The objective of the E2C project, part of the Interreg 2 Seas Programme, is to stimulate investment in and implementation of Power-to-X technologies by developing innovative direct and indirect conversion processes for the chemical industry towards higher TRL's, while making use of renewable electricity and lowering the carbon footprint. With these technologies, valuable fuels and platform chemicals can be produced from renewable raw materials while decreasing costs and increasing flexibility. The focus of the E2C project is on Power-to-Chemicals and Power-to-Fuels (both liquids and gases). The project has developed two pilot demonstrators and two bench scale pilot installations with supporting feasibility evaluations, thereby lowering the risks of investment for companies, especially SMEs, and positioning the 2 Seas region as an innovation leader in Power-to-X sustainable technologies.

SECTOR COUPLING THROUGH POWER-TO-CHEMICALS AND POWER-TO-FUELS

Transitioning from fossil fuel-based electricity generation, such as from coal and natural gas, to an electricity system based on renewable electricity sources, such as solar and wind, presents challenges. Given the intermittent nature of such renewable energy sources, in order to balance supply and demand, a growing capacity in these generation sources will need to be combined with a range of energy storage technologies. Mechanical storage, such as water pumps, represents useful energy storage options in some cases, however, these may be constrained by geographical factors. Chemical storage in batteries will continue to be an important form of storage in the future, but it remains limited in scale and is dependent on scarce resources. Converting power into chemicals represents another form of energy storage, albeit temporarily, whereby excess power is converted, either directly or indirectly, into useful chemicals or fuels.

The production of hydrogen through water electrolysis is the most well-known example of a power-to-chemicals process. Often referred to as 'green' or renewable hydrogen, this energy vector can replace fossil-derived hydrogen (normally from natural gas) as a key component in the production of many value-added products, such as methanol, ammonia, formic acid, formaldehyde and other synthetic fuels. Given the considerable potential for renewable hydrogen to support the decarbonization of industry and potentially other sectors, such as transport, it is a key pillar in the EU's Future Integrated Energy System.

However, despite the potential for renewable hydrogen to help decarbonize the chemicals sector, the majority of the chemicals and fuels we use contain carbon, so the complete removal of carbon-based structures from the chemical industry is considered unlikely. A less radical and more sustainable approach is simply to switch the source of the carbon contained in these chemicals from fossil-derived carbon feedstocks to 'captured' carbon sources. Many efforts across the globe are focused on developing and installing CO_2 capture systems to reduce the emissions of CO_2 from fossil fuel-based installations in the industrial and power sector. Although the majority of the existing and planned Carbon Capture and Storage (CCS) projects intend to store the captured CO_2 underground in deep geological structures, the captured carbon could be used as a feedstock for Power-to-X technologies. The capture of anthropogenic CO_2 and its use for the production of goods is often termed as Carbon Capture and Utilization, or 'CCU'. In the future, CO_2 could also be directly removed from the atmosphere, or from the processing of biomass, thereby removing the need for fossil-derived carbon entirely.

By combining Power-to-X and CCU technologies, instead of attempting to decarbonise the chemicals industry, fossil-based carbon can be replaced by recycling the carbon already present in the atmosphere. Through this, a shift from a linear flow of carbon from the earth to the atmosphere, towards a circular flow of carbon can be achieved. However, because carbon dioxide contains relatively little energy, to produce useful chemicals from CO_2, energy in the form of hydrogen and/or electricity will be required. By using renewable energy as the power source, Power-to-X technologies facilitate the conversion of renewable electricity into renewable chemicals and fuels. Indeed, by using CO_2 electrochemical reduction or CO_2 hydrogenation, it is technically possible to produce a broad spectrum of liquid fuels and chemicals, such as synthetic kerosine (jet fuel), methanol or formic acid – without fossil-based carbon.

POWER-TO-X AND CCU PROCESSES ADVANCED WITHIN E2C

Power-to-X technologies can be used to produce value-added chemicals and fuels from CO_2 through two main approaches: CO_2 hydrogenation, often referred to as an indirect conversion route, and the direct electrochemical conversion of CO_2. The CO_2 hydrogenation process is a two-step process. The first step involves the production of renewable hydrogen, which in a second step is reacted with CO_2 in the presence of a catalyst to produce fuels and base chemicals, for example, methanol. The methanol can be further processed to other high value compounds, such as dimethyl ether (DME) and other synthetic hydrocarbons. In the direct electrochemical conversion route, renewable electricity is used to directly convert CO_2 into fuels and chemicals, without the use of renewable hydrogen. One of the key chemical products that could be produced through the electrochemical conversion of CO_2 is formic acid.

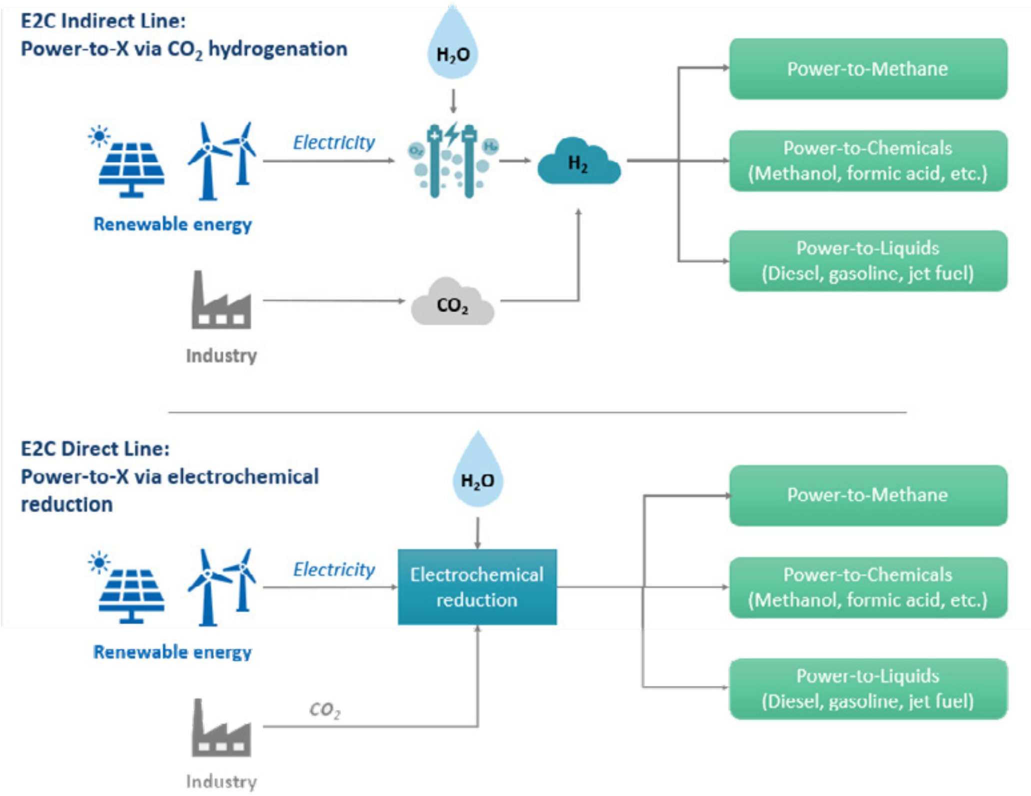

Figure 2 Schematic of Power-to-X via CO_2 hydrogenation (the E2C indirect line) and Power-to-X via electrochemical reduction of CO_2 (the E2C direct line).

In terms of advancement, the indirect conversion of CO_2 is already at an advanced stage in development (TRL 6-9), with the focus on conversion efficiency improvements and cost reduction. The direct conversion of CO_2 is currently at a lower technology readiness level (TRL 3-6), with developments mostly at laboratory scale. Importantly, the E2C project has advanced the development of both CO_2 conversion routes, building pilot demonstrators for the indirect conversion of CO_2 to DME, and for the direct electrochemical conversion of CO_2 to formic acid. For more information on the technical advancements achieved within E2C, please see "The E2C Project: Technology advancements and innovation" section of this document.

ESSENTIAL BUILDING BLOCKS FOR POWER-TO-X AND CCU

With limited other options to decarbonize natural gas and liquid fuels, the role for Power-to-X will become more prominent towards 2050. However the transformation from an industry based on fossil fuels to one based on renewable energy can only happen if the necessary building blocks are made available, namely sufficient renewable power, renewable hydrogen and a source of carbon-based molecules for fuel synthesis.

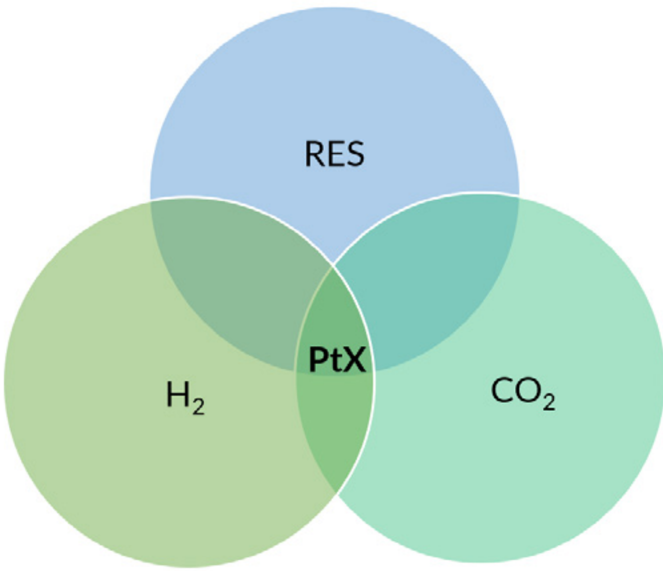

Figure 3 Essential building blocks to realize Power-to-X technologies.

For Power-to-X to be truly sustainable, and contribute to achieving net-zero, whether it is required for hydrogen production or for the direct electrochemical reduction of CO_2, the availability of abundant and low-cost renewable power is one of the three key facilitators of a Power-to-X industry. Power-to-X technologies are likely to be competing with other uses for renewable power, such as its direct use in industry and the residential and transport sectors. Therefore a ramp-up of investment in all renewable energy systems will be needed to achieve low marginal electricity generation costs to allow Power-to-X projects to penetrate the conventional gas and liquid sectors. Since renewable hydrogen is required for the production of so many Power-to-X chemicals and fuels, specifically for the indirect conversion route described above, the proliferation of electrolysers for the production of renewable hydrogen and the associated hydrogen transport and storage infrastructure is another essential prerequisite.

Whilst CCS is purely a CO_2 mitigation technology, CO_2 utilisation, including Power-to-X technologies, offers industry a way of retaining essential carbon-based molecules by recycling carbon. CCS projects are relevant for Power-to-X as they involve significant investment in CO_2 capture and CO_2 transport infrastructure. Such infrastructure could be readily utilised if a more commercially attractive use for the captured CO_2 was proposed as an alternative to storage. The development of energy efficient and environmentally friendly CO_2 capture and transport systems are the final key facilitators for Power-to-X technologies. Whereas the near-term deployment of CO_2 capture is focused on the abatement of CO_2 emissions from the industrial and energy sectors, with the expected phase-out of fossil fuels towards 2050, the deployment of bioenergy with CCS (BECCS) and direct air CO_2 capture (DACCS) technologies will be needed to continue the supply of carbon containing molecules for a future

In a nutshell – the benefits of Power-to-X & CCU

- Reduced CO_2 emissions through the replacement of fossil-fuel based products
- Balancing the gap between variable renewable energy generation and load
- Improving the feasibility of renewable power projects by maximizing energy utilization
- Providing a storage of renewable energy in useful products
- Self-sufficiency for chemical production feedstocks, leading to EU geopolitical independence and further reduced emissions from fossil-fuel transport
- Strengthening innovation and competitiveness of EU chemical sector in a carbon-constrained policy environment

OVERCOMING SPECIFIC BARRIERS FOR POWER-TO-X AND CCU TECHNOLOGIES

Next to the essential building blocks highlighted above, the industry, policy and R&D sectors have important roles to play in the technologies for further development. The continued development of new process concepts and catalysts will broaden the scope for Power-to-X technologies, unlocking new markets and applications. Likewise, the scale-up of existing concepts from laboratory- to pilot-scale, and eventually to industrial demonstration, as achieved within the E2C, is important to build understanding and confidence in Power-to-X technologies and products. The identification and evaluation of new value chains and production routes should continue to be prioritized in future R&D projects, but also amongst sector organisations and government initiatives. Subsequently, policies and regulations are vital to create market demand for Power-to-X products, and by levelling the playing-field between conventional fossil fuel-based and low-carbon fuels and chemicals. A deeper look at possible policy actions can be found later in this document.

POWER-TO-X AND CCU AS DRIVERS FOR ECONOMIC GROWTH IN THE 2 SEAS REGION

Next to the potential benefits of Power-to-X technologies in reducing greenhouse gas emissions, balancing power grids and facilitating industrial circularity, the development of Power-to-X in the 2 Seas region can deliver considerable economic gains. Value for the region can be derived both through demand for Power-to-X products, but also through the supply of knowledge and Power-to-X technologies, the market potential of which is expected to grow exponentially towards 2050.

Figure 4 Map of the 2 Seas programme area (from https://www.interreg2seas.eu/).

The market potential for Power-to-X technologies is potentially enormous. The global market potential for Power-to-X technologies has been estimated to be able to reach up to €2 billion by 2035 (Ramboll, 2021). Although this estimate looks far broader than the specific processes covered by the E2C project, Power-to-X technologies capable of methanol synthesis and dimethyl ether synthesis will increase in importance in line with the expected increased demand for sustainable synthetic fuels and chemicals. The global market demand for CCU technologies alone has been estimated at €550 billion by 2040 (Lux Research, 2022). With no less than 35 industrial companies involved in the E2C project as 'observer partners', including major energy companies, chemical producers and technology providers, the interest in the advancements achieved within the E2C project is clear.

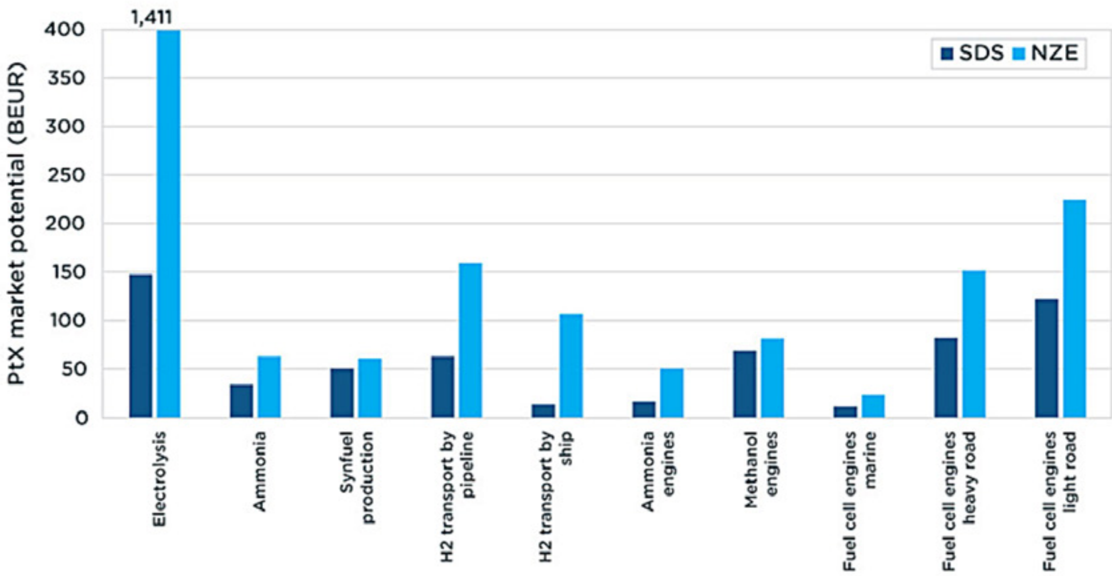

Figure 5: Estimated global market potential for Power-to-X markets in 2035, estimated according to IEA's Sustainable Development Scenario (SDS), and IEA's Net Zero Emissions scenario (NZE) (Ramboll, 2021).

THE IMPORTANCE OF POWER-TO-X AND CCU TO SUSTAINABLY MEET GROWING DEMAND FOR CHEMICAL PRODUCTS

The demand for chemical products has been growing steadily over the previous years, a trend which is expected to continue to 2030 and beyond. Demand for high-value chemicals has grown by approximately 3% annually over the last decade, with demand for methanol increasing by 7% over the same period (IEA, 2022a). The current global production capacity of methanol is estimated at 110 million tonnes, with demand expected to reach 170 million tonnes by 2050 (van der Hoeven, Kobayashi, & Diercks, 2013). The market for dimethyl ether (DME), a derivative of methanol, and also one of the Power-to-X production routes developed in the E2C project, is also expected to see market growth dramatically increase at a rate of 9% per year towards 2030 (Polaris Market Research, 2023). Formic acid, the focus of E2C's direct electrochemical CO_2 conversion process, has a somewhat more modest global market size of 1 million tonnes, but has also experienced growth rates of around 5% per year.

However, despite these opportunities for economic growth, the majority of these projections are based on conventional fossil-derived carbon-based production processes. It is clear that if demand for organic base chemicals is to be met sustainably, a step change will be required from a fossil-based system to one focused on recycling of materials, carbon capture and utilization, and bio-based production processes.

NEW MARKET DEVELOPMENT FOR SYNTHETIC TRANSPORT FUELS

In addition to the potential for Power-to-X to meet the demand for existing high-value chemicals, new markets for Power-to-X products are starting to emerge, particularly from the transport sector. Whereas electric vehicles can be considered the preferred solution for short distances and light vehicles (e.g. passenger cars, urban mobility concepts), other transport sectors, such as road haulage, shipping and aviation, meanwhile are currently lagging behind when it comes to contributions to sustainable mobility. These modes of transport require energy carriers with a higher energy density. Renewable power combined with capture of CO_2 can be used in Power-to-X processes to produce low-carbon and potentially zero-carbon transportations fuels. These so-called e-fuels include hydrogen itself, but also e-methanol, e-diesel, e-ammonia, e-LNG and e-kerosene. The demand for e-fuels could be huge, with 20,000 terawatt-hours of fuel-based energy needed in 2050, equivalent to two trillion litres of diesel (Rolls Royce, 2023).

RENEWABLE POWER AND GREEN HYDROGEN PRODUCTION OUTLOOK

Given that the expected demand for growth for current and future Power-to-X products is expected to remain strong towards 2050, it is important to assess the projected availability and price developments of renewable power and green hydrogen. As mentioned above, access to abundant and low-cost green hydrogen will govern the speed at which Power-to-X technologies can compete with conventional fossil fuel-based production processes. Currently, renewable energy accounts for 22% of all energy consumed in the EU. The EU has agreed to increase this amount to 32% by 2030. Whereas some EU Member States such as Denmark, Sweden and Portugal are approaching a share of renewable energy consumption close to 40%, the current consumption of countries within the 2 Seas region averages between 10-20% (European Environmental Agency, 2022). Despite this, these countries have ambitious targets with regards to renewable power, in particular with North Sea countries including the Netherlands, Belgium and France committing to ramp-up offshore wind to 76 GW by 2030, and 260 GW by 2050 as part of the North Seas Energy Cooperation. The current share of solar, on- and offshore wind power in the 2 Seas region is provided in Table 1.

	Solar PV capacity in 2020 (GW)	Onshore wind capacity in 2020 (GW)	Offshore wind capacity in 2020 (GW)	Offshore wind 2030 target (GW)
UK	13.6	14.2	10.4	40
Netherlands	10.2	4.1	2.5	11
Belgium	5.6	2.4	2.3	4
France	11.7	17.4	0.002	8.8

Table 1: Table comparing the renewable electricity generation capacity and targets of the 2 Seas nations

The EU also has considerable targets for green hydrogen production, but also for the import of green hydrogen into the Union. Through the 'Hydrogen accelerator', part of the REPowerEU Plan announced in May 2022, the European Commission intends to enact a series of supportive policy instruments to reach the ambition of producing 10 million tonnes and importing 10 million tonnes of renewable hydrogen in the EU by 2030. To put this into perspective, this is more than double the EU's current hydrogen demand of 8 million tonnes in 2021 (IEA, 2022a).

Following the announcement of the REPowerEU Plan, European manufacturers committed to increase the total annual electrolyser manufacturing capacity from 1.75 GW in 2022 to 17.5 GW in 2025 (European Clean Hydrogen Alliance, 2022). According to the IEA, (IEA, 2022a), the company strategies announced so far would result in a cumulative output of around 95 GW by 2030, which would be only slightly lower than that required to reach the target of 10 Mt of annual renewable hydrogen production. These targets are reflected by the huge number of electrolyser initiatives identified by the IEA in its Hydrogen Projects Database, with close to 600 different projects understood to be either operational or in various stages of development within the EU (IEA, 2022b). Approximately 230 of these projects are located in the countries of the 2 Seas region.

POWER-TO-X TO COMPETE WITH FOSSIL-BASED PROCESSES TOWARDS 2050

Studies commissioned by the European Commission have provided insights into the necessary economic conditions in which Power-to-X technologies can become competitive with conventional production processes for hydrogen, synthetic gas and synthetic fuels (METIS Studies, 2018). The results underline that the profitability of Power-to-X is primarily subject to the availability of low electricity prices. The study assumed a scenario in 2050 whereby 65% of the EU's net electricity generation is provided by renewable energy technologies, and an EU Emissions Trading Scheme (ETS) price of at least >100 €/tCO_2 prevails. In this study, Power-to-X technologies become competitive first in Member States which exhibit more than 2000 hours of near zero electricity prices due to their high shares of variable renewable energy. Spain, Ireland, Greece, Portugal and Cyprus are identified as countries which will be initially favourable for Power-to-X solutions. However, the study also highlights that the potential reduction in capital investment costs of Power-to-X technologies, higher ETS prices and/or increases in natural gas prices could broaden and accelerate the speed at which competition becomes effective.

CCUS TO BE IMPLEMENTED IN THE COMING DECADES

Carbon capture, utilization and storage (CCUS) is recognized by the European Union as a technology which can provide a key contribution to the reduction of emissions in industry. The possibility of generating negative emissions through the combination of bio-energy with CCS (BECCS) and direct air capture (DACCS) are also recognized as being necessary for carbon removal. With this in mind, a raft of supportive policies are in place to accelerate the deployment of CCUS. The European Union's Innovation Fund is supporting 7 large-scale CCUS projects, providing grants to cover up to 50% of the projects' capital expenditures and operational costs. Furthermore the EU's Trans-European Networks for Energy (TEN-E) policy allows cross-border CO_2 transport infrastructures to be classified as Projects of EU Common Interest or 'PCIs', allowing such initiatives to benefit from grants and a streamlined permitting approval process. In 2021, six CO_2 trans-European infrastructure projects were selected. Of relevance for the development of Power-to-X in the 2 Sea's region, 4 of the 6 projects classified as PCI's involve the Netherlands, Belgium, England and France.

Potential CO_2 transport networks in the 2 Sea's region

- Porthos (Port of Rotterdam) – The development of a multi-user CO_2 pipeline system through the port of Rotterdam, with the possibility for extension to the port of Antwerp.
- Aramis (Shell, Total Energies, Gasunie, EBN) – An extension of the Porthos project with possible land and maritime connections to Belgium, Germany and Northern France.
- DMX Demonstration in Dunkirk (Total Energies) - CO_2 export Multimodal HUB from Dunkirk and its hinterland (France)
- Antwerp@C (Fluxys) – Development of a multi-user pipeline system around the Port of Antwerp for both CO_2 storage and utilization.

Indeed, with the increase in the price of EU ETS credits, combined with additional national funding schemes and carbon taxation policies, the number of CO_2 capture projects to be developed within the EU is expected to grow considerably. Based on current project developments, it has been estimated that up to 10 million tonnes of CO_2 will be captured from industrial sources in the Netherlands by 2035 (RoyalHaskoningDHV, 2021). In November 2022, the Dutch government announced subsidy applications for up to €7 billion to support CCS projects, which combined would capture 3.5 million tonnes of CO_2 by 2028 (Ministry of Economic Affairs and Climate Policy, 2022). The Port of Antwerp has also advanced plans for a CO_2 capture and transport hub. In December 2022, the Antwerp@C project was award €145 million from the European Union's Connecting Europe Facility (CEF) for the construction of shared CO_2 transport and export facilities. The Antwerp@C CO_2 Export Hub will have an initial export capacity of 2.5 million tonnes per annum (Mtpa), with the ambition to reach up to 10 million tonnes by 2030 (Air Liquide, 2022).

Whereas the majority of the projects are focused around the permanent geological storage of CO_2, it can be confidently assumed that the CO_2 capture installations will be operating for many decades to come. Should an enabling policy and regulatory environment for Power-to-X projects appear, it is a distinct possibility that a growing number of CO_2 capture installations could potentially switch from a business case focused on geological storage, to one focused on CO_2 utilisation in Power-to-X applications.

THE E2C PROJECT: TECHNOLOGY ADVANCEMENTS AND INNOVATION

The E2C project was focused on advancing two types of electro-conversion processes which utilize renewable feedstocks and convert them into high value platform chemicals and fuels using Power-to-X technologies. One of the main objectives of the E2C project was to design and construct pilot demonstrators to advance the infrastructure of these two processes.

- Indirect: hydrogen produced from water electrolysis is combined with CO_2 to produce chemicals and fuels.
- Direct: CO_2 is directly converted into platform and specialty chemicals in a streamlined electrochemical process.

Carbon footprinting work completed as part of the E2C project revealed that both of these Power-to-X technologies have the potential to reduce emissions by 70% or more compared to the conventional, fossil-derived equivalents.

TECHNOLOGY STATUS OF RENEWABLE HYDROGEN PRODUCTION

The production of hydrogen is not only an important concept for the indirect electrochemical conversion route for the production of fuels and chemicals, but has a vast global requirement as a feedstock in many other processes including ammonia production and synthetic fuels, with demand expected to increase across multiple sectors. It is expected that the total global hydrogen use could expand from 115 Mt per annum to 500 – 800 Mt by 2050 (Energy Transitions Commissions, 2021). This will result in hydrogen and its derivatives accounting for 15-20% of the final energy demand. At present, more than 90% of the hydrogen produced globally each year is produced from fossil fuels, with Europe predominately utilizing natural gas. In 2018, of the 115 Mt of hydrogen utilized globally, 70 Mt was produced by dedicated production – 71% of this from natural gas and 27% from coal, the remainder of the hydrogen was produced as a by-product through other manufacturing processes. Hydrogen produced from fossil-derived sources, resulted in 830 Mt CO_2 emissions, 2.2% of the global energy related total (Energy Transitions Commissions, 2021). Therefore, for future developments, a more sustainable method for hydrogen production is needed if it is to be produced at the mega-tonne scale required by many Power-to-X technologies.

Alternatively, hydrogen can be produced by the electrolysis of water using renewable electricity, which involves the splitting of water into its two components – hydrogen and oxygen. The benefits of this process include that it does not rely on the utilization of fossil fuels and emits no greenhouse gases, and currently accounts for 2% of the global hydrogen production (IRENA, 2022). There is a significant drive to utilize this technology as a replacement for fossil fuel-derived hydrogen production. However, the electrolysis process is currently very energy intensive, typically using in the order of 50 kWh per kg of hydrogen. In order to be able to apply green technology for future developments in hydrogen production, it is essential to be both an energy efficient and inexpensive process.

As part of the E2C project, the aim was to develop innovative conversion processes for the chemical industry towards higher TRLs by using renewable electricity and lowering the carbon footprint by application of Power-to-X technologies using green hydrogen produced from water electrolysis (WE). Therefore, the E2C project included the development and testing of novel WE concepts. In particular, the development of anion exchange membrane (AEM) electrolysers which exhibit benefits over other more developed electrolyser technologies, such as alkaline WE (AWE) and proton exchange membrane (PEM) electrolysers (see box).

TYPES OF LOW-TEMPERATURE ELECTROLYSERS

Alkaline Water Electrolysers (AWE)

AWE is an advanced and established electrolyser technology currently used within the industrial context at the megawatt range for the production of hydrogen. It is currently favoured for its long technological lifetime and low cost due to the advanced nature of this technology and its use of non-precious metals, such as nickel. However, drawbacks of this technology are its large technological footprint, limited current densities and low operating pressure (Shiva Kumar,2019).

Proton Exchange Membrane (PEM) Electrolysers

PEM electrolysers are a relatively mature technology with commercial application, offering many advantages over the currently applied industrial AWE. These include high pressure operation, high electrical efficiency and hydrogen purity and are smaller in size. However, the main barrier to large-scale sustainable hydrogen production is the high cost associated with PEM electrolysers, particularly in comparison to the cheap fossil fuel alternative. The driver behind this high cost is mainly the use of rare, expensive materials, such as iridium and platinum, that are used as a catalyst within the electrolyser, overall having a negative impact on the scale-up potential of this technology. To achieve competitive green hydrogen prices (<2 €/kg), a reduction in cost, higher efficiencies and longer lifetimes at the component level have to be made.

Anion Exchange Membrane (AEM) Electrolysers

AEM is a relatively novel technology which combines the advantages of the already recognized electrolyser technologies, PEM and AWE, with the promise to eliminate the disadvantages of each of these technologies. AEM technology is more cost effective in terms of design when compared to PEM as it utilizes cheaper non-precious metals, such as nickel and steel, as well as other low-cost cell components, reducing the overall cost of the electrolyser. Additionally, in comparison to the established AWE, AEM technology can allow for operation at a higher current density to produce high purity hydrogen and a fast response to intermittent loads, which is desirable when utilizing renewable energy as the electrical feedstock. Therefore, AEM is seen as an attractive technology for producing clean and low-cost hydrogen.

Current research efforts within the field are focused on developing components with enhanced performance and durability as well as proof-of-concept setups giving a TRL of 2-3. The E2C project has focused on developing AEM technology that matches and exceeds the performance of other electrolyser technologies, which has involved the development of a bench-scale pilot (the Alkaline Test Station) for testing the lifetime of novel electrolyser concepts at the component level. The lifetime is one of the key improvement areas for electrolysers to become more industrially feasible.

To study the degradation of the AEM cell, an accelerated stress testing protocol was developed which mimicked the fluctuations from renewable energy sources. The results obtained revealed the behaviour of various voltage losses within the cell, that could be contributed to catalyst degradation. In addition, with the standard 10 cm^2 AEM cell, an increase in performance was observed, which may be due to membrane thinning (degradation process). However, further analysis is required to prove this.

Developments in the project were also made in terms of scale-up of AEM cells from 10 to 100 cm^2 cells and tested using the Alkaline Testing Station. Differences were observed in terms of performance and catalyst degradation, which were attributed to the difficulty with uniformly dividing the contact pressure, thus emphasizing the importance of proper cell design in scale-up. Moving forward, further harmonisation of utilised conditions and more extensive testing is required to gain more insight into catalyst degradation.

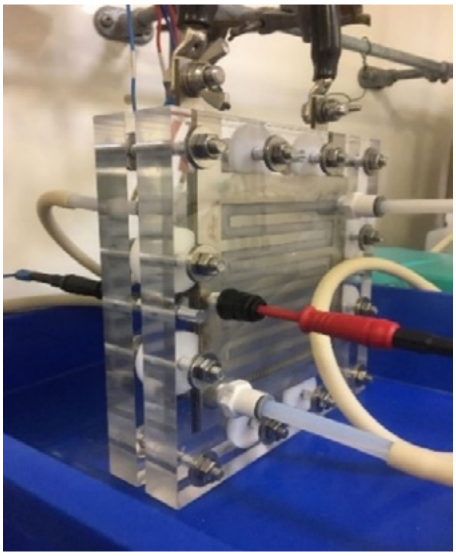

Figure 6 Scale-up of AEM cell (100 cm²)

INDIRECT CONVERSION: CO_2 AND HYDROGEN TO FUELS AND CHEMICALS

The approach known as the indirect conversion route is a two-step process which firstly involves the production of hydrogen from renewable sources, followed by a reaction involving CO_2 to produce high value chemicals and fuels, including dimethyl ether (DME). DME is an environmentally friendly, combustible gas that is currently used as an aerosol propellant and a green refrigerant due to its zero ozone depletion and low global warming potential.

DME has a modest market size but has the potential to grow as it can be utilized as a diesel fuel replacement with only minor modification to current conventional diesel engines. In comparison to diesel fuel, DME has lower CO_2 emissions and is a cleaner, sootless fuel. Additionally, DME has the potential to be utilized in liquified petroleum gas (LPG)-like distribution infrastructure. By implementing DME as a fuel alternative, due to its similar chemical properties, existing infrastructures for LPG and natural gas can be exploited for transport and storage to ensure a cost-effective process.

At present, industrial methods of DME production are from synthesis gas (a mixture of carbon monoxide and hydrogen) primarily using fossil-derived feedstock such as natural gas and coal, although biomass is also used but on a much smaller scale. Conventionally, DME is produced in a two-step process; firstly producing methanol as an intermediate chemical, which is separated and followed by a second step, known as a dehydration reaction, to yield DME. Two different reactors and catalysts (a metallic and acid catalyst respectively) are used during this process, which provide simplicity and ease of control of the reaction through alteration of temperature and pressure for each distinct step of the process.

Alternatively, a one-step process has been investigated in recent years, again utilizing synthesis gas produced from carbon-rich feedstocks. This more succinct route takes place using one reactor unit and a bifunctional catalyst. This simpler reactor design results in much lower DME production costs. However, the separation and purification process following this one-step method is more complicated in comparison to the two-step method, therefore, the two-step process is favoured. Overall, the synthesis gas process (one- and two-step) for DME synthesis is an energy consuming and a greenhouse gas emitting process. Thus, a more energy efficient and environmentally friendly design solution is desired for the future production of DME.

One of the main objectives of the E2C project was to demonstrate Power-to-X showcases at industrially relevant scales (TRL 6-7) to establish the valuable infrastructure, and in turn lower development risks for industry to stimulate investment. However, several technical and economic hurdles had to be overcome, including meeting the need for demonstrators to convince industry to invest in further development and implementation of these technologies.

From the outset of the E2C project, the technology for the indirect conversion route existed and was fairly well developed at a TRL of 5. By construction of the E2C pilot demonstrator, this would advance the TRL to 7, therefore being at a more industrially relevant scale. This resulted in the design and development of the novel process Sorption-Enhanced DME Synthesis unit, abbreviated to SEDMES. The drive behind the SEDMES unit is to combine green hydrogen production from an electrolyser with CO_2 to synthesize DME directly, as shown in the figure. Consequently, this would avoid the application of fossil-derived carbon sources with SEDMES providing a versatile and powerful route from CO_2 to high value chemical products.

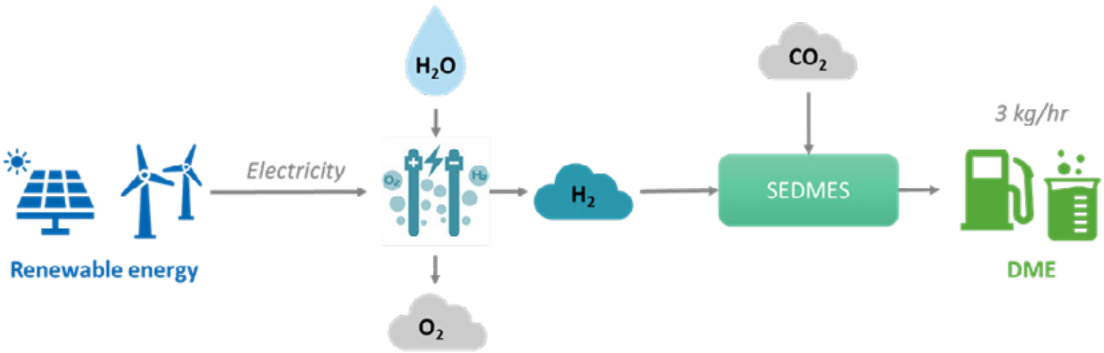

Figure 7: Overview of the envisioned Power-to-X process to convert CO_2 to DME.

Research activities through the E2C project have culminated in the pilot demonstrator at TNO in Petten, Netherlands, shown in Figure 8. The SEDMES demonstrator consists of two pilot units: an electrolyser for hydrogen production by water electrolysis and the SEDMES unit for the continual production of DME from the reaction between hydrogen and CO_2. The SEDMES process looks to utilize captured CO_2 and electrification technologies with the aim to help achieve 2050 climate targets The demonstrator unit has been designed with a capacity of 3 kg/hr and to be mobile for on-site testing at industrial sites. The unit will be made available for stakeholders to use within further R&D activities.

Figure 8: The SEDMES pilot unit as it currently is at TNO Petten

Further developments are ongoing to demonstrate the high efficiency carbon conversion technology in an industrial on-site environment.

DIRECT ELECTROCHEMICAL CONVERSION OF CO_2

The streamlined direct conversion route makes direct use of renewable electricity for the electrochemical conversion of CO_2 into a variety of specialty chemicals, such as formic acid (FA). The technologies for this process were less developed than the indirect conversion route, with developments at the beginning of the project situated at the laboratory scale (TRL 3). Therefore significant advances were needed towards conditions and performances relevant for industry. The E2C project focused on further developing component and reactor designs, with the overall aim to bring the direct conversion route to TRL 6 by piloting the technology in a relevant environment.

Power-to-Formic Acid is a Dutch national project coordinated by Coval Energy where the formic acid technology is being optimized and scaled up to a bench-scale system. Building upon this project, the E2C project has used the production of formic acid, an important platform chemical, from CO_2 as the showcase for the direct route pilot demonstrator.

Formic acid is a high value chemical commodity that exhibits antibacterial properties, which makes it a highly desirable product for many industries. This includes the like of the agricultural market for preservation of feedstock of animal fodder and the leather and tanning industry, as well as other chemical and pharmaceutical industries. In 2021, the global formic acid market reached 710 thousand tonnes and is expected to show continued growth from the established uses but also through potential future applications. These possible routes include being used as a hydrogen carrier molecule. As previously highlighted, hydrogen has a wide range of applications, including use as a fuel. However, safe storage and transport is difficult to achieve in a safe manner. Therefore, formic acid can be used as an alternative, temporary, hydrogen carrier molecule. It can be decomposed to liberate H_2 and CO_2, but also offers the possibility for reverse transformation back to formic acid, as such serving as a platform for chemical energy storage.

Industrially, formic acid production is through a methyl formate hydrolysis reaction, which is a carbon intensive process, dependent on the utilisation of fossil fuels and thus not sustainable. This reaction is a two-step process performed at elevated temperature and pressure, firstly reacting methanol with carbon monoxide to produce methyl formate. The methyl formate goes on to react with water resulting in the formation of formic acid and methanol.

DIRECT ROUTE ELECTROLYSER DESIGNS

Technological developments in the E2C project focused on two different types of electrolysers with either two or three compartments. Independent of the utilised electrolyser , the overall reaction is between CO_2 and H_2O which takes place in the electrochemical reactor, resulting in the formation of formic acid.

Two-compartment electrolysers

The 2-compartment design introduces CO_2 at the cathode dissolved in the catholyte, where it reacts to produce formate, which remains in the catholyte. Formic acid is not formed within the electrolyser itself but is later produced in the downstream process in which the formate is protonated to from the formic acid.

Three-compartment electrolysers

The 3-compartment electrolyser introduces CO_2 at the cathode and formate ($HCOO^-$, deprotonated form of FA) is created and solubilized in the catholyte. The formate then travels from the cathode side to the middle compartment with the electrolyte through an anion exchange membrane. It is here that the formate is protonated to form formic acid with the protons that are incoming from the anode compartment through a cation exchange membrane. The produced formic acid is purified in a downstream process.

The main benefit of this particular design is that it directly produces formic acid rather than formate; however, there are possibly higher losses in FA yield and overall energy efficiency (extra resistance and higher cell voltage).

The direct electrochemical route developed as part of the E2C project provides a solid alternative for the utilisation of CO_2 as a reactant, and a method to store/valorise renewable electricity to produce an industrial feedstock at industrially relevant concentrations (85% wt. FA concentration). Through the development of process design, new electrodes and catalysts, the final output of the E2C project, the pilot demonstration system called ZEUS, was constructed and installed at the TNO facility in Rijswijk, Netherlands (see Figure 9). The demonstrator consists of multiple stacked electrochemical cells, with the ability to convert 1 kg of CO_2 per hour into platform chemicals, such as formic acid.

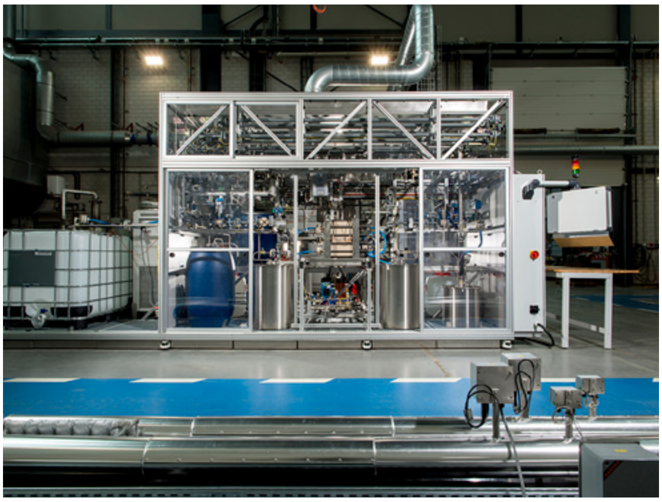

Figure 9 The ZEUS pilot unit as it currently is at TNO Rijswijk.

ASSESSING THE ECONOMIC VIABILITY OF CO_2 CONVERSION ROUTES

Techno-economic analysis (TEA) is important for determining the economic feasibility and main influencing parameters for new processes, while helping to better allocate development resources. A TEA has been performed on both the production cost of DME, through the application of SEDMES (using H_2 produced by a PEM electrolyser), i.e. the indirect line, and the electrochemical conversion of CO_2 to formic acid (FA), i.e. the direct line. This analysis is used to indicate which factors have a significant influence on the overall viability of the process. To further understand the influence of each factor, a sensitivity analysis was performed.

The values for the key economic parameters used to perform the analysis, including plant lifetime, CO_2 and electricity costs, annual interest rates, etc., were based on existing knowledge from previous projects and literature data or had been assumed to adopt a standard in industry and engineering.

INDIRECT CONVERSION ROUTE

During the analysis for the indirect route, several assumptions were made:

- The cost of CO_2 varies significantly depending on the capture technology and source used. Therefore, a relatively low CO_2 price of 70 €/t CO_2 was assumed, based on the estimated average CO_2 abatement costs of current technologies for the industry and power sector. A range from €50-250 per ton was used in the sensitivity analysis.
- Similarly, energy prices are dependent on many factors in the future energy market and the impact on the Power-to-X SEDMES process for a broad range of energy prices was studied. For the base case, a value of 50 €/MWh was adopted, based on the Dutch Climate and Energy Outlook 2019.

The first cost analysis of the envisioned process producing DME at a 23 kt/year scale from CO_2 and H_2, using a 40 MW electrolyser, had a production cost of ~€1.3 per kg. Despite the production cost being higher than the current market price for fossil-based DME (€0.56/kg), the results have shown to be more promising than other studies of DME production processes from CO_2, which are estimated at ~€1.4 per kg.

The high production cost is due to the high contribution of the operational costs (OPEX), which exceed the capital cost (CAPEX) contributions by 2.75 times. The OPEX mainly comprises of electricity (72%) and CO_2 costs (14%), with the electricity usage primarily related to the production of hydrogen (99.2%) in the PEM electrolyser. Thus, it is evident that the cost driving factor for DME production is directly related to the cost of hydrogen production. This is further supported by the impact of the electrolyser costs to the total installation cost, where hydrogen production contributes 78% of the installation cost. Therefore, it is important to design a process with maximum hydrogen conversion into DME.

Sensitivity Analysis

From the preliminary sensitivity analysis data, it was highlighted that the downstream process to the SEDMES step had a low impact on DME production costs, therefore further optimizations of the downstream process unit were left out of the scope of the E2C study.

For the study, further assumptions were made, including for the installation cost for the PEM electrolyser assumed to be 950 €/kW. This was on the lower side of reported ranges in literature. The electrolyser was assumed to use 49 kWh per 1 kg of H_2 (efficiency of 68% low-heating value).

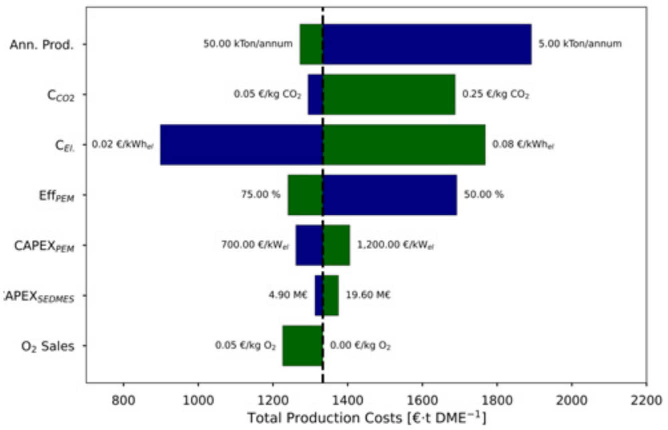

Figure 10: Sensitivity analysis on the main cost contributing factors to the Power-to-X SEDMES process. H_2 is produced by PEM electrolysis and reacts with captured CO_2 to produce DME. Ann Prod: Annual Production Scale; C_{CO2}: carbon dioxide cost; C_{El}: electricity cost; Eff_{PEM}: efficiency of the PEM electrolyser; $CAPEX_{PEM}$: capital costs electrolyser; $CAPEX_{SEDMES}$: capital costs SEDMES unit. Blue and green bar indicate lower and higher values compared to the base case, respectively.

The results of the sensitivity analysis are summarised in the figure, which indicate the central value of around 1300 €/t DME to represent the base case. The DME production costs are dominated by the PEM electrolyser at the given efficiency and electricity cost. Therefore, improving the electrolyser efficiency is one possibility to achieve lower DME production costs. For example, by increasing the efficiency to 75%, the cost drops to below 1200 €/t DME.

Another promising development to cut CAPEX costs of the electrolyser would be to replace the PEM electrolyser with its less expensive AEM alternative. However, this should not come with a high loss in efficiency. As part of the E2C project, AEM electrolysers with non-noble metal catalysts were developed to reduce the electrolyser costs (further information on AEM electrolysers can be found above in The E2C Project: Technology advancements and innovation section of this document).

Additionally, as indicated in the sensitivity analysis, the reduction of the electricity price has one of the highest potentials to bring down the production cost. Regions with high wind and solar availability, such as coastal areas, will probably have high supplies of renewable electricity in the future, leading to significantly reduced prices and even contributing to solving grid balancing problems. If the Power-to-X SEDMES process is compatible with the intermittency of energy, this provides the process with the opportunity to use the power excess for the production of DME.

Production scales of DME with the Power-to-X SEDMES process was also investigated within the sensitivity analysis. By increasing production scale from 23 to 200 kt DME/year, the DME cost is brought below 1300 €/t DME, outperforming the conventional DME synthesis route. Additionally, the SEDMES Power-to-X technology allows for DME production at the very small scales envisioned for decentralized Power-to-X technology. An annual production of 5 kt/year only increases CAPEX by ca. 150 €/t DME. This is an additional advantage of a sorption-enhanced technology over conventional DME production, which is unattractive for small scale production.

The costs of the Power-to-X SEDMES process are also sensitive to the cost of CO_2. The CO_2 price constitutes 10% of the total production cost. The breakeven cost for CO_2, that is required to make the process economically viable, is -0.31 €/kgCO_2, meaning that incentives for CO_2 utilisation and/or costs for emission should amount to this value. Although it is foreseen that policy changes in CO_2 emissions will have a high impact on the price formation, 310 €/tCO_2 is significantly more than any suggested carbon dioxide tax to date.

A final area of investigation was the impact of the CAPEX of the SEDMES unit. Reducing the capital costs of this installation has a limited effect on the DME production price. Another option to make the Power-to-X SEDMES process more attractive is to sell the produced oxygen from the PEM electrolyser as a product (credit 0.05 €/kg). It is important to note that post-treatment steps, such as compression and piping, were not taken into account during the sensitivity study.

Scenarios for the future Power-to-X SEDMES process

As already described, several factors have a large impact on the DME production price and the economic viability of the Power-to-X SEDMES process. Additional studies were conducted analysing the effect of these parameters in an optimistic price scenario on the economic indicator Net Present Value (NPV). The costs of the Power-to-X SEDMES process will be impacted largely by the cost of CO_2. For these calculations other parameters are assumed to stay the same as for the base case.

The figure highlights the NPV with in a plant lifetime of 20 years, showing two best case scenarios. Case 1 is indicative of a positive price for CO_2, i.e. when CO_2 should be purchased after being captured, and Case 2 reflects the possibility of when the cost of CO_2 emissions allowance certificate is significantly increased, such that Power-to-X SEDMES technology receives money from the CO_2 supplier. It is clear that Case 1 does not become profitable even after exploitation of the unit for 20 years. Therefore, reducing CO_2 capture costs and changes in policy towards CO_2 emissions are the critical actions to take in order to make the business case attractive as presented by Case 2.

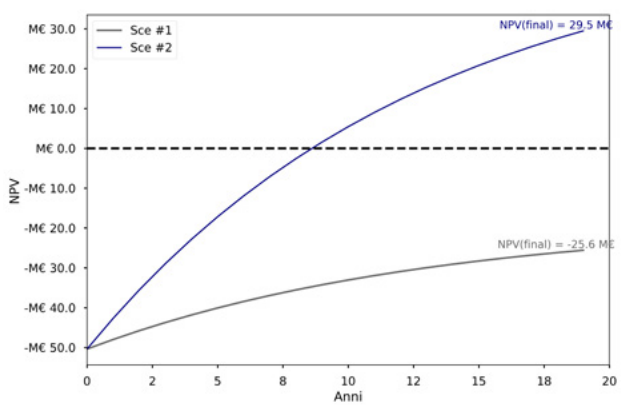

Figure 11: Net present values for two scenarios of CO_2 prices. Case #1: indicative of a positive price for CO_2. Case #2: the possibility of when the cost of CO_2 emission allowance certificates is significantly increased, therefore Power-to-X SEDMES technology receives money from the CO_2 supplier.

Recommendations from the results

The main cost contributing factors within the Power-to-X SEDMES process are related to the hydrogen production by the PEM electrolyser. The energy costs have the largest impact on the production price, followed by the CAPEX of the PEM electrolyser. Therefore, research directions within the E2C project were focused towards reducing electrolyser costs by enhancing efficiencies and the use of less expensive materials by investigating AEM electrolysers with non-noble metals. This technology may lead to less expensive systems but should be improved in terms of efficiency and lifetime.

With the sensitivity analysis for the economic indicators, the prices for CO_2 and in particular electricity are found to influence the economics of the process significantly. Regions with high wind and solar availability, such as coastal areas, will most likely have high supplies of renewable electricity in the future, leading to significantly reduced prices, but also to grid balancing problems. If the Power-to-X SEDMES process is compatible with the intermittency of electricity, this provides the process with the opportunity to use the power excess for the production of DME. Therefore, the compatibility of the Power-to-X SEDMES process with intermittent electricity is an interesting research direction. Next to electricity price, the CO_2 price has an impact on the production cost. A detailed scenario analysis will be useful to set the boundary conditions of the future market situation for which the process will become economically competitive. Reducing CO_2 capture costs and employing a change in policy towards CO_2 emissions are the critical actions to take in order to make business case attractive as highlighted in the optimised scenario.

Finally, the carbon footprint has to be examined to determine if the DME produced via the Power-to-X SEDMES process is indeed more environmentally benign than the conventional route and if it can be classified as for example a Renewable Fuel of Non-

Biological Origin (within RED II). This is anticipated to be influenced by CO_2 source, electricity source and DME application. Finally, future research is expected to give a clear picture of the technical, economic and environmental attractiveness of Power-to-X SEDMES process.

Direct conversion route

The techno-economic analysis for the E2C direct conversion route involved independently studying each technology (2- and 3-compartment cells), with a sensitivity analysis being performed for both separately. These could then be compared and assessed in terms of the preliminary economic analysis to determine which is the most economically promising technology.

An important indicator that was considered when analysing the techno-economic viability is the total production capacity of FA from any of the direct route technologies, and how that may impact the FA market and economics of the process. For the selection of a suitable production scale, there were three factors that had to be considered:

- Production capacity should be such that it allows for a good integration within the current market of the product and does not cause an imbalance that can drop the market price of the commodity.
- Necessary CO_2 input to be consistent with possible CO_2 sources of the 2 Seas region.
- Necessary electricity supply to run the plant with a particular production capacity of FA needs to be in line with the available energy supply from the grid in the 2 Seas region.

From an industrial point of view, it is always recommended to go as high as possible in scale to minimise capital expenses per unit of production, so the understanding of the limiting factor in scale is critical to find the optimum in profitability of the process. Hence, a production scale of 10 kt/annum FA was chosen, as it fits the abovementioned considerations.

The total production costs refers to the cost of production per unit of product at the end of the process, i.e. after downstream processing, per kg of 85% wt. FA aq. solution. This was to ensure a fair comparison between the two technologies (2- and 3-compartment electrolysers) for the direct route.

In terms of an estimation for capital expenditure for the electrolysers, an adapted procedure taken by Mayyas et. al. has been utilized. This primarily involves using a bottom-up manufacturing cost analysis, studying the impact of economies of scale on the final electrolyser costs with an overview of the internal components of the cell, as well as Balance of Plant costs for installation of the electrolyser.

As there can be uncertainty on many factors in the analysis, including technology development, optimal production routes and efficiencies, etc., the cost figures give only an indication. Notably, it must be underlined that all the process parameters used for the TEA have been assumptions, with the uncertainty of the presented results being ± 50%. Further analysis is required to include the experimental findings from the developed installations of the E2C direct route, so the results can be better established and closer to a hypothetical industrial CO_2 to formic acid process.

Results from the study

The initial TEA, conducted for the base case of the electrochemical production of formic acid from CO_2, revealed a total production cost 5-10% above the current market price of fossil-based formic acid for both direct route technologies. A marginal benefit in terms of total costs is established for the 3-compartment case, ca. 5% lower costs than the 2-compartment case. The base case calculations assumed an electricity price of €5/MWh, a CO_2 price of €200/t, an annual interest rate (AIR) of 8% and a total production capacity 10 kt/annum.

Despite the base case being unprofitable and yielding no economic benefit at the end of lifetime under these assumptions, the process has the potential for economic gain with adjustments to the AIR and to the production capacity. For the 3-compartment electrolyser, minimal economic gain is possible with a lower AIR of 2% (total production capacity 10 kt/annum). However, a more substantial gain is projected by increasing the total production capacity to 50 kt/annum, at varying AIR values (2, 8 and 15%), which is explained through the economies of scale: the CAPEX per kg of product decreases as the production capacity goes up.

For the 2-compartment electrolyser, there are resemblances with the 3- compartment line. Again, by increasing the total production capacity to 50 kt/annum the process becomes profitable. However, this is only for an AIR of 2 or 8 %.

Sensitivity Analysis

The sensitivity analysis of both technologies highlights similarities in terms of process parameters (technology performance) and economic indicators (availability and price of necessary resources). In terms of the economic indicators, both electricity and CO_2 prices, and production volume, are the most important in determining the final production costs. Possible discounts were considered from the sale of oxygen (0.05 €/kg), which could make a dent in the FA production costs, but no post-treatment for the O_2 has been included within the analysis and the considered benefits of oxygen sales are on an optimistic side.

The major cost difference in the two technologies comes from electricity consumption and the downstream purification strategy utilised by each technology. The 2-compartment electrolyser has a lower OPEX in the electrolysis process in comparison to the 3-compartment cell due to the 2-compartment electrolyser having a lower cell voltage. However, for the 2-compartment line, additional processes are required for purification (electrodialysis and azeotropic distillation) as a result of the production of formate at the electrolyser which drives up costs. This results in the 3-compartment line standing out as the more cost-effective technology. Yet, a possible advantage of the 2-compartment line is the fact that it may produce a slightly higher concentration of formate than in the 3- compartment electrolyser for FA. This should be confirmed by experimental data.

Importantly, when assuming the best-case scenario for process parameters and economic indicators for both the 3- and 2-compartment lines, the great potential the direct route has to offer can be seen. This outcome must certify the direct electro-conversion of CO_2 to FA to be a promising decarbonisation technology.

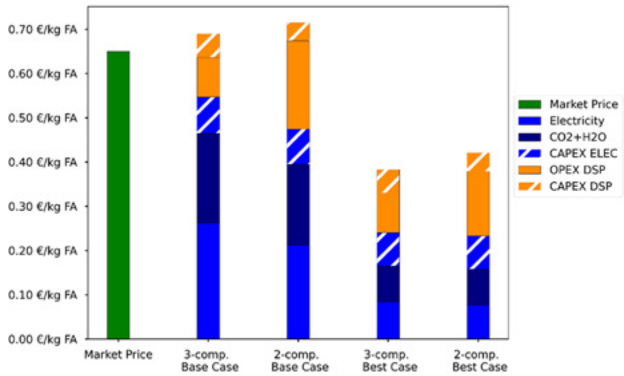

Figure 12: Comparison of the base case with the best case scenarios for both the 3- and 2-compartment process parameters.

Recommendations from the results

When comparing both technologies, the 3-compartment line stands out to be a more cost-effective process in comparison to the 2-compartment line. This is mainly due to the choice of the downstream purification strategy necessary for the 2-compartment line, which produces formate rather than formic acid at the electrolyser stage, in turn driving up the cost of product purification.

However, the 2-compartment electrolyser might present a crucial advantage in having a more concentrated product stream compared to the

3-compartment electrolyser design, which might lower the purification costs for the 2-compartment line. A more thorough analysis on the purification processes for both the 3- and 2-compartment lines is necessary to better estimate these costs.

With the sensitivity analysis for the economic indicators, the prices for electricity and CO_2 can influence the economics of the direct route heavily. A detailed scenario analysis will be extremely useful to set the boundary conditions of the future market situation for which the direct route will become economically competitive. Next to this, the production capacity can determine the viability of both the 3-compartment and 2-compartment lines due to the economy of scale benefit. However, there is a maximum in the FA production volume, dependent on the local CO_2 availability, the grid capacity, and also the local FA market.

OPTIMIZING THE DESIGN AND CONTROL OF INTEGRATED SYSTEMS

The intermittent nature of renewable energy sources is a critical aspect in the integration of Power-to-X and CCU applications. Green hydrogen generation using electrolysers that run on renewable energy sources have seen an increase in recent years for the storage of surplus energy, due to the advantages of electrolysers over conventional methods, such as batteries and ultra-capacitors, for long term storage and transport. PEM-based electrolysers are better suited for the coupling with renewable energy storage compared to traditional alkaline electrolysers due to their faster start-up times and fast dynamic load changing capability. More information of different types of electrolysers is available in the section The E2C Project: Technology advancements and innovation of this document.

The intermittent nature of renewable energy sources can affect the performance and operation dynamics of the PEM electrolyser. For example, at a very low power output from the source, i.e. when the power is struggling to run the electrolyser, the rate of hydrogen production may be lower than the rate of gas crossover through the electrolyser membrane, which can be dangerous for the electrolyser as well as the operator. The intermittent sources may also lead to lower efficiency as the electrolyser may not operate at the nominal temperature. Therefore, it becomes necessary to study the effect of the intermittent sources on the performance of the PEM electrolyser.

Mathematical modelling plays a very crucial role towards the objective of developing tools to test electrolysers under different conditions in order to understand the various phenomena taking place inside the electrolyser and predict its performance in a cost-effective way. The mathematical modelling acts as a dynamic connection between the electrolyser and the intermittent power source, as well as assisting researchers in the design optimization and developing controls for the system.

METHODOLOGY

The key objective of this part of the E2C project was to demonstrate the use of the generic dynamic multi-physics model for the performance of a single-cell PEM electrolyser running on intermittent sources (solar and wind energy). The experimental setup utilized for the study was commercially supplied by the Heliocentris® and consisted of a laboratory scale, commercial, single-cell PEM electrolyser of 300W connected to a hybrid multi-source (HMS) platform.

The model of the electrolyser was first tuned with the help of experimental data with the key parameters for the cell identified using an error optimization technique within the software MATLAB®. The objective was to find the values of the parameters to minimize the difference between experimentally measured characteristics and the ones generated by the model. The bounds for the parameter values were taken based on the values from the literature for a better estimation (Olivier et al., 2017a; Carmo et al., 2013; Bessarabov et al., 2016; Bessarabov et al., 2018). Other parameter values, such as recirculation pump flow, height and cross-sectional area of hydrogen separator, were taken based on the system specifications provided by the manufacturer.

The developed algorithms were first tested offline, i.e. virtually in a simulation environment, followed by implementation on the real system for real-time fault detection. The developed model was then available for use by the project partners for conducting performance analysis, such as calculations of total hydrogen production based on available green electricity and efficiency calculations.

RESULTS AND RECOMMENDATIONS

The PEM electrolyser can be fed by various electricity sources. The electrical input system powered by solar and wind energy has been termed as a hybrid multi-source system (HMS). HMS is mainly composed of a wind turbine generator, photovoltaic system, and storage system, for example, batteries feeding a local load such as the PEM electrolyser. Modelling of the HMS was also important from both a performance and diagnostic point of view and was conducted as part of the study.

Model Development

Bond graph (BG) based models were developed for a PEM electrolyser and an HMS platform. The modelling was done in modular fashion in order to have a library of various components that can be assembled in order to obtain the global model of the system. The BG models were converted into block diagram representations in MATLAB® Simulink from an implementation point of view. The generic dynamic multi-physics model for the PEM electrolyser was adapted for a single-cell PEM electrolyser running on intermittent sources and was validated against the experimental platform. The mean absolute percentage error between simulation and experimental data was found to be 4.8%, which is within the acceptable limit for simulations and for the development of control and diagnosis algorithms. Overall, the predicted performance was in good agreement with the expected behaviour of the electrolyser found in the literature.

Model Simulation

Following the development of the model, a performance simulation of the PEM electrolyser was conducted over a 12 hour period while running on intermittent sources alone, i.e. no battery considered. During this period, cell efficiency, cell temperature and pressure of the system at various points were monitored. It was determined that to improve upon both efficiency and hydrogen production rate, the number of electrolysis cells should be increased. Within this study, intermittent power was directly taken as an input for the model to predict the electrolyser's performance. However, in a real electrolysis system running on renewable energy sources, the controller with a buffer power source, such as a battery, with operating mode management would always be present. This is important to maintain the constant input power to the cell in reference to the set point for stable operation and to avoid faster degradation of the cell membrane.

Offline diagnostics

Subsequently, the refined model was used for developing robust diagnostics for online supervision of the PEM electrolyser. The diagnosis algorithms were first tested offline by simulating faults in the model of the system to check their effectiveness. The faults included membrane faults, increases in thermal resistance of the cell which can lead to overheating, and crossover of oxygen from the anode to cathode side. Simultaneous occurrence of multiple faults is a very rare event, but the sequential fault can be very common within industry. Therefore, it was assumed that these faults occurred one at a time.

To emulate the actual system, the model developed was used to allow for the possibility of testing different fault scenarios without endangering the actual system. Of the faults tested offline, all were successfully detected. However, these were not isolated due to having a similar fault indication. In order to make the faults able to be isolated from each other, either additional sensors are needed to be placed or the estimation technique could be used to calculate the parameter values from the residual to compare it with the known good parameter values.

Online diagnostics

To implement the developed algorithms on the experimental platform, a graphical user interface (GUI) was developed to allow for the monitoring of various components of the HMP including the electrolyser. For performing the online diagnosis, the real-time measurements of the system are fed to the diagnostic model in order to compute the residuals and these residuals are monitored for fault detection. Due to difficulties in introducing an actual fault into the system, which could cause permanent damage to the system or could be hazardous to the surroundings, no actual component level fault was introduced.

Similar to the offline diagnostic tests, three faults were considered for emulation into the actual system, two faults in the sources/HMS platform and one fault in the electrolyser. A blockage fault was emulated in the real system, i.e. the electrolyser, by manually turning off the outlet valve without stopping the hydrogen production. This would disrupt the hydrogen flow from the electrolyser to the bottle and would have a direct impact on the cell voltage. This fault, and the other two faults emulated were successfully detected.

Result Summary

- A generic model (modular design) has been developed for performing behavioural studies and efficiency estimations that can fit any configuration of PEM electrolyser ranging from laboratory scale to industrial scale. The model has been further extended for fault diagnosis and failure prognosis studies.
- The behavioural model has been extended to a diagnostic model for supervision of PEM electrolysers running on intermittent sources (wind and solar).
- The diagnostic model has been integrated with the prognosis of PEM electrolysers for the estimation of remaining useful life.
- The developed generic model can be utilized by the project partners and other stakeholders with the parameter values for their PEM electrolyser. The model can also be adapted for other types of electrolysers with similar configurations. The model has been adapted for the AEM electrolyser cell developed as part of the E2C project.
- The developed GUI has been implemented for demonstration on the pilot scale multisource PEM electrolysis platform.

POLICY RECOMMENDATIONS TO SUPPORT POWER-TO-X DEPLOYMENT

Power-to-X and CCU technologies have a crucial role to play in in the energy transition towards a net-zero future. Not only can Power-to-X technologies now contribute to reducing emissions from existing industrial processes, but in combination with carbon capture and utilisation, they can enable the transformation of the chemical industry from one based on fossil-based carbon to one based on recycled carbon. Power-to-X is needed to meet the demand for current chemical-based products, as well as a host of zero-carbon e-fuels for the transport, maritime and aviation sectors. However, in most cases, Power-to-X applications and products will struggle to compete with conventional production processes and action is needed to create the right market conditions to allow the technology to flourish.

This paper has outlined the foreseen advantages and deployment hurdles for Power-to-X, as well as showcased the technical advancements made to two promising Power-to-X value chains through the R&D impacts achieved within the E2C project. These interesting developments can only be profited from if the necessary policy and regulatory environment is created through European and Member States decision-making. This section of the paper will outline a series of steps that policymakers should consider in this regard. These recommendations are tailored towards the three previously outlined key facilitators of Power-to-X technologies; ***renewable power, renewable hydrogen, and sufficient carbon-based molecules.***

MAINTAIN MOMENTUM FOR RENEWABLE POWER

In many European electricity markets, a combination of policy interventions and regulations involving Contracts-for-Difference and carbon pricing have progressively driven down the carbon intensity of electricity grids. In many cases the marginal cost of renewable power generation is cheaper than that of fossil fuels. Despite these positive trends, new challenges are emerging, such as the cost-effective balancing of variable power production due to the growing capacity of wind and solar. As a result, focus is shifting from not only individual technology costs, but also towards how to optimize the overall system generation costs. The E2C project recommends a number of actions to realise this shift towards a society powered by renewable power:

- **Regulatory measures** - Consider enacting decarbonisation obligations or forms of quantitative targets for renewable power usage on large electricity users, such as heavy industry or transportation companies. Increasing the demand specifically for renewable power will create clear incentives both for renewable power generators, but also for energy storage projects. Many companies are already taking voluntary steps to do this, but this could be formalized explicitly in regulation.

- **Incentivisation** – First and foremost this would involve the removal of direct or indirect fossil fuel subsidies and tax breaks and reforming the electricity markets to allow for long-term generation contracts, but short-term for ancillary services, peak capacity services, flexibility mechanisms. For specific sectors, with very high-power usage, but exposed to considerable international competition, such as aluminium production for example, bespoke incentive schemes may be required.

- **De-risking investments through Contracts-for-Difference** – The CfD model has proven to be an effective policy intervention in countries such as the UK and the Netherlands, whereby governments provide a long-term guaranteed price for renewable power generation.

- **Boosting innovation, supply chain optimization and skills development** – Innovation both in generation and storage technologies, but also on smart demand-side applications are still needed. Next to technical and economic considerations, streamlined planning procedures and the identification of key skills for sufficient human capacity cannot be overlooked.

ENCOURAGE DEVELOPMENT OF RENEWABLE HYDROGEN PRODUCTION

Renewable hydrogen is expected to play a key role in a future climate-neutral economy, enabling emission-free transport, heating and industrial processes, including Power-to-X and inter-seasonal energy storage. Clean hydrogen produced with renewable electricity is a zero-emission energy carrier, but is not yet as cost competitive as hydrogen produced from natural gas. The majority of EU Member States recognise the important role of hydrogen in their national energy and climate plans for the 2021-2030 period. The recent agreement of the EU's recast Renewable Energy Directive has provided welcome clarification setting out clear rules and standards for green hydrogen as well as renewable liquid and gaseous transport fuels of non-biological origin (RFNBO's), however deployment support must now be ramped up to meet the EU's goals of 40 GW installed capacity by 2030. Recommended actions include:

- **Enhancing technology development** - Government and collaborative private-sector action is needed to bring to market key technologies and capabilities across production (e.g. electrolysers with faster ramping), transportation and storage (e.g. new forms of bulk hydrogen storage such as rock caverns) and use (e.g. direct reduction of iron with hydrogen).

- **Encouraging the development of hydrogen clusters** – Reinventing industrial clusters from ones based around fossil fuel-based process integration, to ones based on hydrogen-producing and utilising industries will support the production, storage, transport and end-use of hydrogen to develop concurrently. Furthermore, clusters can provide producers with greater certainty of demand and can enable users to share costs for transport pipelines.

- **Policy incentives** – Similar to renewable power, Contracts-for-Difference, which provide a premium to renewable hydrogen producers, can create sustainable business models for large scale investments in electrolysers. Mandates for renewable hydrogen use in industry could also be considered, but only if enough production capacity is available to meet demand. Financial incentives on the demand-side could also help offset the high cost to consumers in using renewable hydrogen.

- **Utilisation standards** - Rules and standards for blending with natural gas, including safety and purity. Improvements in the energy efficiency and availability of hydrogen-utilising technologies, such as boilers, will be needed to ensure that hydrogen use is viable both commercially and domestically.

SECURING A SUPPLY OF RECYCLED CARBON MOLECULES THROUGH CO_2 CAPTURE

Whereas the concepts of carbon capture and storage (CCS), and carbon capture and utilisation (CCU) have often been framed as being in competition with one another, this is not necessarily the case. CCS is needed now to enable rapid and fast emission reductions in line with the Paris Agreement. As more investments are made in CO_2 capture technologies, it is inevitable that performance improvements and cost reductions will be realized. The improvements will also be to the benefit of CCU and therefore

Power-to-X projects, which both rely on the same CO_2 capture technologies. However, whereas sufficient CO_2 is likely to be able to be captured from industrial and fossil-based power production for the next few decades, eventually Power-to-X projects will need to source non-fossil-based sources of CO_2 from direct air capture and biomass-based capture processes.

Policy initiatives for CCS are emerging throughout Europe and are focusing on providing direct subsidies to cover the operation and capital costs. In countries that have adopted such an approach, such as the UK and the Netherlands, this appears to be catalysing significant industry interest. However a number of technical challenges require continued attention:

- **Technology improvements** – CO_2 capture processes must be made as energy efficient and as environmentally benign as possible. Innovative capture purposes should be encouraged which do not lead to increased harmful emissions to air, land and water. Improving efficiency and reducing the costs of DACCS technologies is important in the long run.

- **Support Infrastructure developments** – For CCS projects to move forward, access to transport and storage infrastructure is a natural prerequisite. CO_2 transport infrastructure must be built at a similar speed and scale as that seen for natural gas transportation networks. Specific policy support and EU coordination should be enhanced if sufficient transport and storage capacity is to be realized.

- **Innovative CCS/CCU value chains** – Policy attention should already be given to identifying innovation business models which are able to combine both CCS and CCU off-takers as part of individual capture projects. Examples of such projects are proposed in the Netherlands, where captured CO_2 is proposed to be used or stored dependent on seasonal demand from off-takers. The identification and generation of such experiences can assist in the eventual transition from a predominately CCS-focused industry to one focused on CCU.

FOCUS ON POWER-TO-X AND CCU

Of course, along with creating the necessary preconditions, tailored policies and incentives are needed to improve the business case for investments in Power-to-X and CCU. They must be underpinned by a transparent and robust measurement, reporting and verification framework to provide confidence that emissions reductions are actually being achieved. The design of such a framework is challenging, due to the wide range of potential products being sold in different markets (base chemicals, speciality chemicals, fuels) and the inherent complexity in determining the achieved emissions reductions. Presently, policies supporting CO_2 use are scarce, due to the relative novelty of the processes and uncertainties in emissions accounting.

Most Power-to-X and CCU processes and products are still at early stages of technological development and are unable to compete with the existing fossil-derived products, especially in the absence of policies that value lower-carbon alternatives. While a carbon price could drive the market for some CO_2-derived products, additional policy measures are needed for the initial commercialisation phase. Policy support needs to recognise the early-stage challenges of Power-to-X and CCU, including the commercial gap with conventional products, the regulatory/legal barriers, and the importance of creating a robust emissions accounting framework. Policy recommendations tailored to Power-to-X applications include:

- **Boost research, development and demonstration** – Projects such as E2C illustrate the technical advancements that can be achieved through collaborative R&D projects. Further similar projects, covering different Power-to-X and CCU processes and products are needed. Specific targets of such research should be directed to overcoming technical challenges specific to Power-to-X applications. Furthermore more research is needed into the impacts of utilising Power-to-X derived feedstock chemicals (such as methanol) on the carbon footprint of the overall chemicals industry.

- **Develop national strategies** - Government should adopt a clear strategy for the scale and timing of Power-to-X and CCU deployments which is consistent with the emissions savings dictated by the Paris Agreement. Priority should be given to e-chemicals and fuels in order to maximise avoided emissions, reduce the need for fossil-fuel production and maximise the use of existing technologies. This could also include designating areas for Power-to-X clusters, combining access to renewable hydrogen and CO_2 can help reduce the need for extensive lengthy infrastructure such as pipelines. Denmark is one of few countries that has developed a clear government strategy for Power-to-X, outlining clear policy actions to support the technology (Danish Ministry of Climate, Energy and Utilities, 2021).

- **Regulatory and policy action to enable a Power-to-X and CCU market** – Early market opportunities for Power-to-X fuels and chemicals that are scalable, commercially-feasible and can deliver emissions reductions, should be identified and enabled. Demonstration projects should be supported through grant-funding at a number of different scales that produce a variety of different chemicals and fuels. In the mid-term, structural policies such as targeted power price subsidies for Power-to-X installations, mandates for Power-to-X product use as well as public procurement schemes could be considered.

- **Showcase the economic benefits of Power-to-X and CCU** – Both the European Commission and individual countries could assess the potential economic benefits of a Power-to-X sector, including technology and knowledge development and export, e-chemicals and e-fuel export potential, as well as growth in job creation. These assessments can help garner political and public support for Power-to-X and CCU technologies. Again, Denmark has commissioned such a study in 2021 (Ramboll, 2021).

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The Interreg 2 Sea's Programme

Interreg 2 Seas 2014-2020 is a European Territorial Cooperation Programme covering England, France, the Netherlands and Belgium (Flanders). The Programme is part-financed by the European Regional Development Fund (EDRF) and has a total of €241 million to co-finance projects in the 2014 - 2020 period. One of the specific objectives of the Programme is to increase the delivery of technological innovation applications in the region, for which the E2C project has received €4.6 million from the ERDF to boost innovation in the area of Power-to-X.

FINANCIAL SUPPORTERS