



**Deliverable 7.3:**  
**Qualitative evaluation report of socio-economic aspects concerning a roll-out of the specific developed electrocatalytic „simultaneous-factories” and a renewable ethylene oxide market in Europe**

# **CO<sub>2</sub>-based Electrosynthesis of Ethylene oXIDE**

**Grant Agreement Number: 768789**

**H2020-SPIRE-2017**

**DELIVERABLE REPORT**

## DOCUMENT INFORMATION

Deliverable Report	<b>D7.3: Qualitative evaluation report of socio-economic aspects concerning a roll-out of the specific developed electrocatalytic „simultaneous-factories” and a renewable ethylene oxide market in Europe</b>
Date	30.06.2021
Report prepared by	<b>Energieinstitut an der Johannes Kepler Universität Linz, Austria</b> Johannes Lindorfer, Valerie Rodin, Hans Böhm, Karin Fazeni-Fraisl
Project	<b>CO<sub>2</sub>EXIDE –</b> <b>CO<sub>2</sub>-based electrosynthesis of Ethylene oXIDE</b> Grant Agreement No.: 768789 (H2020-SPIRE-2017)
Project coordinator	<b>Fraunhofer-Gesellschaft zur Förderung</b> <b>der angewandten Forschung e.V., Straubing, Germany</b> Dr. Luciana Vieira, Dr. Arne Roth
Type	<b>Deliverable Report   Public</b>

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 768789. The authors would like to express their gratitude to the European Commission for this financial support.

# Table of Contents

<b>Abstract</b> .....	<b>6</b>
<b>1 Introduction</b> .....	<b>11</b>
1.1 Power-to-EthyleneOxide – sector coupling option	11
1.2 Global market perspective of ethylene oxide	12
1.3 Global market perspective of ethylene	15
1.4 Global hydrogen peroxide market	19
<b>2 Setting the scene on socio-economic aspects for a co2exide technology roll-out</b> .....	<b>20</b>
2.1 Competition for resources	21
2.1.1 Renewable electricity supply.....	22
2.1.2 Critical raw materials .....	23
2.2 Social acceptance in a PtX context	25
2.2.1 Market acceptance .....	26
2.2.2 Socio-political acceptance .....	28
2.2.3 Community acceptance .....	29
2.2.4 Spatial impact: landscape/land use & land use conflicts.....	30
2.2.5 Reliability/robustness.....	31
2.2.6 Risk assessment.....	32
2.2.7 Environmental and sustainability considerations .....	32
2.2.8 Embedding in the energy system.....	33
2.2.9 Distributive justice.....	33
2.3 Conclusion of socio-economic aspects	33
2.4 Biogenic CO <sub>2</sub> -Potential	35
<b>3 Objectives of the present study</b> .....	<b>37</b>
3.1 Study context	37
3.2 Application and reasons	37
3.3 Limitations in the usability from assumptions or methods	38
3.4 Power-to-X potential as interlinkage of the electricity and chemicals sector	38
3.4.1 GIS-based biogenic CO <sub>2</sub> potential analysis for Europe.....	40
3.4.2 Localization of large PV and wind farms.....	41
3.4.3 Consideration of existing refineries and ethylene pipelines .....	42
3.4.4 Matching CO <sub>2</sub> and RES sources.....	43
3.4.5 Limitations of the GIS-based analysis.....	45
<b>4 Techno-Economic Assessment</b> .....	<b>46</b>
4.1 Scope of the study	46
4.1.1 Fossil product benchmarks.....	46
4.1.2 Reference unit .....	47

4.1.3	Boundary conditions and application scenarios .....	48
4.1.3.1	Technology description CO2EXIDE .....	48
4.1.3.2	System boundaries .....	49
4.1.3.3	Generic case.....	50
4.1.3.4	Boundary Conditions - Case Studies .....	51
4.1.4	Analysis of RES availability and quality for the case studies .....	60
<b>4.2</b>	<b>Indicators and Methods TEA</b>	<b>63</b>
4.2.1	Literature research.....	63
4.2.2	Evaluated techno-economic indicators .....	63
4.2.2.1	Net present value (NPV).....	63
4.2.2.2	Payback time (PBT).....	64
4.2.2.3	Levelized Costs of Product (LCoP).....	64
4.2.3	Learning curve model CoLLeCT .....	65
<b>4.3</b>	<b>Input data inventory</b>	<b>67</b>
4.3.1	General input data .....	67
4.3.2	Technical parameters and assumptions .....	67
4.3.2.1	Electrochemical reactor unit (ERU) specifications .....	67
4.3.2.2	Ethylene enrichment unit (EEU) specifications .....	71
4.3.2.3	Ethylene epoxidation unit (EOU) specifications .....	72
4.3.2.4	Technical maturity of the overall system .....	72
4.3.3	Economic parameters and assumptions.....	73
4.3.3.1	CAPEX .....	75
4.3.3.2	OPEX.....	78
<b>4.4</b>	<b>Results and Discussion</b>	<b>81</b>
4.4.1	Base scenario .....	82
4.4.1.1	Composition of cost shares.....	82
4.4.1.2	Product sale revenues .....	85
4.4.1.3	Net present value (NPV) and payback time (PBT).....	85
4.4.1.4	Product generation costs (LCoP).....	87
4.4.2	Comparison of case studies .....	89
4.4.3	Uncertainty and sensitivity analysis .....	91
4.4.3.1	Sensitivity of plant profitability.....	91
4.4.3.2	Sensitivity of product costs .....	93
<b>5</b>	<b>Overall Conclusions and Recommendations</b> .....	<b>95</b>
5.1	General conclusions	95
5.2	Techno-economic conclusions	96
5.2.1	Limitations of the TEA.....	96

<b>References .....</b>	<b>98</b>
<b>Abbreviations.....</b>	<b>109</b>
<b>List of Figures.....</b>	<b>110</b>
<b>List of Tables .....</b>	<b>114</b>
<b>Acknowledgements.....</b>	<b>116</b>

## ABSTRACT

### Background and motivation

Carbon capture and utilization (CCU) technologies are a chance to reduce global carbon dioxide (CO<sub>2</sub>) emissions in order to support the energy and climate transition goals, whereas the focus is often on fossil CO<sub>2</sub> from conventional processes.[1,2] Hence, using green CO<sub>2</sub> from renewable sources like biomass allows to produce fully renewable products that could replace fossil-based materials in the long term [3] while opening up valorization opportunities of yet unused “waste” streams – finally adding to the development of a circular economy.

### ***Ethylene (Oxide) – High-value chemicals via electrocatalytic conversion***

Ethylene oxide (EO) is a highly important chemical in global industry [4], hence EO production via CO<sub>2</sub>-based electrochemical synthesis offers a promising pathway for CCU technologies. Today's State-Of-The-Art (SOTA) production processes usually base on direct oxidation of ethylene with oxygen in a catalytic reactor, yielding ethylene oxide, CO<sub>2</sub> and water (H<sub>2</sub>O) as products. [5]

In recent years, the focus of research activities, e.g. by Mobley et al. [6], shifted towards replacing the oxygen (O<sub>2</sub>) by CO<sub>2</sub> whereas the proposed process generates EO and carbon monoxide as products. The CO<sub>2</sub>EXIDE project aims to produce ethylene by electrocatalytic conversion of CO<sub>2</sub> and H<sub>2</sub>O, followed by the chemical conversion of the intermediates ethylene and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) to ethylene oxide. To ensure the sustainability of the produced EO, the main focus is on the use of already available biogenic CO<sub>2</sub> from industrial sources, which is defined as carbon neutral to the environment [5].

### ***Linking fluctuating renewable energies and the chemicals sector***

The transition towards a more sustainable and environmentally friendly energy system has to be accompanied by an increased installation of fluctuating renewable power sources such as wind power and photovoltaics. Apart from their large potential for reduction of greenhouse gas emissions in power generation, these technologies are characterized by a strongly fluctuating and intermittent power output. To enable increased installation of these renewable power sources and at the same time secure energy supply, energy storage and conversion technologies, such as Power-to-X (PtX) via electrolysis and CCU technologies, will be required. Consequently, the underlying processes should be compatible with excess energy or off-peak power and be feasible for decentralized application, as adjunct to wind parks or solar power.

### ***Biogenic CO<sub>2</sub> potential***

The total European biogenic (and fossil) CO<sub>2</sub> potential from stationary emission sources has been evaluated in CO<sub>2</sub>EXIDE WP2 and published by Rodin et al. [7]. In this study, focus is on the consideration of specific point sources of CO<sub>2</sub> in PtX and CCU case studies. The main sources are combustion of biomass, CO<sub>2</sub> from biogas upgrading to biomethane and industrial

fermentation processes, e.g. brewing processes and bioethanol production for biofuel application. CO<sub>2</sub> from the atmosphere (Direct Air Capture, DAC) and CO<sub>2</sub> from combustion processes demands for high technical effort to separate the CO<sub>2</sub> and was thus excluded from the evaluations in this work. DAC may still play an important role in the sequestration of CO<sub>2</sub> from diluted and dispersed sources in the long-term, as the technology has the potential for significant further development and optimization [8]. In this work the focus is on high-purity biogenic CO<sub>2</sub> point sources for PtX and CCU case studies such as biogas and biomethane plants as well as bioethanol fermentation plants.

## **Qualitative evaluation of techno- and socio-economic aspects concerning a CO<sub>2</sub>EXIDE roll-out**

The analyzed technology is a CCU and PtX technology that enables the utilization of (excess) electricity from volatile renewable energy resources, such as photovoltaics or wind power, for the valorization of CO<sub>2</sub> as carbon source for bulk chemicals production. The overall purpose is to produce renewable, sustainable bulk chemicals to substitute usually fossil-based chemicals. The targeted products ethylene (C<sub>2</sub>H<sub>4</sub>) and ethylene oxide (C<sub>2</sub>H<sub>4</sub>O) are crucial intermediates in the production chain of various materials and products. In the novel CO<sub>2</sub>EXIDE process, ethylene and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) are produced from water (H<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) via electrocatalytic reactions. In a second step, these two intermediates are used to synthesize ethylene oxide.

### ***GIS-based potential analysis***

For the impact and exploitation scenarios, a database of existing biomethane upgrading and bioethanol production plants in Europe was addressed and a database of biogenic CO<sub>2</sub> sources was generated. Additionally, existing large-scale PV and wind power installations as fluctuating potential energy suppliers were geographically localized. In a GIS-based approach, the two datasets were merged and utilized for technology roll-out and exploitation scenarios.

### ***Techno-economic scenarios***

For different scenarios, the investment cost of the total CCU-PtX-plant are estimated based on the main plant components as well as downstream processes, considering additional costs using common cost engineering factors. Beside the investment costs and the operational conditions, the costs for electricity and CO<sub>2</sub> as well as potential ETS remuneration play a role for the calculation of the production costs of chemicals from electrocatalytic conversion of CO<sub>2</sub> in a future technology roll-out scenario. The optimal plant configuration is analyzed from a techno-economic perspective by calculating the production costs for the CCU products for different plant configurations, energy sources and locations.

The analyzed technology is a CCU and PtX technology that enables the utilization of (excess) electricity from volatile renewable energy resources, such as photovoltaics or wind power, for the valorization of CO<sub>2</sub> as carbon source for chemicals production. The overall purpose is to produce renewable, sustainable bulk chemicals to substitute usually fossil-based chemicals.

The targeted products ethylene (C<sub>2</sub>H<sub>4</sub>) and ethylene oxide (C<sub>2</sub>H<sub>4</sub>O) are crucial intermediates in the production chain of various materials and products. In the novel CO<sub>2</sub>EXIDE process, ethylene and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) are produced from water (H<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) via an electrocatalytic reaction unit. In a second step, these two intermediates are used to synthesize ethylene oxide.

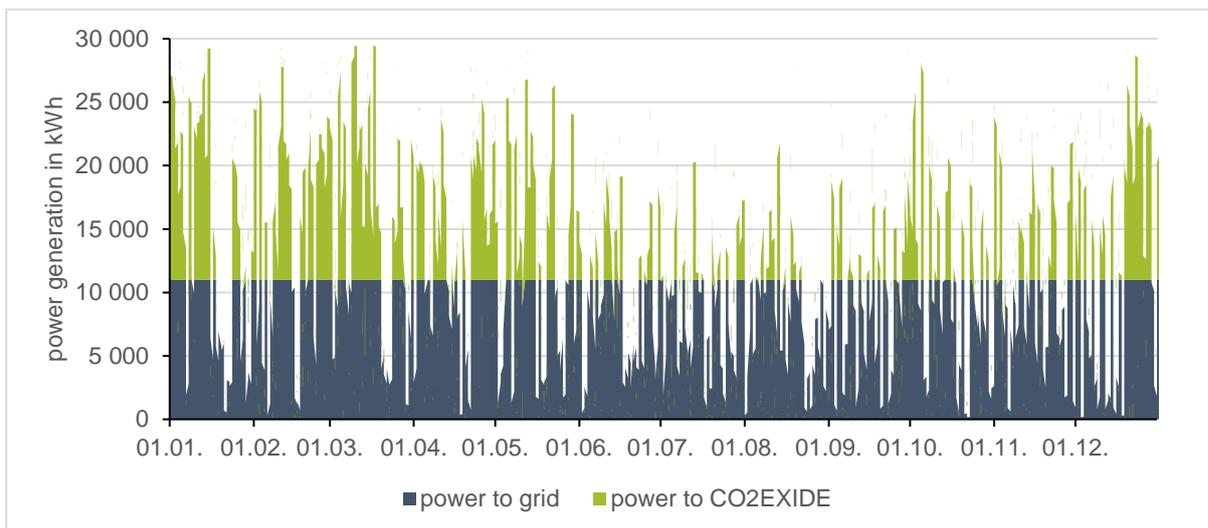
The study presents a techno-economic assessment (TEA) of this technological concept, evaluating the production cost of a commercial plant in 2030 as well as the net present value (NPV) based on today's fossil benchmark cost. For the assessment, the implementation at several locations in Europe, that offer favorable conditions (resources, consumers) for an industrial implementation of the process, is compared. Additionally, sensitivity analyses are conducted in order to evaluate the influence of energy and resource efficiencies of the production steps as well as resource and changes in the CO<sub>2</sub> compensation price. Finally, the process is compared to benchmarks, such as the existing conventional ethylene oxide production chains in Europe and other CCU/PtX technologies.

### ***Method and input data***

The techno-economic assessment is based on process simulations for performance and cost conditions referred to 2030, taking into account enhancements in technology development, specifically concerning the electrocatalytic reactor (produces ethylene and hydrogen peroxide as intermediates) and the subsequent epoxidation reactor (produces ethylene oxide from the intermediates). For estimating investment costs of major equipment, reference was made to commercially available, comparable technologies, such as PEM electrolyzers and large-scale column reactors. An in-house component-level learning-curve tool was used to generate as accurate as possible cost estimations as input for the TEA. [9] The operational cost base on the projected resource and energy demands and efficiencies for 2030, based on process simulations and experts' estimates. Additionally, common cost factors from literature for large chemical plants were taken into consideration, based on the technology readiness level of the CCU/PtX value chain. For the setting of the overall process, an average European location was chosen, considering the locally available resources and prices for CO<sub>2</sub>, water and electricity. More specifically, case studies for Austria, Germany and the UK were conducted in order to reflect local conditions. The predominant goal was to estimate the production cost of the main and side products and to gain knowledge about the most critical cost factors. This was done via sensitivity analysis. Furthermore, the theoretical NPV of the technology set-up was calculated, taking into considerations today's fossil product benchmark prices and linear depreciation. The overall method is based on generally accepted guidelines for CCU assessment. [10,11]

The optimal plant configuration was analyzed from a techno-economic perspective by calculating the production costs for ethylene oxide for "CO<sub>2</sub>EXIDE plants" with a different nominal power for different power sources for the electrocatalytic converter – photovoltaic power plants, wind farms and the electricity grid. Different use cases arise from the local/regional availability of renewable power from the investigated sources.

For the grid-connected CO<sub>2</sub>EXIDE plant, it is assumed that the power is supplied by an ideal power grid, presuming that the required power is available at all times. When operating the system with electricity from a wind farm or photovoltaic power plant, only the directly generated power can be used in the electrocatalytic converter. In the following Figure 0-1, typical electricity production characteristics from renewable sources are shown. Surpluses and peak loads not utilized by the electricity grid could therefore be used to operate a PtX process, such as a CO<sub>2</sub>EXIDE plant.



**Figure 0-1: Typical electricity production characteristic of a 30 MW wind farm. The power is divided in the share of grid feed-in and power for the CO<sub>2</sub>EXIDE plant (in this example the maximum grid feed-in is set to 11 MW, the surpluses are utilized by the electrocatalytic reactor unit with a nominal power of 75 MW). Source: Energieinstitut.**

Beside the investment costs for the plant and the operational conditions, the costs for electricity input play a major role for the calculation of the production costs for ethylene oxide in a future technology roll-out scenario (e.g., for 2050). Additionally, the cost for CO<sub>2</sub> capture, the carbon source for the electrocatalytic converter, have a wide range from about 5–350 €/t, depending on the CO<sub>2</sub> source and technology. In general, with the exception of direct air capture, the costs for CO<sub>2</sub> capture are roughly 50 €/t CO<sub>2</sub>. However, it must be mentioned that for CO<sub>2</sub> from biomethane upgrading and bioethanol, the costs can also be significantly lower, at about 5 €/t CO<sub>2</sub>. [7] This has been discussed extensively in Deliverable report 2.1.

### **Major results**

For the base scenario, taking CO<sub>2</sub> cost of 0 €/kg into consideration in the base case (due to integration of the process in an existing biomethane upgrading process) and electricity cost of ca. 36 €/MWh, the average production cost (levelized costs of product mix – ethylene oxide, hydrogen peroxide, methane, hydrogen, (LCoP)) range around 0.86 €/kg, which would be within the range of the different considered product selling prices - including side products such as methane, hydrogen and surplus hydrogen peroxide, i.e. are in the order of magnitude compared to other CCU/PtX value chains.[12,13] However, assuming that by-products cannot be

economically exploited and ethylene oxide is the only utilizable product, the related LCoP are at approx. 5.78 €/kg ethylene oxide, being significantly higher compared to fossil alternatives that have a selling price around 1.5 €/kg. In order to make the sustainable green ethylene oxide competitive with fossil alternatives, the sensitivity analysis shows that energy efficiency, electricity prices and CAPEX are the most relevant factors. Regarding the latter, increased plant life is a crucial factor as well. Resource prices and assumed ETS remuneration based on GWP savings influence the economic performance as well, but way less than previously named factors.

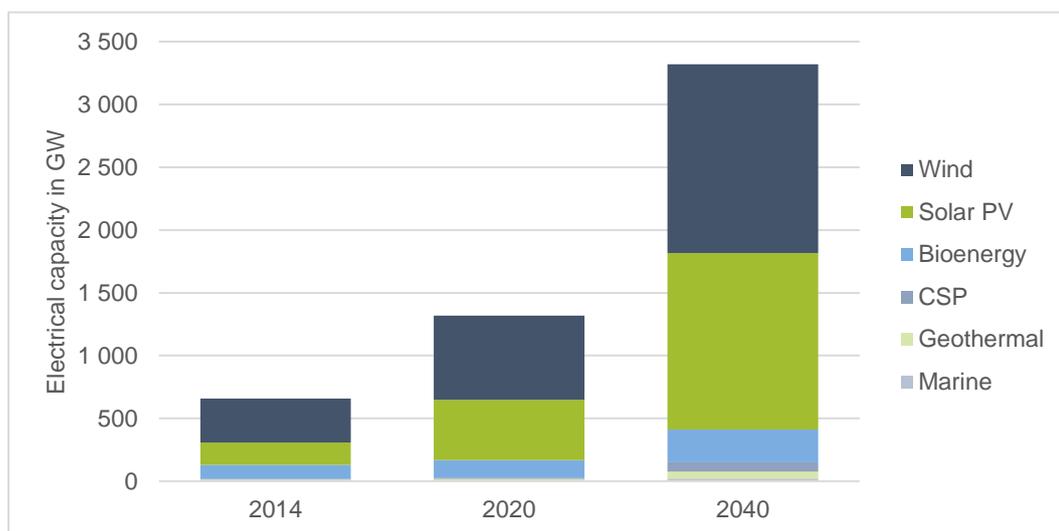
### ***Limitations***

As the analyzed core technology has a low Technology Readiness Level (TRL) of 3-4, only a simplified equipment list is available for the TEA. Furthermore, the energy efficiency of the process is assumed to be much higher when the technology reaches a TRL of 7-9 compared to the current state. This was partly taken into consideration via the scale up to the reference year 2030 (see section 4). The first limitation was encountered by adapting known technical and economic conditions of related technologies, for which cost and efficiency data as well as learning curves are available. Furthermore, sensitivity analyses were conducted to show a realistic range of energy demand and cost development. Finally, the focus in the TEA itself was laid on the main process rather than supply chains or product sales in order to rule out several variables that influence the overall result significantly (Cradle-to-Gate scenario). However, the case study was designed in a way that local resources with short transport routes are available. Also, product marketing was assumed being possible in an acceptable geographical range.

# 1 INTRODUCTION

## 1.1 Power-to-EthyleneOxide – sector coupling option

Striving for a more sustainable and environmentally friendly energy system has to be accompanied by an increased installation of fluctuating renewable power sources such as wind power and photovoltaics. Apart from their large potential for reduction of greenhouse gas emissions in power generation, these technologies are characterized by a strongly fluctuating and intermittent power output. According to the IEA (International Energy Agency), by 2040, the European Union has more than 740 GW of renewables capacity in operation, of which almost 70 % is intermittent. Wind power takes over as the largest source of electricity supply shortly after 2030 and the high share of variable renewables overall places the EU at the forefront of the challenge to tackle large-scale integration of fluctuating renewables. Worldwide, renewables provide nearly 60 % of power capacity additions in the IEA scenarios and the following figure shows the expected future capacity of fluctuating renewable power sources in the world, which provide high potential for synergistic interlinkage of the electricity and chemicals sector with the CO<sub>2</sub>EXIDE technology (sector coupling).



**Figure 1-1: Prognosis of future installed power of fluctuating renewable power sources.**

**Source: Energieinstitut, data based on IEA (2018) World Energy Outlook 2018. [14]**

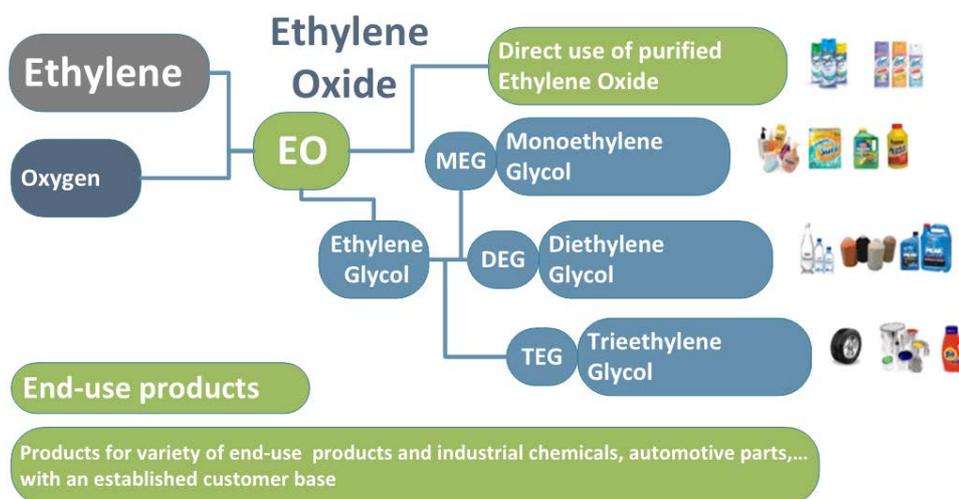
To enable increased installation of these renewable power sources and at the same time secure energy supply, energy storage and conversion technologies, such as Power-to-X technologies, will be required.

A large number of carbon capture and utilization (CCU) research projects aim at the development of technologies for the conversion of (bio-based) carbon dioxide (CO<sub>2</sub>) into industrially relevant chemicals. In line with the energy transition, the underlying electrochemical processes need to be suitable for the utilization of excess energy or off-peak power and feasible for decentralized application, as adjunct to wind parks or solar power. To ensure the climate neutrality of CCU products, the usage of biogenic CO<sub>2</sub> is preferred. Based on a recycling of CO<sub>2</sub> and

by primarily using renewable energy and water, the CCU technologies combine a modular nature for the feasibility of a decentralized application with targeting high energy and material efficiency. This work covers the aspect of the theoretical potential and limitations of green carbon dioxide sources for Power-to-X (PtX) technologies, driven by renewable surplus electricity.

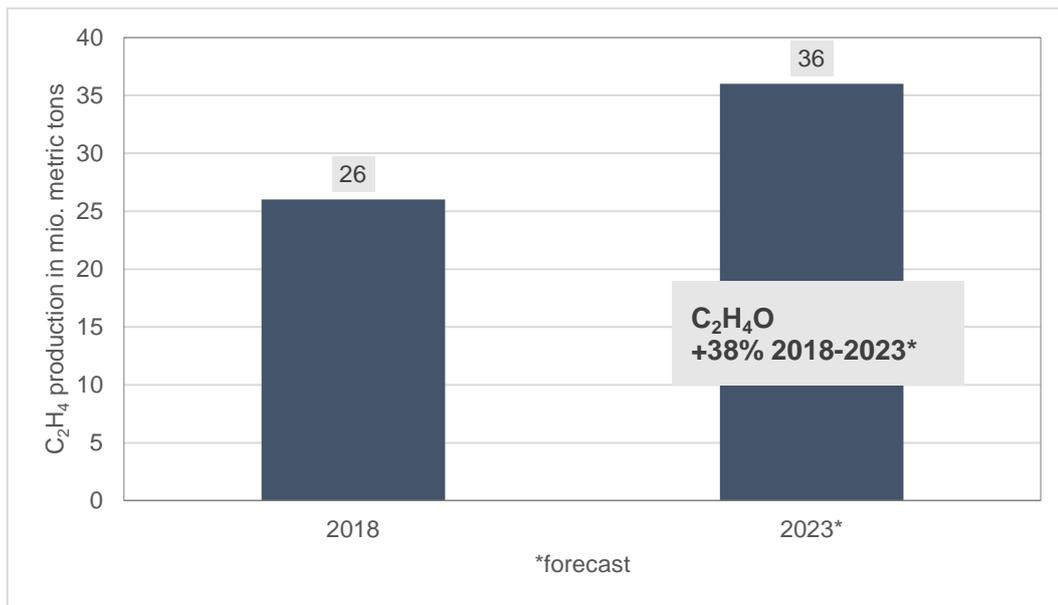
## 1.2 Global market perspective of ethylene oxide

Ethylene Oxide (also known as Oxirane and Epoxyethane) is one of the most versatile chemical intermediates. It is used mainly in the production of ethylene glycols, surfactants, ethanolamines and glycol ethers. Ethylene oxide production on industrial scale is carried out, mainly, by the direct oxidation of ethylene. The CO<sub>2</sub>-based, renewable intermediates ethylene and hydrogen peroxide and the product ethylene oxide provide the vital option to substitute the fossil-based routes.



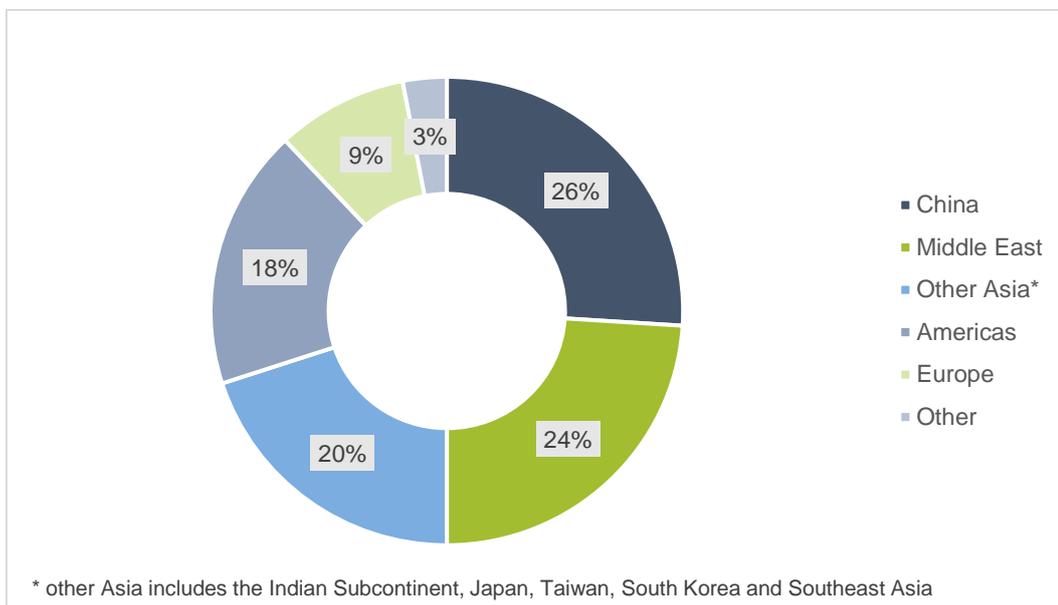
**Figure 1-2 Overview of Ethylene Oxide Market Segments: Source: Energieinstitut based on IHS Markit Chemical Economics Handbook, Ethylene Oxide, 2020 [15]**

Ethylene oxide is a strained, reactive molecule produced on a vast scale as a plastics precursor. The current method of synthesis involves the direct reaction of ethylene and oxygen at high temperature. Ethylene oxide is also used directly in the gaseous form as a fumigant and sterilizing agent. The production capacity of ethylene oxide worldwide is expected to expand by ten million metric tons in five years, from some 26 million metric tons in 2018, reaching approximately 36 million metric tons in 2023.



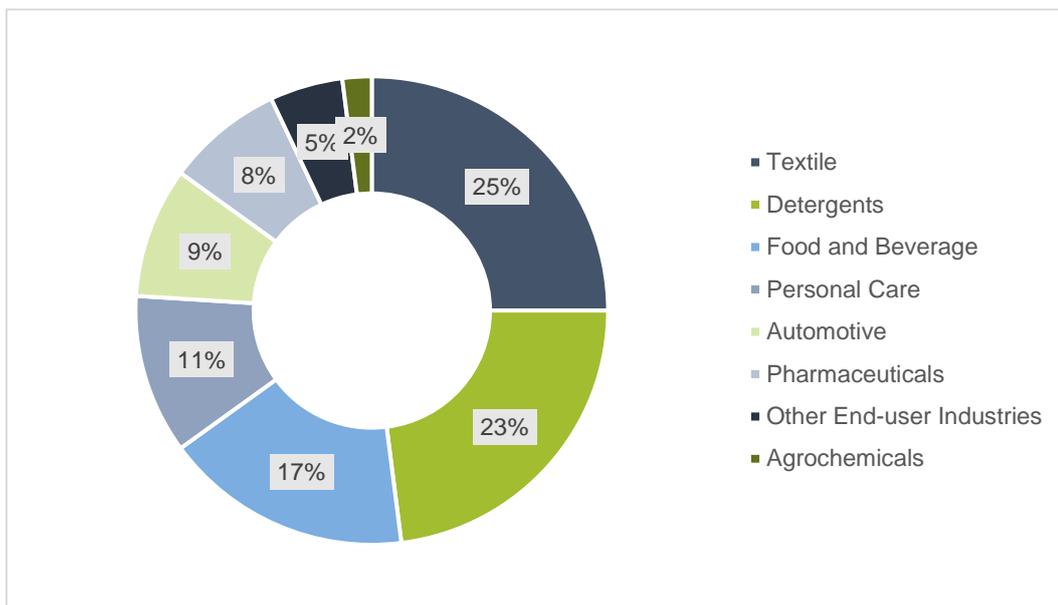
**Figure 1-3: Production capacity of ethylene oxide worldwide in 2018 and 2023 (in million metric tons): Source: Energieinstitut based on globaldata.com (2020)**

Ethylene oxide is a dangerous chemical to transport, therefore it has a region-based focus and Asia-pacific region dominates the ethylene oxide market currently. China accounts for the major consumption of ethylene oxide and its derivatives in the Asia-Pacific region. From the European perspective it is to highlight that we are facing growing markets with growing dependencies.



**Figure 1-4. Distribution of worldwide consumption of ethylene oxide (2020) Source: Energieinstitut based on [15] and [16].**

Actually, the global ethylene oxide & ethylene glycol market is driven by growing demand from PET bottle manufacturers and the textiles industry, and a growing global demand for antifreeze in the automotive industry.

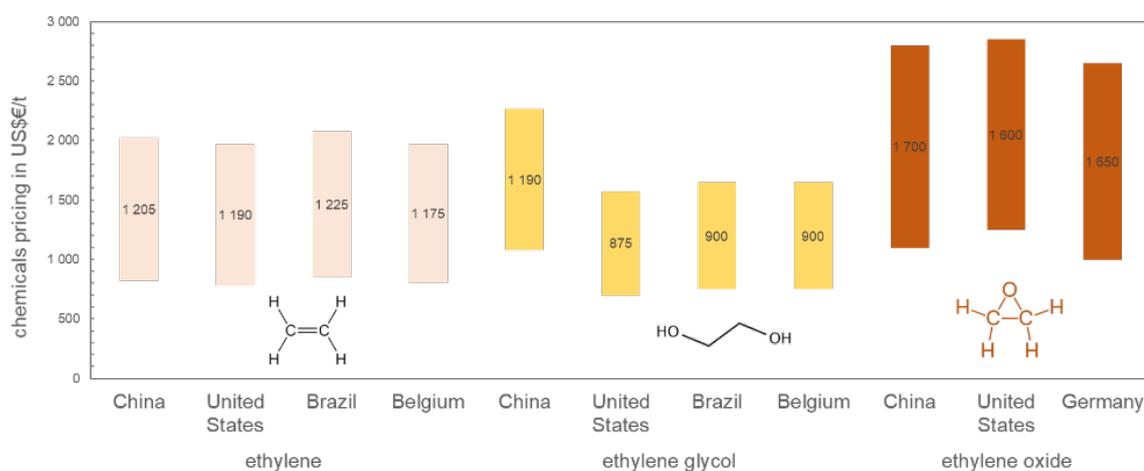


**Figure 1-5: World end-user industry of ethylene oxide (2020). Source: Energieinstitut based on [15] and [16].**

Today's State-Of-The-Art (SOTA) production processes usually base on direct oxidation of ethylene with oxygen and a recycle gas in a catalytic reactor, the products are ethylene oxide, CO<sub>2</sub> and water (H<sub>2</sub>O). Production technologies for ethylene oxide plants based on the direct oxidation process are licensed by large industries like Shell. Due to improved catalysts and production technology, large plants with capacities of up to 400 000 t/a can be built. The technologies are very similar and mainly differ on the use of air or pure oxygen for oxidation. In both cases, Ag-based catalysts are used and, due to thermodynamics, a lot of heat has to be dissipated, and CO<sub>2</sub> is generated as unwanted byproduct and carbon leak. During the absorption stage of the production process, a stream of gas comprising of between 30-100 % CO<sub>2</sub> by volume is removed and vented. The data on the rates of CO<sub>2</sub> generation in the production of ethylene oxide are extremely limited. The basic process is operated at a ratio of 6:2 for ethylene oxide:CO<sub>2</sub>, i.e., which means that it produces about three times as much ethylene oxide as CO<sub>2</sub>. Despite the constant catalyst improvements over the years in the conventional ethylene oxide process, the approximately 15 % burning of ethylene feedstock represents a loss of roughly 1.9 billion USD/year in feedstock based on the 2016 ethylene oxide production capacity (approx. 26.4 million t/year) and the 2016 ethylene price (67.1 US-cents/kg). In addition, the CO<sub>2</sub> by-product (approx. 9.3 million t/year) poses strong environmental concern as a greenhouse gas.

As the direct oxidation of olefins is only possible for ethylene, the newest available technology, which has been realized in a large-scale plant, is the propylene oxidation performed with hydrogen peroxide in a HPPO-process (Hydrogen Peroxide Propylene Oxide). The hydrogen

peroxide for the HPPO process is an aqueous solution produced in a hydrogen peroxide plant located at the same production site as the HPPO plant, to reduce transport costs for large volumes of hydrogen peroxide. The heterogeneous catalyst used in this reaction is a titanium silicate catalyst. A propylene excess is required to obtain a PO yield of about 95% referred to propene, while hydrogen peroxide is completely converted. The reaction conditions are relatively mild: single liquid phase, temperature range between 30 and 80 °C, pressure range between 10 and 30 bar. The titanium zeolite catalyst has also been formulated so that it can be used in a fixed-bed reactor system, which enables good conversion and selectivity characteristics, along with a suitable catalyst lifetime. According to a market report published by Transparency Market Research [17], the global ethylene oxide market is dominated by Asia/Pacific, North America and Western Europe, being mature markets and expected to grow only at a sluggish rate. Average market prices for ethylene, ethylene oxide and ethylene glycol are compiled in the following Figure 1-6 for benchmarking the optimal CO<sub>2</sub>EXIDE plant configuration.

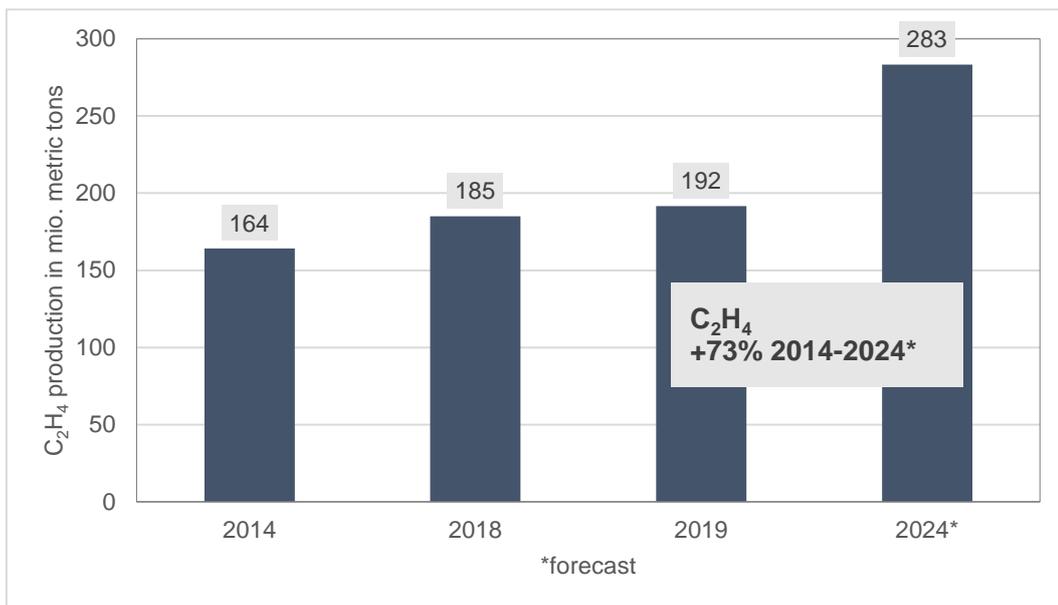


**Figure 1-6: Market prices for ethylene, ethylene oxide & ethylene glycol (4-year-average).**  
**Source: Energieinstitut based on data from [18] - chemicals pricing data & production cost reports.**

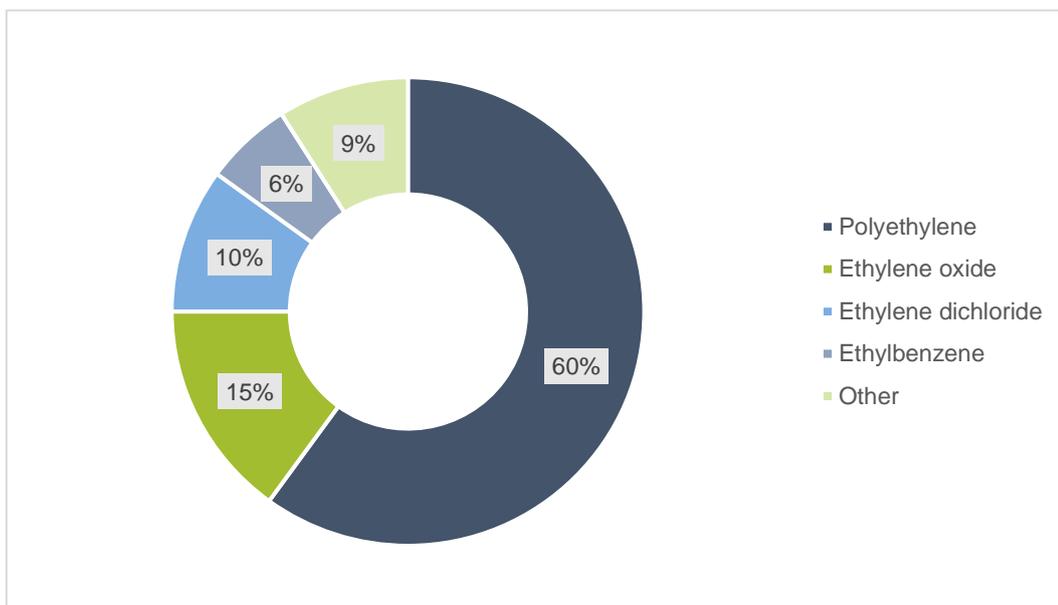
### 1.3 Global market perspective of ethylene

Ethylene, the precursor of ethylene oxide, is one of the most-produced petrochemical building block. The global demand for ethylene in 2015 is estimated at 143 million tons. By far the predominant manufacturing route to ethylene is steam cracking gaseous feedstock (ethane, propane, or butane) or liquid feedstock (naphtha or gas oil). This noncatalytic cracking process is run at very high temperatures, up to 850 °C with significant greenhouse gas emissions and energy demand. Different production options for „green“ ethylene and ethylene oxide have recently been investigated. Electrochemical routes, as developed in CO<sub>2</sub>EXIDE, are at the lowest level of maturity, but, if successfully developed and implemented, promise radical innovation in the chemicals production sector.

The production capacity of ubiquitous hydrocarbon ethylene had a global production capacity amounting to 191.5 million metric tons in 2019. By 2024 it is forecast that this will increase to 283 million metric tons.



**Figure 1-7: Production capacity of ethylene worldwide from 2014 projected to 2024 (in million metric tons). Source: Energieinstitut based on [19].**

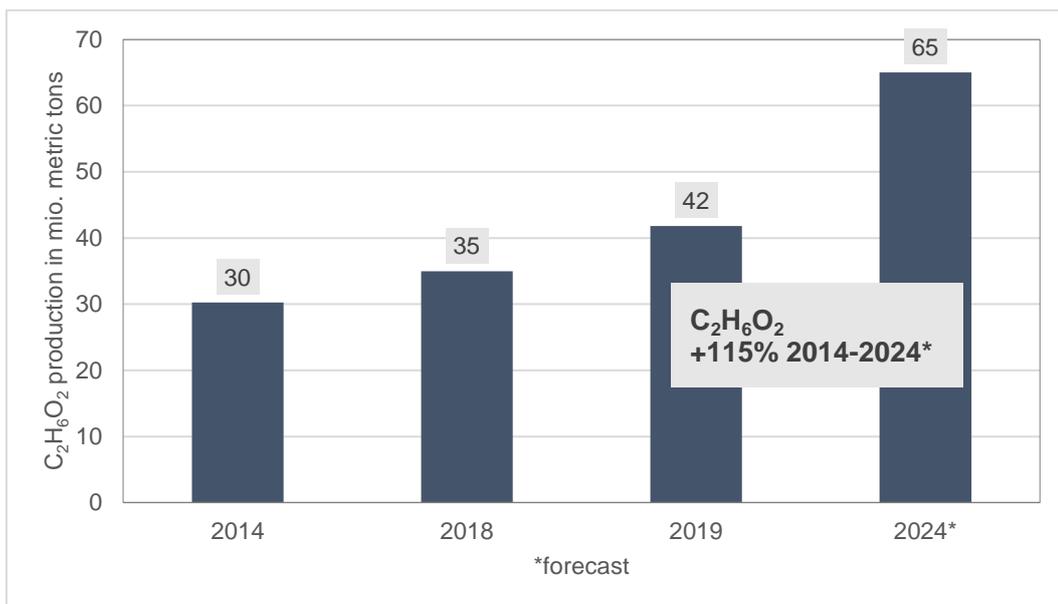


**Figure 1-8: Global demand distribution in 2015 for products derived from ethylene, broken down by end product. Source: Energieinstitut based on [20].**

Ethylene glycols (mono-, di-, triethylene glycol) constitute by far the single-largest outlet for ethylene oxide, accounting for over 80% of the ethylene oxide market in 2020. All those intermediates consequently imply high growth rates. Besides these positive implications for sustainable projects in this field, the prices really dropped in the last months based on the low

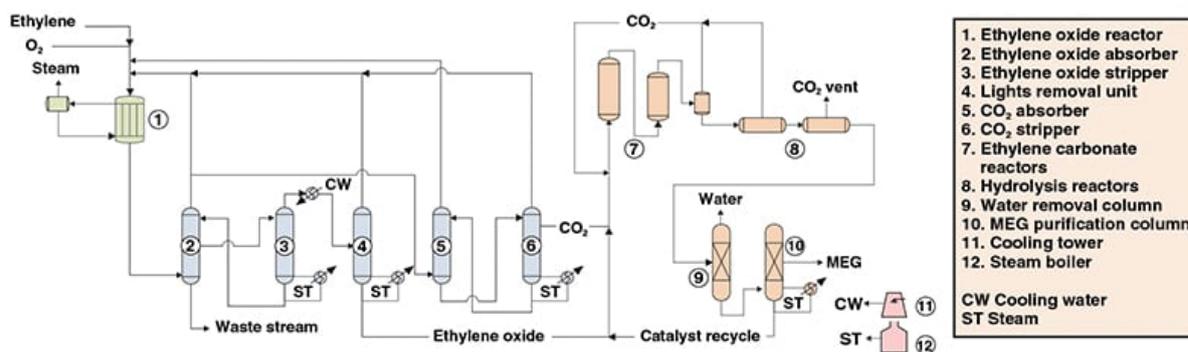
demand as an effect of the global pandemic, but a recovery has already started, especially in Asia.

Monoethylene glycol (MEG), also known as ethylene glycol (EG) or simply glycol, is a diol mainly used for the production of polyester fibers and polyethylene terephthalate (PET) resins. It is also used in antifreeze applications and in pharmaceuticals and cosmetics. MEG is conventionally produced through the hydrolysis of ethylene oxide. Ethylene glycol is expected to have a global production capacity amounting to more than 65 million metric tons in 2024. That is a fairly significant increase of the world's production capacity of ethylene glycol in 2019, which was nearly 42 million metric tons.



**Figure 1-9: Production capacity of ethylene glycol worldwide from 2014 to 2024 (in million metric tons). Source: Energieinstitut based on [21].**

Figure 1-10 depicts MEG production from ethylene via a process similar to the OMEGA catalytic process from Shell Global Solutions [22]. In the described process, MEG is produced via ethylene oxide, which is manufactured in an integrated plant utilizing Shell ethylene oxide technology. An important feature of the process is the negligible production of diethylene glycol (DEG) and triethylene glycol (TEG), which occur as byproducts in other ethylene glycol production processes.



**Figure 1-10: Monoethylene glycol (MEG) production, according to a process similar to the Shell OMEGA process. Source: [23]**

**Ethylene oxide production.** Ethylene and oxygen are fed to a multi-tubular reactor, forming ethylene oxide. This exothermic reaction, conducted in fixed beds in the reactor tubes, occurs in the gaseous phase with the use of a silver catalyst supported on alumina. Steam is generated by the heat of reaction.

**Ethylene oxide recovery.** The reactor product stream is fed to the ethylene oxide absorber for light fractions removal by water quenching. Part of this gaseous overhead stream is recycled to the reactor, while the other part is sent to a carbon-dioxide-removal unit composed of an absorber and a stripper. In this unit, CO<sub>2</sub> is separated to be used in ethylene carbonate production.

A diluted ethylene oxide stream removed from the absorber is fed to the ethylene oxide stripper, where it is concentrated and recovered in the overheads. The crude ethylene oxide stream is condensed. Residual light gases are recovered from it and recycled to the reactor. The resulting ethylene oxide stream is directed to the next section.

**Ethylene glycol production and purification.** Ethylene oxide is reacted with CO<sub>2</sub>, forming ethylene carbonate, which is then hydrolyzed to form MEG and CO<sub>2</sub>. Both reactions are carried out in the liquid phase using homogeneous catalysts.

CO<sub>2</sub> streams from the reaction steps are recycled to the ethylene carbonate reactor. MEG is purified in two distillation columns where water is removed, leading to the final MEG product. The catalyst is separated and recycled to the ethylene carbonate reactors.

**Table 1-1: Literature values on energy and material flows of fossil based ethylene oxide and MEG production in Europe.**

Parameter	Unit	Ethylene Oxide (EO)	Monoethylene glycol (MEG)	Source
Load factor EU-28	%	86	83	[24]
<b>Inputs</b>				
Ethylene	t/t EO	0.70 – 0.85		[25]
Oxygen	t/t EO	0.75 – 1.1		
Ethylene oxide	t/t MEG		0.789	[25]
			0.51 t ethylene/t MEG	
<b>Energy consumption</b>				
Electricity	GJ/t	1.2	0.2 – 0.3	[24]
Fuel	GJ/t		0.75 – 1.1	[24]
Steam	GJ/t		3.6 - 8	

As EO is a highly important chemical in global industry, ethylene oxide production via CO<sub>2</sub>-based electrochemical synthesis offers a promising pathway for CCU. In recent years, the focus of research activities, e.g., by Mobley et al. [6], shifted towards replacing the oxygen (O<sub>2</sub>) by CO<sub>2</sub>. The CO<sub>2</sub>EXIDE project aims to produce ethylene by electrocatalytic conversion of CO<sub>2</sub> and water, followed by the chemical conversion of those intermediates to ethylene oxide. To ensure the sustainability of the produced ethylene oxide, the main focus lies on the use of already available biogenic CO<sub>2</sub> from industrial sources, which is defined as carbon neutral to the environment [5].

#### 1.4 Global hydrogen peroxide market

The global \$2.44 billion hydrogen peroxide market is currently satisfied through a well-established two-step anthraquinone route known as the Riedl–Pfleiderer process. Said process is used for the production of over 90 % of the world's hydrogen peroxide. [26] This energy-intensive process entails the requirement of fossil-fuel-sourced hydrogen, harmful organic solvents, and expensive Pd catalysts. Hence, to benefit from economies of scale, most hydrogen peroxide production facilities are large-scale and centralized to allow for cheaper levelized cost of peroxide production. [26] This, however, brings in additional safety issues and costs during transport and storage as concentrated hydrogen peroxide is hazardous. In contrast, renewable hydrogen peroxide generation using electrolysis will be beneficial as it would allow on-site decentralized production.

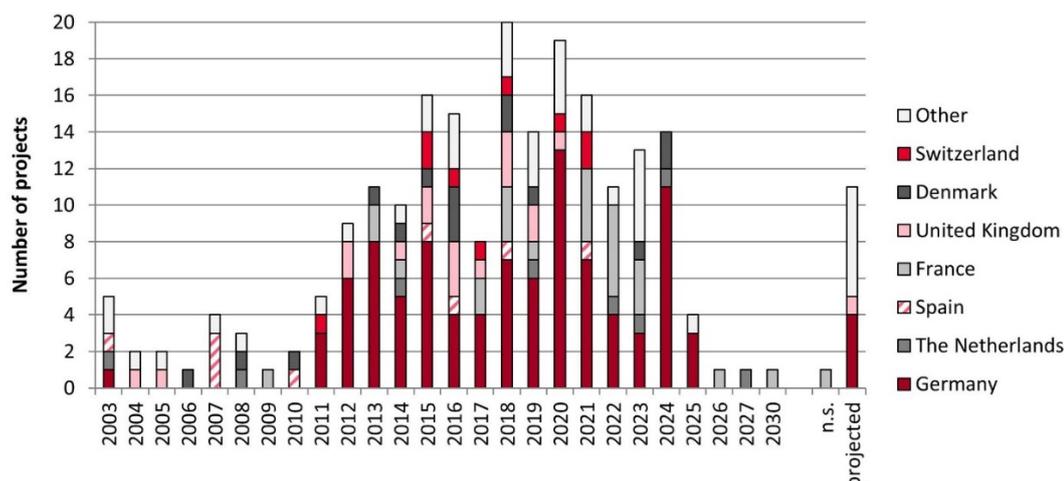
The potential economic benefits of renewable Power-to-X is increasingly well-recognized by governments and industry, notably by companies engaged in the fossil fuel and its derivate industries who intensify their global decarbonization efforts. A testimony to this is the sheer number of PtX demonstration plants being trialed worldwide: as of 2019, over 190 such plants

are in operation to establish potential feasibility and scale-up of these various technologies. [27]

## 2 SETTING THE SCENE ON SOCIO-ECONOMIC ASPECTS FOR A CO<sub>2</sub>EXIDE TECHNOLOGY ROLL-OUT

The technological approach developed in the CO<sub>2</sub>EXIDE project belongs to the technology cluster of so-called Power-to-X (PtX) approaches as it uses renewable electricity and biogenic CO<sub>2</sub> for the production of ethylene oxide (C<sub>2</sub>H<sub>4</sub>O). The umbrella term Power-to-X subsumes technologies which use electricity to generate energy carriers or chemicals. [28] Accordingly it is viable to draw conclusions for the CO<sub>2</sub>EXIDE technology based on the socio-technical implications found in literature for PtX technologies in general. The difference of the pathway developed in CO<sub>2</sub>EXIDE compared to many other PtX pathways is that CO<sub>2</sub>EXIDE directly converts CO<sub>2</sub> and water into the chemical ethylene oxide through direct electrocatalytic reduction of CO<sub>2</sub>, i.e. without the intermediate step of water electrolysis for hydrogen production and downstream hydrogenation of CO<sub>2</sub>. Compared to the widely studied PtX approaches applying the CO<sub>2</sub> hydrogenation, the direct reduction of CO<sub>2</sub> is still less advanced. [29] Nevertheless, the challenges and opportunities of the two major technology pathways are comparable.

On the one hand, Power-to-X (PtX) is a promising option for the medium- to long-term storage of electrical energy, where these technologies will play a key role for the energy system, with an increasing expansion of the fluctuating regenerative lead energy sources wind and solar radiation as a central flexibility option. On the other hand PtX is an important contributor to the decarbonization of industry and the mobility sector through the provision of hydrogen and hydrocarbons. [30] There has been a very dynamic development concerning the deployment of PtX projects in Europe in recent years, and is further projected. As shown in Figure 2-1, the deployment of PtX projects has started around 2011 with a peak in 2018 and 2020 so far. Germany, France and the Netherlands appear as front runners in that field in Europe.



**Figure 2-1: Historical development of PtX projects in Europe and outlook on projected projects.**  
**Source: Wulf et al. [31]**

Although there is a strong drive towards realizing PtX projects, there is still a lack of PtX facilities in industrial scale as there is still a lack of economic feasibility compared to other technological routes producing energy carriers, fuels and chemicals. In general the following overarching challenges for PtX technology development and roll-out are identified [28]:

- Further research on technology routes in order to facilitate a numbering up and up-scaling as well as an increase in process efficiency. Together with process integration and serial production of components a cost decrease can be achieved.
- Internalizing external costs (e.g. through environmental damage) on fossil energy carriers and fossil derived chemicals will improve price competitiveness of innovative PtX products.
- An adaption of regulatory boundaries by introducing an accounting for system benefits (e.g. facilitating renewable energy integration, carbon cycling, etc...)
- Techno-economics of the CO<sub>2</sub>EXIDE scenarios and potential pathways (see also sections 4.4 and 5)
- Strategies and trajectories for streamlined PtX technology deployment

Additionally, further challenges concerning the deployment of PtX technologies arise from resource competition as well as public and market acceptance. These aspects are addressed in detail in the following sub-chapters.

## 2.1 Competition for resources

PtX technologies utilizing CO<sub>2</sub> require two major production factors, which crucially influence their economic viability:

- an economically advantageous and viable source of CO<sub>2</sub>
- an economically competitive and sustainable source of electricity. [30]

Especially electricity costs determine the production costs of PtX products, besides the CAPEX. Further information on the economic feasibility of the CO<sub>2</sub>EXIDE pathway can be found in sections 4.4 and 5. Increasing electricity prices are a major threat to technology deployment. [32] Besides the economic issue related to market price for electricity and the capture costs of CO<sub>2</sub>, the overall availability of biogenic CO<sub>2</sub> and renewable electricity may represent a future constraint too for the deployment of PtX technologies. A detailed description of CO<sub>2</sub> sources and availability has already been given in CO<sub>2</sub>EXIDE report D2.1. Accordingly, this section only discusses the implications of the future availability of renewable electricity for PtX, respectively the CO<sub>2</sub>EXIDE approach. Another relevant aspect is the availability of raw materials for technology components in the long term. The CO<sub>2</sub>EXIDE technology in the context also competes with other PtX technology pathways.

### **2.1.1 Renewable electricity supply**

In the view of the European Green Deal, which aims to achieve climate neutrality by 2050 through a deep decarbonization of all sectors of the economy, the electricity used for PtX pathways and hydrogen production should majorly come from renewable resources. [33] The production of renewable hydrogen based on renewable electricity is one of the EU's priorities for setting up a decarbonized economy. [34] For future energy system integration, a core strategy will be the electrification of end-use sectors (heat pumps in buildings, electric vehicles in transport or electric furnaces in certain industries) using renewable electricity to facilitate decarbonization. [33] Accordingly, renewable electricity will play a key role in decarbonization and is therefore one of the most important resources for a future energy system.

In this context the major question is about the future availability of renewable electricity for meeting the demand of all sectors. Based on the technical potential of renewable electricity production, 88 out of 109 NUTS-2<sup>1</sup> region show excess electricity potential and 84 have an excess electricity potential of over 50 % [35], which indicates that there will be an increased need for strategies to utilize or store this excess electricity. According to Hydrogen Roadmap Europe, annual hydrogen production should increase until 2050 to approx. 2,250 TWh [36] which are approx. 68 Mt. This is an increase by a factor of ~7 from today's production levels. Assuming an electrolyzer energy demand of 55.62 kWh/kg H<sub>2</sub> the renewable electricity demand for hydrogen (H<sub>2</sub>) production in 2050 can be estimated to be approx. 3,200 TWh. The major uncertainty today lies in estimating the future sectoral electricity demand. The EU's Energy Roadmap 2050 estimates the future electricity demand to be between 3,200 TWh and

---

<sup>1</sup> NUTS = *Nomenclature des unités territoriales statistiques*. NUTS-2 resolution gives information on basic regions, e.g. for the application of regional policies and includes medium sized regions as well as cities with millions of inhabitants.

4,100 TWh in 2050. [37] A study conducted by Fraunhofer ISI comes to comparable results of 3,400 TWh – 4,300 TWh in 2050. [38] In a newer calculation of the German Umweltbundesamt (German Environment Agency), the electricity demand in the EU is estimated to >10,000 TWh in 2050. Thereof 5,300 TWh – 6,300 TWh are estimated to be used for Power-to-Gas and PtX applications. The renewable electricity production in the year 2050 is estimated with ~14,450 TWh. [39] These estimations clearly show that the availability of electricity as a resource for PtX strongly depend on the development of renewable electricity production capacities in Europe.

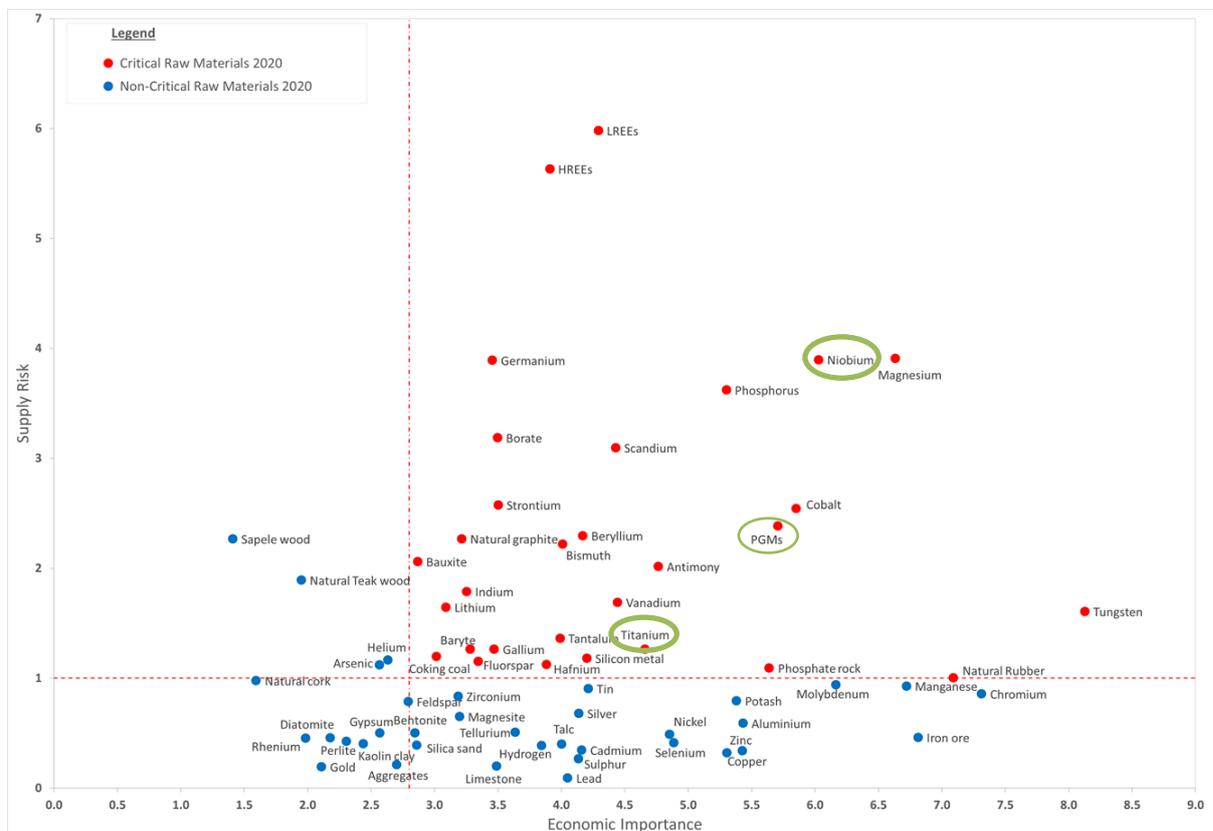
As production costs for PtX products are reported to be comparably low in other regions than Europe, regions such as North Africa and the Middle East become interesting for a future PtX technology deployment. [40] When it comes to renewable electricity supply, the production potentials in North Africa and the Middle East are named as additional potential for a future carbon neutral energy supply of the European Union. These regions are seen as promising production regions for renewable hydrogen using electrolysis technology. [41] Challenges in this context in the desert regions are water supply and transport options as well the availability of CO<sub>2</sub> sources (except direct air capture). [39] The challenge is that locations with a high renewable electricity potential are not necessarily regions with good water supply or infrastructure availability. [42] So, a regional and global scale PtX technology deployment is not only a question of resource availability but also of resource distribution. Currently there are still several uncertainties concerning the future development of a global PtX deployment. These uncertainties are strongly interconnected with geo-political circumstances and governance in general: Industrialized countries need to weigh the options of large-scale imports compared to the costs of domestically produced low carbon products.

Countries with abundant renewable electricity resources may also decide whether to export the PtX products or attract demanding industries to settle directly on-site. If the path of large-scale imports is chosen, this of course creates new dependencies. Nevertheless, one of the key differences of the current situation with oil and gas supply is that hydrogen trade will be less asymmetric as it is possible to produce hydrogen nearly everywhere in the world and the production is not dependent on existing geological formations. Accordingly, many countries can become prosumers. In future bilateral or multilateral cooperation can be expected for the establishment of resource protection. For future economic competitiveness and energy independency it is important to have control over the value chains of low-carbon energy technologies. Especially early movers will be able to sell technology and become technology leaders. [43]

### **2.1.2 Critical raw materials**

Besides renewable electricity it is a fact that increasing hydrogen production capacities in Europe also demand certain critical raw materials for, e.g., electrolyzer production. Iridium, tantalum and platinum are for example raw materials which are incorporated into an electrolyzer. In case of CO<sub>2</sub>EXIDE, the electrolysis cell's electrode material (anode) was made of titanium plates coated with IrO<sub>2</sub> or niobium plates which are coated with boron doped diamond, for the

cathode copper coated H3C2 GDL was used. So, three critical raw materials are applied for cell manufacturing: titanium, niobium and iridium. Also, the latter belongs to the “Platinum Group Materials” and this group has been identified to be among the critical raw material assessment in 2020 done by the JRC. [44] Figure 2-2 gives an overview of those raw materials found to be critical in 2020. A raw material is defined to be critical if the supply risk is rated at 1 or above and the economic importance is rated at 2.8 or above. [44]



**Figure 2-2: Raw materials identified to be critical. Source: European Commission (2020) [44]**

It is a fact that the demand of critical raw materials will rise in future due to the deployment of new technologies (e.g. fuel cells, batteries, electrolyzers, ICT, etc...). [44] This clearly underpins the potential pitfalls concerning resource availability when it comes to deploying PtX technologies. In this context the CO<sub>2</sub> electrolysis cell competes with water electrolysis for hydrogen production in terms of raw materials.

Europe has to import critical raw materials as well as rare earth elements, as it has only minor domestic production. The key players are, e.g., China for rare earth elements and titanium, South Africa for iridium and Brazil for niobium. It is expected that the supply bottlenecks for critical raw materials and rare earth elements for renewable energy technologies in Europe will increase in future. About 92% of the iridium imported in the EU comes from South Africa, 45 % of the titanium is imported from China and 85 % of the niobium is imported from Brazil. [44]

As many critical raw materials come from politically unstable or “sensitive” countries, Europe’s resource supply is also somehow dependent on geo-political conditions which can be classified

as a risk. Besides the creation of economic dependencies due to the EU's demand of critical raw materials, the rising competition will further intensify problems with human right violations, child labor and environmental degradation. [45] The Governance Indicators published regularly by the Worldbank clearly indicate that, for instance, South Africa and China – two major suppliers for critical raw materials – lack political stability, government effectiveness, regulatory quality, rule of law and control of corruption. [46] Accordingly, diverse measures are needed to tackle this challenge: increase R&D for improving material efficiency and substituting materials, boosting recycling business and circular economy, diversifying material supply, sustaining investments for new mining and refining activities, etc.[47]

## 2.2 Social acceptance in a PtX context

Before starting with the relevant aspects of public, social and market acceptance relevant for the deployment of PtX technologies and further the CO<sub>2</sub>EXIDE technology pathway, the different concepts of acceptance are clarified. Social acceptance encompasses three pillars: socio-political acceptance, market acceptance and community acceptance.

The socio-political acceptance is the broadest understanding of acceptance and means the societal acceptance. While people may agree with an overall policy (e.g., deployment of renewables), but they may not agree with the measure (e.g., local deployment of renewable energy technologies) when it comes to local implementation. Accordingly, the concept of socio-political acceptance can lead to misleading interpretation and outcomes and interpretations depend on the investigated level (global, national, regional, local). Community acceptance refers to the local level and therefore to the specific acceptance of decisions and renewable energy technology deployment by local stakeholders, residents and local authorities. Within community acceptance the NIMBY aspect comes to play. The third concept of social acceptance is the market acceptance, where market adoption of an innovation plays a key role. [48]

As previous experience with other energy infrastructures shows, e.g., with overhead power lines or wind turbines, broad social acceptance is a key success factor for large-scale diffusion and transformation. [49] Especially in recent years, public acceptance has become a relevant variable in the planning and approval of energy infrastructures (renewables and electricity grids) and in public discourse in general, with the definition spectrum ranging from an attitude of acquiescence to active support. Accordingly, social acceptance must also be taken into account at an early stage when planning PtX strategies. The main challenge for assessing the acceptance of PtX technologies at the present time lies in the fact that the technology development stages of the various processes are still relatively low for the most part - to date, there are few concrete empirical values relating to larger applications that are perceived by the public. At the same time, this circumstance offers the opportunity to proactively identify relevant criteria for the social acceptance of PtX technologies in order to be able to incorporate them into the development process at an early stage and, at the same time, to offer opportunities for stakeholders to participate in shaping them. Table 2-1 presents the six major dimensions identified by research to be crucial for social acceptance and a non-exhaustive list of the major

aspects influencing social acceptance. Within the societal dimension existing values, norms as well as cultural habits, etc... play a key role for social acceptance as well. [49]

**Table 2-1: Overview on aspects influencing social acceptance of renewable energy and infrastructure projects. Source: own table based on Christina Friedl and Johannes Reichl (2016) [49].**

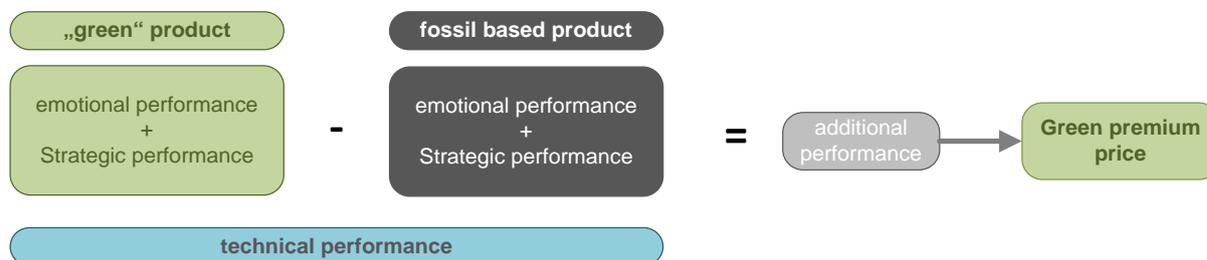
Dimensions	Aspects influencing social acceptance
Project specific and technical	location, plant, size, performance, quality, type of infrastructure
Ecological	direct emissions (noise, smell, dirt, etc...), change in landscape, impact on fauna and flora, nature, sensitive nature spaces
Social, societal, emotional	human health, changes in quality of life, individual concerns, immediate proximity, visibility of changes
Procedural and formal	compliance, approvals, transparent process, information exchange, participation possibilities and dialog, fairness, trust, expropriation
Political	political support, commitment and influence, cooperation, communication, political landscape, interest in re-election
Macroeconomic, national	value added, tourism, recreation, business relocation, urban sprawl, infrastructure, region-specific structure

### 2.2.1 Market acceptance

In contrast to low-temperature electrolysis, which has already established itself in technical applications with polymer electrolyte membrane (PEM) and alkaline electrolysis, the electrochemical CO<sub>2</sub> conversion to ethylene oxide is currently still at laboratory to demo scale - Technology Readiness Level (TRL) of 3 to 4, where 9 is the highest value and means the commercial operation of a plant on an industrial scale. Accordingly, the promising CO<sub>2</sub>EXIDE process with targeted system efficiencies of approx. 80 % could be used in the future as an important building block for climate-neutral and efficient production of base chemicals. The prerequisite for being climate-neutral is that the CO<sub>2</sub>, electricity and heat, come from renewable energy sources.

A main driver for market acceptance and in this context market uptake and investments in the technology is the competitiveness with fossil derived products. It is estimated that PtX technologies aiming at the production of chemicals will not achieve competitiveness with their fossil counterparts in the medium or even in the long term (without assuming any disruptive changes in the fossil chemical market). Accordingly, it is questionable if there will be any investments in this technology in the medium term without any subsidies or financial support for policy. Nevertheless, one of the major drivers for the deployment of PtX chemical production could be the lack of alternatives for a decarbonization or “greening”. In this context especially the chemicals market seems to be promising for PtX derived products. [50] For a comparison of ethylene oxide derived in the CO<sub>2</sub>EXIDE process in comparison with fossil counterparts see section 4.2.1. In that comparison it becomes obvious that the current production costs of green ethylene oxide significantly exceed those of the fossil product, which is currently the biggest constraint concerning market acceptance of the green alternative.

One major uncertainty concerning market acceptance and uptake is if a “green” premium price can be achieved in future for green ethylene oxide. The concept of the “green” premium price shown in Figure 2-3 is derived from biobased products and can also be anticipated for other green products such ethylene oxide derived from a PtX process and its downstream end-user product.



**Figure 2-3: The concept of the „green premium price“. Source: Energieinstitut based on Par-tanen et al (2020) [51]**

According to the concept of the green premium price it will be crucial in the future that buyers of ethylene oxide are willing to pay more for the green option as they might achieve a strategic advantage by “going green”. This is of course strongly connected to consumer perceptions, if they demand a green product (e.g., a fully green water bottle) and if they are willing to pay more for this option. [51] One driver for the demand of green chemicals of the industry will be – among others of course – policy and European regulations. For a discussion on that please see chapter 2.2.2 on the socio-political acceptance.

In the case of ethylene oxide other alternatives than the PtX route developed in the CO<sub>2</sub>EXIDE project exist. This biobased route is based on sugar. Sugar is one of the most important sources for biobased chemicals and fuels. [52] It is agreed today that biomass and among this sugar and starch crops have to supply human nutrition needs first, and that agricultural residues should be prioritized for industrial production purposes. [53] Due to sustainability constraints also the use of agricultural residues such as lignocellulosic materials (e.g. cereal straw) for sugar production will be limited in future. [54] Accordingly, alternatives to biomass use for greening/de-fossilizing chemical production will be needed in future. This is the point where PtX technologies for “green” chemical production come into play. Their potential to sustainably produce “green” chemicals without biomass use is seen as one of the great opportunities for these technologies for future market uptake. [32]

Additionally, another topic of market acceptance in case of ethylene oxide from the CO<sub>2</sub>EXIDE process is the consumer acceptance of CCU products. Similar to the overall PtX topic, a recent study found that the consumers are not familiar the concept of CCU. In general – after being informed on the concept of CCU – the majority of survey participants indicated an openness to buy CCU based products. Interestingly, it was found that the openness to buy CCU based products is not connected to the kind of product or the type of carbon capture applied. A broad acceptance is indicated, also regardless of how the carbon is sourced. [55] This is partially surprising, as the origin of resources is of increasing interest for many customers – on the

other hand these results indicate that the discussion on the origin of the CO<sub>2</sub> – whether biogenic or fossil – is only discussed on the level of policy makers and scientists, i.e. laypeople lack knowledge on fossil and biogenic CO<sub>2</sub> sources and the differences. For the ethylene oxide produced via the CO<sub>2</sub>EXIDE process this is potentially positive as the consumers are open minded to buying CCU products.

### **2.2.2 Socio-political acceptance**

Within the current work the socio-political acceptance is understood as

- the acceptance of the CO<sub>2</sub>EXIDE in the context of policies
- the societal acceptance from a more general perspective.

According to European policies, above all the Green Deal and related policies [56], there is high need for PtX technologies and acceptance of them especially if they use renewable electricity as well as biogenic CO<sub>2</sub>. Beyond the well-known energy related policies [33,34] also the Chemical Strategy within the Green Deal could be a booster for the CO<sub>2</sub>EXIDE concept. The Chemicals Strategy names – among others – the following points which indicate that sustainable chemical production will become more and more important in the future:

- boosting the investment and innovative capacity for production and use of chemicals that are safe and sustainable by design, and throughout their life cycle
- promoting the EU's resilience of supply and sustainability of critical chemicals.

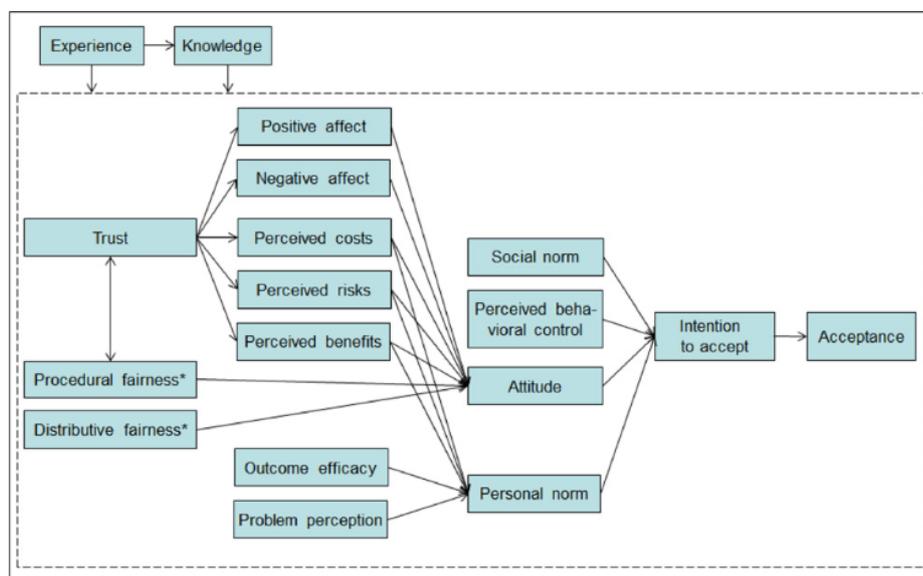
Additionally, it is mentioned that chemicals should follow a “sustainable-by-design” approach which explicitly calls for “minimizing the environmental footprint of chemicals in particular on climate change”. The environmental advantages of ethylene oxide produced within the CO<sub>2</sub>EXIDE process concept are shown in Del 7.2. Accordingly, the green ethylene oxide produced in an electrochemical process fully contributes to the claims of the Chemical Strategy. Another interesting aspect of the Chemicals Strategy is that it calls for stronger policy and financial support as well as regulatory tools. [57] Financial support as well as regulatory tools (e.g., blending target for green chemicals, binding target for renewable share in plastic products, binding target for CO<sub>2</sub> reduction of chemicals, etc...) may speed up market acceptance of green ethylene oxide. Nevertheless, it is rather unclear if these policy instruments will be established and how targeted they will be. Accordingly, the effects cannot be foreseen up to now.

As broad diffusion of the topic into communities has not yet taken place, the lack of information still remains and puts challenges on estimating the acceptance of a technology roll-out for CO<sub>2</sub>EXIDE technology at this point in time. From a societal perspective recent survey showed that the majority of people agrees with the climate related policies and also agrees with spending public money for climate mitigation actions. For instance, a high acceptance of spending public money for renewable energy installations is reported. In contrast – as expected – an opposition towards price increases for energy to achieve better energy efficiency has been reported. [58] Although the overall perceptions of renewable energy technologies and climate policies in the society are positive, this differs from country to country and the perception may change if it comes to project realization or significant changes which directly affects people's

life.[59,60] For the CO<sub>2</sub>EXIDE process concept this indicates that people generally will tend to favor the green production approach compared to the fossil one. It is also reported that raising awareness for the problems of the current energy system increases the potential acceptance of emerging energy technologies. [61] Nevertheless in case of realization a detailed investigation will be necessary on community acceptance level (see chapter 2.2.3) as it is not assessable how PtX technologies or green chemicals will affect people’s lives in future.

### 2.2.3 Community acceptance

In particular, the level of community acceptance (local acceptance) for the CO<sub>2</sub>EXIDE process – and PtX pathways in general - can hardly be assessed yet, due to the low degree of deployment of the technological concept. Thus, a low visibility and no immediate existing concern is recognizable. [50] The knowledge of the community on renewable or emerging technologies in general often low. As people lack familiarity with a certain technology, they often do not want to take a stance on it, especially in early stages of development. The lack of information may cause ambivalence towards emerging technologies. In theory deploying information for people will increase acceptance of a certain technology although people may tend to take short cuts and build up an opinion without considering the hard facts. [62] Figure 2-4 displays the Technology Acceptance Framework developed by Huijts et al (2012), which clearly shows that of course knowledge is just an input factor for individual acceptance which may positively or negatively influence an individual’s trust in a technology which is the starting point developing acceptance or not. [63]



**Figure 2-4: Technology Acceptance Framework according to Huijts et al. [63]**

The overall CO<sub>2</sub>EXIDE process concept is at TRL 3-4. Accordingly, several aspects relevant for community acceptance cannot be fully determined at the current stage. Consequently, the following section deals with general aspects of emerging technology acceptance and gives

more general recommendations of how to achieve future acceptance of the CO<sub>2</sub>EXIDE technology. This early reflection in the sense of a proactive acceptance analysis offers the opportunity to anticipate possible areas of conflict, to enable the participation of social actors and to achieve acceptable solutions in the process of technology development.

In total, the acceptance matrix contains six different categories, which have been classified as relevant for a proactive community (and also market) acceptance assessment: [64]

- Risk assessment;
- Reliability/robustness of CO<sub>2</sub>EXIDE technology;
- Spatial effectiveness: landscape/land use & land competition;
- Distributive justice, market access, actor diversity;
- Environmental and sustainability considerations
- Fit into the energy system/integrability.

The concrete acceptance developments are determined by the respective framework conditions, e.g., the assumed scale of the expansion or the dimensioning of the future installed CO<sub>2</sub>EXIDE capacity as well as the legal framework, funding regime, etc. The visibility or perception of the technology depends to a large extent on the total installed capacity, but also on the size of the individual plants.

What is the most important factor for the success of the project? From a community acceptance point of view, not only the CO<sub>2</sub>EXIDE process concept itself, but also the relevant infrastructure necessary to run the process, should be a matter of concern. Accordingly, renewable power generation plants, transport infrastructures such as pipelines, transmission grids, increased road transport as well as chemical industry plants and facilities for CO<sub>2</sub> capture are system components which can be of community concern. [50]

As relevant framework conditions, these factors must be included both in the methodological acceptance analysis and in the interpretation of the data collected.

In the following chapters, initial results of the prospective acceptance assessment for CO<sub>2</sub>EXIDE are presented; upstream and downstream processes in the CO<sub>2</sub>EXIDE pathway are not yet considered. The majority of the following assessments of acceptance factors are based on interviews with experts from science and industry. In general, it was found that for the acceptance of emerging technologies on community level the trust in industry as well as the municipality can be crucial. So, it is recommended that industry and municipalities cooperate closely to achieve a positive environment for technology implementation. [61]

#### **2.2.4 Spatial impact: landscape/land use & land use conflicts**

In the short to medium term, CO<sub>2</sub>EXIDE will not change the landscape in Europe, as current PtX applications are either still at laboratory scale (conversion to hydrocarbons) or are tested in the energy sector (especially electrolysis operations). Initial prototype plants and larger plants will most likely be integrated at existing sites, such as chemical parks, due to the infra-

structure already in place ("low hanging fruits"). Consequently, at such locations, there is unlikely to be any real perceptible impact on the landscape or new spatial effects arise, as a single facility blurs into the overall profile of an industrial center. In the long term, the first effects on the landscape will occur when industrial-scale plants are built on greenfield sites. These also require additional infrastructure, which is likely to have a further impact on the landscape. Consequently, the CO<sub>2</sub>EXIDE approach focus on valorization of existing rather small-scale biogenic CO<sub>2</sub> sources like biomethane or bioethanol plants. However, the future land requirements of possible electrocatalysis plants built in rural areas are not related to the requirements that arise, for example, from power lines and the expansion of renewable energies in order to supply the installed electrocatalytic capacity with electricity and could possibly even be neglected.

In order to ensure acceptance, competition for land should be avoided. [40] Literature recommends to differ between a functional change of land and an aesthetic change of land. [50] As the CO<sub>2</sub>EXIDE process is likely to be integrated into existing chemical or refinery sites there will not be any functional or aesthetic change of land. The aesthetic changes connected to the increase in renewable electricity production capacities is not completely related to PtX processes, but to the overall needs for decarbonizing the energy system. Therefore, this potential aspect cannot be attributed to a potential roll-out of CO<sub>2</sub>EXIDE, but needs to be attributed to the overall requirements for changing the energy system.

Additionally, due to water consumption of the process, water availability could be a sensitive issue for community acceptance especially in countries where water is scarce, such as the Middle East, but due to climate change there also could be more regions in Europe where water scarcity could become an issue for community acceptance of emerging technologies. [40]

### **2.2.5 Reliability/robustness**

There are currently no hard figures (failure rates, duration, etc.) regarding the reliability of a larger CO<sub>2</sub>EXIDE system, as the technology is still at a low TRL with further R&D needs, so no long-term experience values can be drawn on. Among other things, long-term tests are required on individual large-scale cells and stacks to test degradation of the cells during a consistent operation (i.e., without significant power and load changes). Frequent start-up and shut-down of the stacks, on the other hand, leads to faster degradation of the cells.

An issue concerning reliability could be the availability of renewable electricity and the flexibility of the CO<sub>2</sub>EXIDE process to react to the mechanisms on the electricity market (e.g., on/off cycles due to renewable electricity production patterns). [50] If the production process will be established abroad and the green ethylene oxide imported, the implementation of technical standards is recommended to enhance acceptance of the imported product. These technical standards should ensure the use of the best available technology or state-of-the art technology as well as reliable emergency plans and measures for damage and risk prevention. [40]

### **2.2.6 Risk assessment**

The health and environmental risk related to the inputs CO<sub>2</sub>, H<sub>2</sub>O and electricity can be classified as low, the produced ethylene oxide poses a risk in the event of a leakage and is also viewed critically by the public. In normal operation, the synthesis gas is fed in as required, further processed in direct downstream processes or filled directly on site (e.g., in pressure cylinders).

The probability of a leakage is similar to that of commercial industrial and chemical plants, since a CO<sub>2</sub>EXIDE plant has closed pipe circuits. If ethylene oxide escapes in the event of a leak, it is harmful to the environment and humans if inhaled, depending on the concentration it is a highly flammable gas, which also poses a risk of explosion - it is therefore important to ensure appropriate safety standards.

In terms of community acceptance, the risk assessment of people is subjective and often a technology is rated to be harmful if the knowledge about the technology is low. Accordingly, risk perception plays a significant role for early-stage technology deployment. [50] In this regard it can be recommended to give people the chance to visit a "first-of-its-kind" or demonstration plant applying the CO<sub>2</sub>EXIDE process concept and to actively inform the community about the implementation from the beginning on.

### **2.2.7 Environmental and sustainability considerations**

Apart from the possible long-term space requirement (see subsection 2.2.4), no further impact on biodiversity or habitat is foreseeable with the sole CO<sub>2</sub>EXIDE process considered and any downstream processes after the CO<sub>2</sub>EXIDE plant's gate neglected. The reactants and products do not come into direct contact with the environment, due to the required closed system operation. In the event of leakage, the product ethylene oxide is harmless to the environment and humans (see above). In normal operation, the significant electrical energy requirement can generate indirect emissions especially if not provided 100 % from renewable sources. As long as the electricity and CO<sub>2</sub> comes from sustainable sources or processes, indirect emissions are minimized. The impact of the product gas ethylene oxide on the environment has already been described in the "Risk assessment" section.

For a broad acceptance – community and also market acceptance - of green products and PtX products combining sustainability regulations and certifications are advantageous. Sustainability criteria for enhancing acceptance could be: energy sourcing, technical standards, CO<sub>2</sub> source, fair wages, labor security, etc. [40] The CO<sub>2</sub>EXIDE process concept already shows today the advantages of using biogenic CO<sub>2</sub> and renewable electricity and is therefore compliant with said recommendation. In the long term, also the development of certification schemes for green PtX products may enhance and secure community as well as market acceptance. Ideally this will be set up globally and of course needs to encompass various products. [40] Ethylene oxide may only be one of these products.

### **2.2.8 Embedding in the energy system**

Generally speaking, CO<sub>2</sub>EXIDE as a PtX technology facilitates sector coupling and depending on process configuration (e.g., use of excess electricity) improves system flexibility. The product ethylene oxide is a drop-in chemical and therefore perfectly fitting into current production processes of chemical industry. These aspects can be classified as strengths [32] of the technology, enhancing acceptance. It appears that the first CO<sub>2</sub>EXIDE plants will primarily be integrated into existing sites in the future. On the one hand, this will reduce investment and operating costs, as the feedstock CO<sub>2</sub> is hard to transport and synthesis gas produced can eventually be used directly in downstream processes located nearby thanks to short transport routes. On the other hand, existing sites have existing infrastructures that can be used or expanded at a manageable cost - this refers primarily to the required CO<sub>2</sub>, water and electricity connections with sufficiently large capacity.

Integrating the CO<sub>2</sub>EXIDE process concept to existing site and utilizing existing infrastructure will help to generate community acceptance for technology deployment as this for example may reduce competition for land and the visible changes in the environment are lower compared to “green field solution”. [40]

### **2.2.9 Distributive justice**

A more decentralized production may strengthen regional value chains and services of general interest. If this added value is realized in the region depends on various aspects. One of these aspects is, if facilities are erected and operated by investors from the regions or abroad. [50] In the current development stage of the CO<sub>2</sub>EXIDE process concept it is not assessable if this will lead to a more decentralized production. The common claims for the use of existing infrastructure and avoiding land competition give the evidence that the process concept is likely to be established centrally. Concerning the costs for end users, it is not yet precisely foreseeable if and when there will be the demand for “green” ethylene oxide in future and how the market price for fossil product evolve. At the moment no scientifically viable statement on the future costs for end consumer due to the use of green (PtX derived) chemical can be made.

## **2.3 Conclusion of socio-economic aspects**

As shown, the CO<sub>2</sub>EXIDE technology is in an early stage of development, in which only a slight public awareness exists and the spatial perception of the technology is not given. Consequently, the evaluation and classification of the technology in terms of acceptance are still largely shaped by discourse among experts and scholars. The early stage of development opens up the scope for design and offers the opportunity to proactively include societal concerns in the development process. For this purpose, the importance of interdisciplinary dialog and exchange increases, especially in the expert discourse, in order to integrate different considerations and evaluation categories as early as possible. Acceptance in a policy context can be rated to be high, as the concept is in line with the major policies and ideas of the EU's Green Deal. An important prerequisite is to use renewable electricity and biogenic CO<sub>2</sub> for electrocatalysis. Concerning future renewable electricity supply a potential threat to the technology

could be rising electricity prices in Europa as more and more actors request renewable electricity to achieve decarbonization associated with potential additional costs on grid balancing, grid expansion, electricity storage, etc.

In order to raise future societal and especially community acceptance, creating knowledge among the public about the problems of the current energy and production system could be a milestone. Additionally, practitioners from industry and municipalities should work together in case a larger scale roll-out is planned to generate the community's trust.

With regard to the CO<sub>2</sub>EXIDE approach, it becomes clear that the land consumption and the resulting perception will most likely affect the landscape in the medium term. In the long term, the perception depends mainly on the actually realized expansion dimension and the application of the technology. However, the land consumption of the implementation in the outdoor area is disproportionate to the indirect expansion requirement of renewable energies to supply the installed electrocatalytic conversion capacity with electricity. From an acceptance point of view, it can be recommended to use existing infrastructure and possibly integrate a large scale CO<sub>2</sub>EXIDE process to an existing site – realize it on “brownfield” – as this will reduce functional and aesthetic land use change (compared to “greenfield” realization). This of course needs site planning efforts.

The current high costs of the production routes will have a restraining effect on the ambitions of the economic players and thus on the rapid diffusion of the technology. On the other hand, the fact that integration into existing plants is possible and that the technology has a high potential for sustainable and efficient bulk chemical production with high purity is a positive factor. Market acceptance can be boosted, if the green value of ethylene oxide produced via the CO<sub>2</sub>EXIDE process can be covered by the market price. In the long run, establishing production standards and certification schemes for green PtX products may increase market acceptance as well as societal and political acceptance.

In addition to the early assessment of the technology-related acceptance factors described above, the participation of social actors in the diffusion process is also important for embedding the technology in society. In addition to accompanying communication and documentation possibilities, concrete participation is also required, e.g., via regional value creation or citizen energy models and integrated regional energy concepts.

If the CO<sub>2</sub>EXIDE process concept is scaled up in future, a detailed acceptance analysis based on the detailed site planning is needed. Scaling up needs further development – not only from a technological point of view but also from a systemic and organizational point of view. Perner and Bothe (2018) determine the following seven steps to further develop PtX technologies also taking into account increasing market and societal/political acceptance: [40]

1. Integrated PtX to climate policy as an innovative option to reduce CO<sub>2</sub> emissions and to enhance the integration and use of renewable energy. Additionally, PtX products are a building block to decarbonizing the industry by delivering green building blocks.
2. International production and trade of PtX technology and products is a chance and

should therefore be recognized by policy makers. Establishing international standards and a certification scheme for the trade of green PtX products could be useful in this regard.

3. PtX technologies need further development. Also, for the CO<sub>2</sub>EXIDE process concept further development and scale up (e.g., installing pilots, demonstration plant size) will be an important next step.
4. Create a level playing field for PtX by adapting taxes and levies to make pilot and demonstration activities attractive and facilitate early-stage deployment.
5. For accelerating market acceptance, capturing the value of green PtX products such as ethylene oxide for the CO<sub>2</sub>EXIDE process can be boosting. This can be done by e.g., introducing CO<sub>2</sub> saving targets for the chemical sector or renewable obligations for products such as plastics.
6. By establishing international partnerships on PtX production and trade as well as international cooperation, technology transfer and technological learning can be facilitated.
7. For increasing the acceptance, the implementation of environmental and social production standards is of special importance. Again, a certification scheme may be part of this solution.

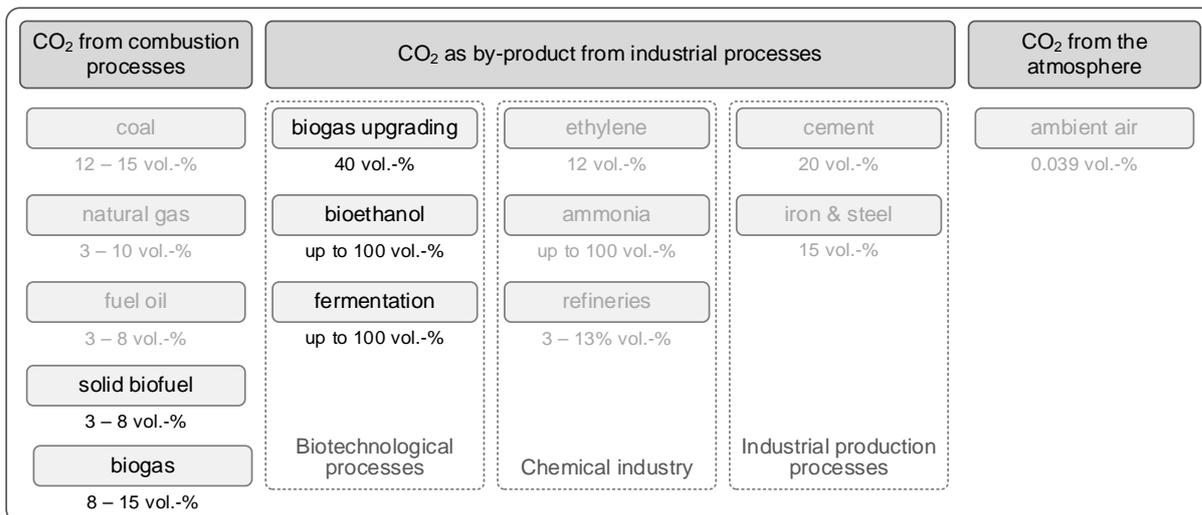
## 2.4 Biogenic CO<sub>2</sub>-Potential

From a socio-economic perspective also the availability of a renewable and sustainable carbon source for the PtX process is a major aspect. The total European biogenic (and fossil) CO<sub>2</sub> potential from stationary emission sources has been evaluated in CO<sub>2</sub>EXIDE Work Package 2 (WP2) and published by Rodin et al. [7] In this study, focus is on specific point sources of CO<sub>2</sub>, i.e. specific case studies. The main sources are combustion of biomass, CO<sub>2</sub> from biogas upgrading to biomethane and industrial fermentation processes, e.g. brewing processes and bioethanol production for biofuel applications. CO<sub>2</sub> from the atmosphere (Direct Air Capture, DAC) and CO<sub>2</sub> from combustion processes demands for high technical effort to separate the CO<sub>2</sub> and was thus excluded from the evaluations in this work. DAC may still play an important role in the sequestration of CO<sub>2</sub> from diluted and dispersed sources in the long-term, as the technology has the potential for significant further development and optimization. [8] In this work, the focus lies on high-purity biogenic CO<sub>2</sub> point sources for PtX and CCU case studies, such as biogas and biomethane plants as well as bioethanol fermentation plants.

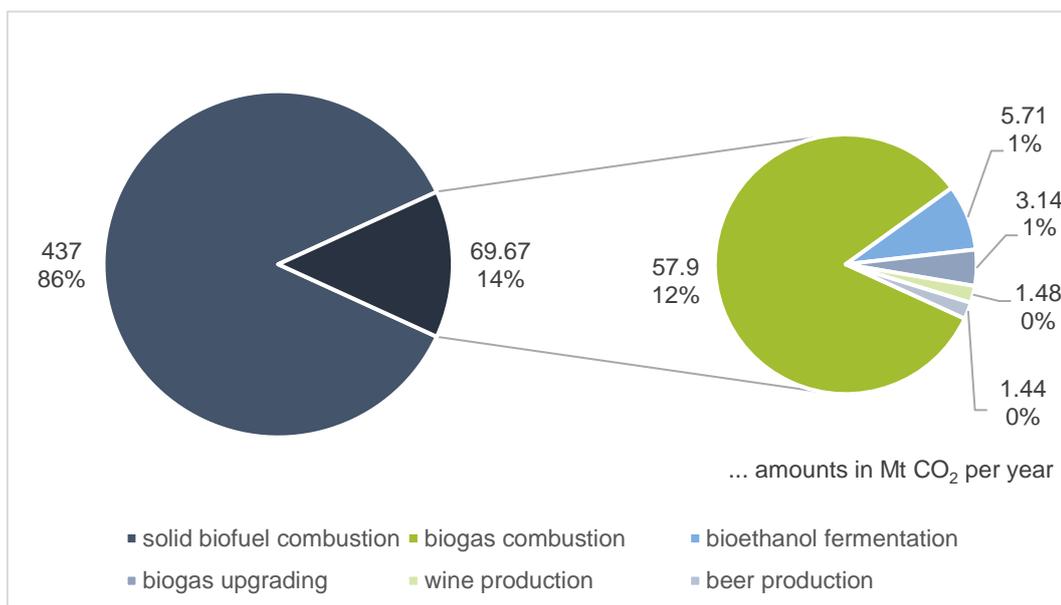
In total approximately 506 Mt of biogenic CO<sub>2</sub> are produced annually in Europe

- Of which 86 % imply cost intensive flue gas purification
- 58 Mt from biogas combustion (CHP) consist of CO<sub>2</sub> from biogas production (~20 Mt) & CO<sub>2</sub> from combusting the methane content (~38 Mt) → to be harvested
- In addition to the 58 Mt, currently ~3 Mt CO<sub>2</sub> are separated by biogas upgrading
- 1.5 Mt of ~4 Mt CO<sub>2</sub> from bioethanol fermentation is already commercialized

Thus, annually ~5.5 Mt CO<sub>2</sub> is available from biogas upgrading and bioethanol fermentation under current conditions. Up to 58 Mt/year from currently directly combusted biogas could be made available with low effort. Different sources of biogenic CO<sub>2</sub> can be classified as illustrated in Figure 2-5. The focus in the CO<sub>2</sub>EXIDE roll-out scenarios within this study is on high-purity biogenic point sources such as biogas and biomethane plants as well as bioethanol fermentation plants. The European theoretical potential concerning available biogenic CO<sub>2</sub> is shown in Figure 2-6.



**Figure 2-5: Classification of potential biogenic CO<sub>2</sub> sources including the typically available CO<sub>2</sub> concentration. Source: Energieinstitut based on [65]**



**Figure 2-6: Biogenic CO<sub>2</sub> potential in Europe. Source: Energieinstitut based on data from [7]**

### 3 OBJECTIVES OF THE PRESENT STUDY

This report consists of two parts in order to reflect the Socio-Economic Analysis (SEA) and the plant specific Techno-Economic Assessment (TEA) of the CO<sub>2</sub>EXIDE technology in a European market-roll-out scenario.

The CO<sub>2</sub>EXIDE technology is expected to contribute to the following targets:

1. Produce largely used High-Value Chemicals (HVC) that are completely climate-neutral
2. Reduce the CO<sub>2</sub> burden of the atmosphere, i.e. long-term binding of CO<sub>2</sub> in products
3. Stabilizing the electricity grid via utilization of renewable excess power

In order to meet these targets, in the following assessments, the determining factors are locally produced renewable energy and green CO<sub>2</sub> as input for the CO<sub>2</sub>EXIDE technology pathway.

As an alternative (for example), the CO<sub>2</sub>EXIDE process could also be integrated into existing steam cracker plants in order to convert the CO<sub>2</sub> emissions from fossil ethylene oxide production on-site. This would allow to reduce CO<sub>2</sub> emissions (especially when renewable electricity is used), while ethylene oxide production is increased. However, such a scenario is out of scope of this study as a 100 % renewable alternative to fossil ethylene oxide shall be examined.

#### 3.1 Study context

In the SEA, the market potentials in Europe and a future roll-out scenario of a TRL 7-9 CO<sub>2</sub>EXIDE process are evaluated. This includes literature research on the current and estimated future CO<sub>2</sub> demand (competing utilization pathways), review of total CO<sub>2</sub> availability in Europe (cf. D2.1 and [7]), a GIS-based (Geographical Information System, GIS) location analysis of stationary biogenic CO<sub>2</sub> sources in Europe and favorable conditions for CO<sub>2</sub>EXIDE as well as an assessment based on the tool SAMBA.

As the TEA should be carried out assuming real but as optimal conditions as possible, locations with favorable conditions have been chosen, based on results derived from the SEA. The investigated case studies are located in Austria, Germany and the United Kingdom. Based on CO<sub>2</sub>EXIDE report D7.1, the Austrian case study also serves as the benchmark case. The period under consideration covers 20 years with assumed start of operation in 2030 or 2040. Data input bases on information from laboratory measurements and modelling in course of the CO<sub>2</sub>EXIDE project as well as literature data on related state-of-the-art processes.

#### 3.2 Application and reasons

This study shall investigate the potential of the CO<sub>2</sub>EXIDE product ethylene oxide (C<sub>2</sub>H<sub>4</sub>O) and its side products that are common bulk chemicals which are currently produced solely from fossil resources. Furthermore, the limits of the market rollout should be investigated based on the availability of local renewable resources. In this way the findings shall support future R&D

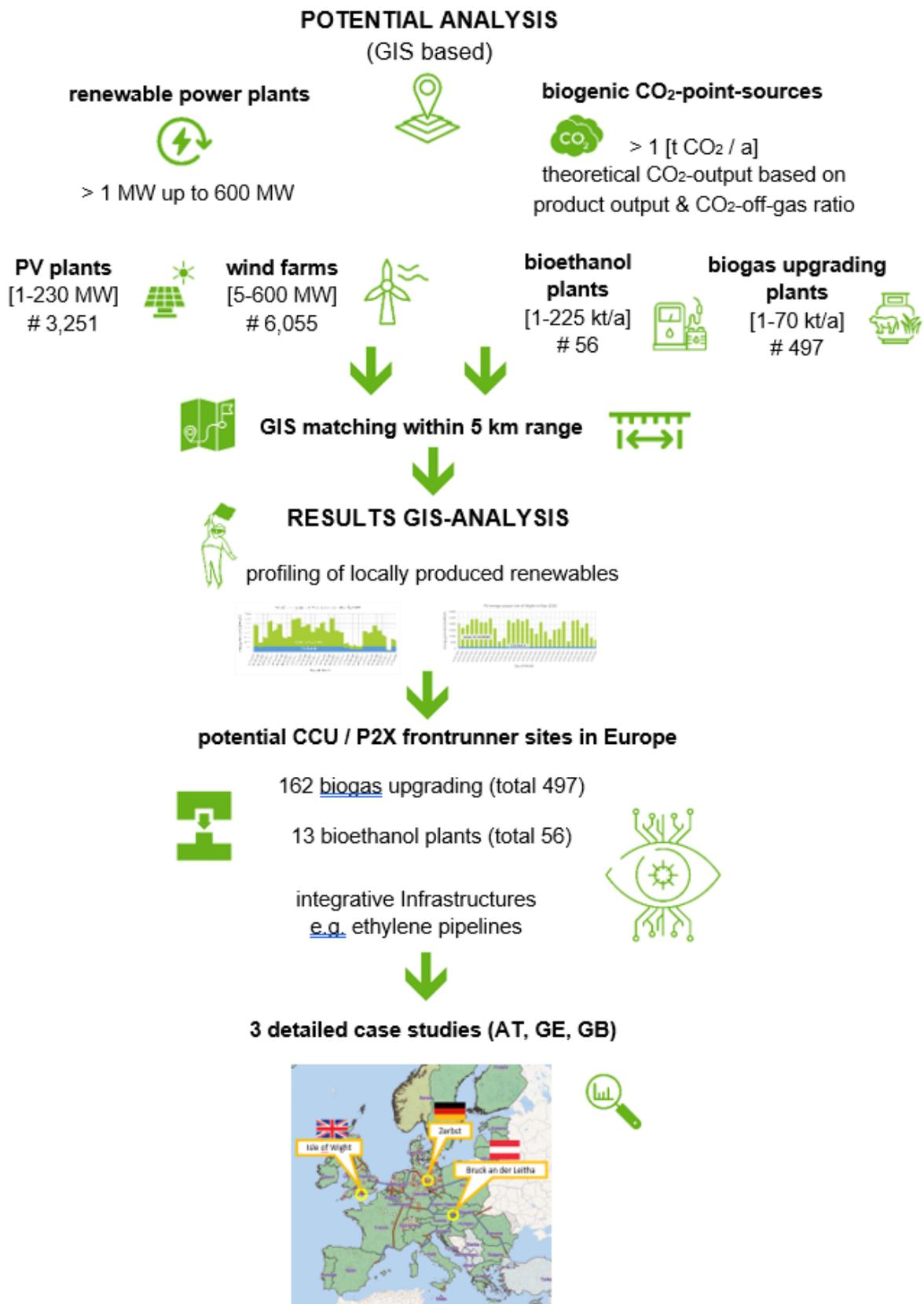
actions regarding specific components of the CO<sub>2</sub>EXIDE process and show the market potential of the technology to justify the support of further R&D activities.

### **3.3 Limitations in the usability from assumptions or methods**

As the analyzed core technology has a low Technology Readiness Level (TRL) of 4-5, only a simplified equipment list is available for the TEA. Furthermore, the energy efficiency of the process is assumed to be much higher when the technology reaches a TRL of 7-9 compared to the current state. The first limitation was countered by adapting known technical and economic conditions of related technologies, for which cost and efficiency data as well as learning curves are available. Furthermore, sensitivity analyses are conducted to show a realistic range of energy demand and cost development. Finally, the focus in the TEA itself was laid on the main process rather than supply chains or product sales in order to rule out several variables that influence the overall result significantly. However, the case studies were designed in a way that local resources with short transport routes are available. Also, product marketing is possible in an acceptable geographical range in all case studies.

### **3.4 Power-to-X potential as interlinkage of the electricity and chemicals sector**

For the techno-economic, impact and exploitation scenarios, a database of existing biogas upgrading and bioethanol production plants in Europe was addressed and a database of biogenic CO<sub>2</sub> sources was generated. Additionally, existing large-scale PV and wind power installations ( $\geq 1 \text{ MW}_{\text{el}}$ ) as fluctuating potential energy suppliers were geographically localized. In a GIS-based approach, the two datasets were merged and utilized for technology roll-out and exploitation scenarios. In a last step, existing refineries and the European ethylene pipeline network were taken into consideration, to identify potential locations for CO<sub>2</sub>EXIDE plants, which have access to a) biogenic CO<sub>2</sub>, b) local RES and c) are located close to existing chemicals infrastructure, i.e. distribution sites.



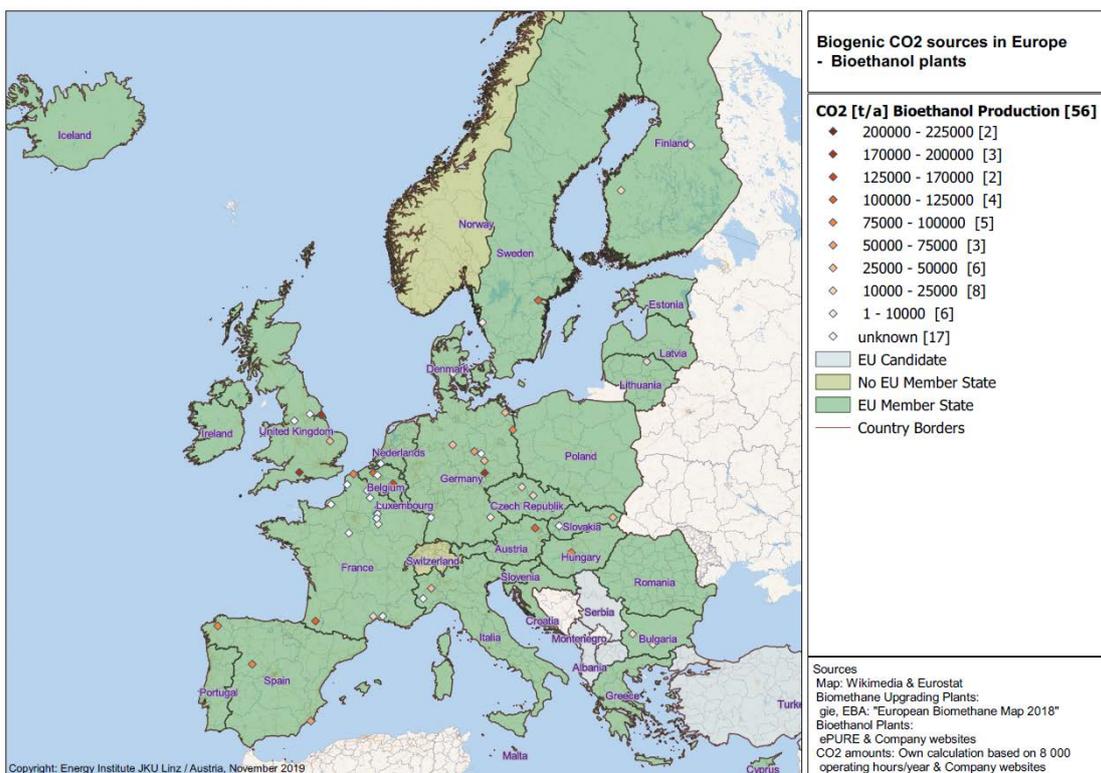
**Figure 3-1: Procedure of GIS-based potential analysis for Europe.**  
Source: Energieinstitut.

### 3.4.1 GIS-based biogenic CO<sub>2</sub> potential analysis for Europe

The data of biomethane upgrading plants was gathered from the 2018 biomethane map [66] and its associated database prepared by Gas Infrastructure Europe (GIE) and European Biogas Association (EBA). The biomethane capacity information has been used to calculate the yearly CO<sub>2</sub> production for 8 000 operating hours and 40%-vol. CO<sub>2</sub> in the raw biogas. A detailed information of the location of the biomethane plants is given in [66] and its updated version in [67]. Most of the biomethane plants are located in Germany, followed by France and the UK [67]. The data of bioethanol production sites was gathered from EPURE and company websites. The produced CO<sub>2</sub> amount was either taken from company websites directly (as at some plants the CO<sub>2</sub> already is utilized/sold) or calculated. Latter calculations are based on the available information on bioethanol production as well as stoichiometric calculations, based on the following stoichiometric equation:



This means, 1 kg ethanol produced leads to the theoretical CO<sub>2</sub> potential of approx. 0.96 kg. See also Rodin et al. [7] for further information on CO<sub>2</sub> potentials in Europe. For some companies neither the ethanol/biomethane nor the CO<sub>2</sub> production is available, only the location. Despite this, these locations are included in the QGIS analysis. Finally, the most important data for the following data analysis in QGIS were the location and the CO<sub>2</sub> production capacity in t/a.

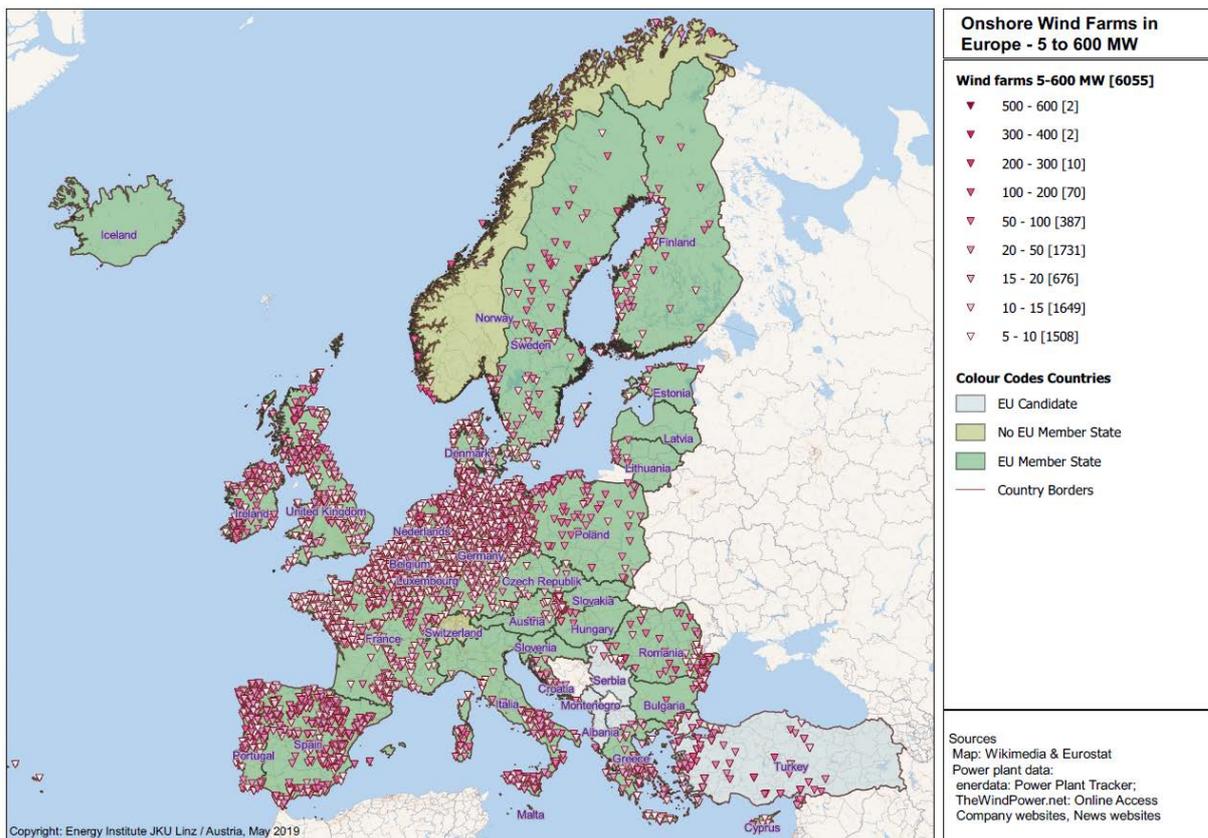


**Figure 3-2: Exemplary results of the GIS processing of existing bioethanol plants. Color indicates the theoretical CO<sub>2</sub> potential. No claim to completeness. Source: Energieinstitut based on data from [68] and company websites.**

### 3.4.2 Localization of large PV and wind farms

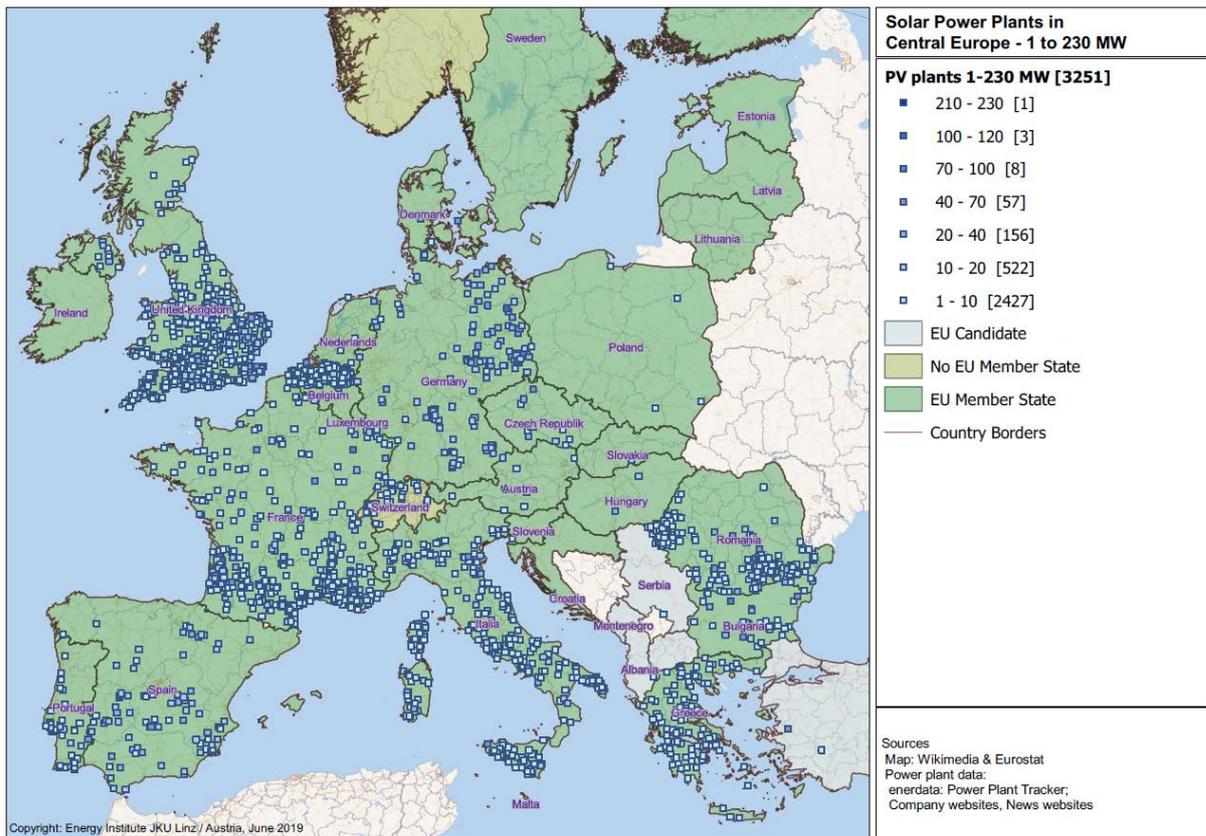
For the localization of large PV and wind farms across Europe, plant data (location, capacity i.a.) were gathered from different data sources as well. Focus herein was on on-shore power plants, i.e. this affects mainly wind power. Key information was gathered from the Power Plant Tracker from [69] as well as [70] with status 2019. Furthermore, specific company websites, e.g., from large power plant and grid operators as well as manufacturers, were referred to, in order to gain an as holistic as possible picture of the European PV and wind power plant landscape. In the case of parks with partially shut down / under construction systems, only the plant units in operation were recorded.

In total, ~3,619 wind farms of 1 to 5 MW in operation were identified. Additionally, ~6,055 wind farms with 5 to 600 MW in operation were localized. Most of them are located in Germany, Belgium, Denmark followed by France, UK, Ireland and Spain. See also Figure 3-3 for an overview.



**Figure 3-3: Exemplary results of the GIS processing of existing onshore wind farms 5 to 600 MW. Color indicates the rated power. No claim to completeness. Source: Energieinstitut based on data from [69,70] and company websites.**

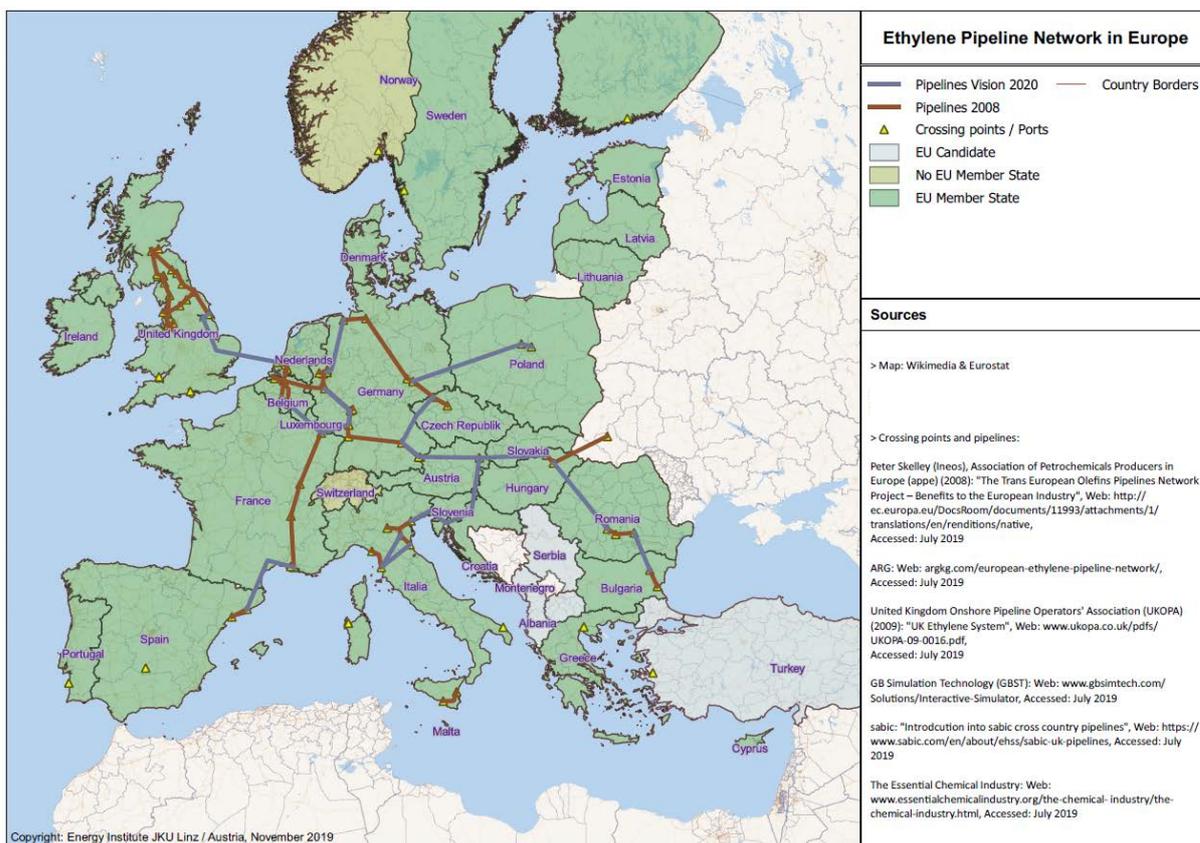
In total, ~3,251 PV plants with 1 to 230 MW capacity in operation were identified across Europe. Most of them are located in the UK. See also Figure 3-4 for an overview.



**Figure 3-4: Exemplary results of the GIS processing of existing PV plants 1 to 230 MW. Color indicates the rated power. No claim to completeness. Source: Energieinstitut based on data from [69] and company websites.**

### 3.4.3 Consideration of existing refineries and ethylene pipelines

As ethylene and ethylene oxide are important bulk chemicals, there is a wide European infrastructure of producers and consumers as well as distribution pathways, such as pipelines. Below Figure 3-5 gives a rough overview of existing and planned pipelines as well as some large production/utilization sites. As the information was gathered via desk research from various sources, there is no claim on completeness nor currency of the information given, e.g., some of the “vision 2020” pipelines probably are already built or overruled. Nevertheless, the location of pipelines and large facilities producing/consuming ethylene (oxide) allows to narrow down the number of ideal CO<sub>2</sub>EXIDE locations.



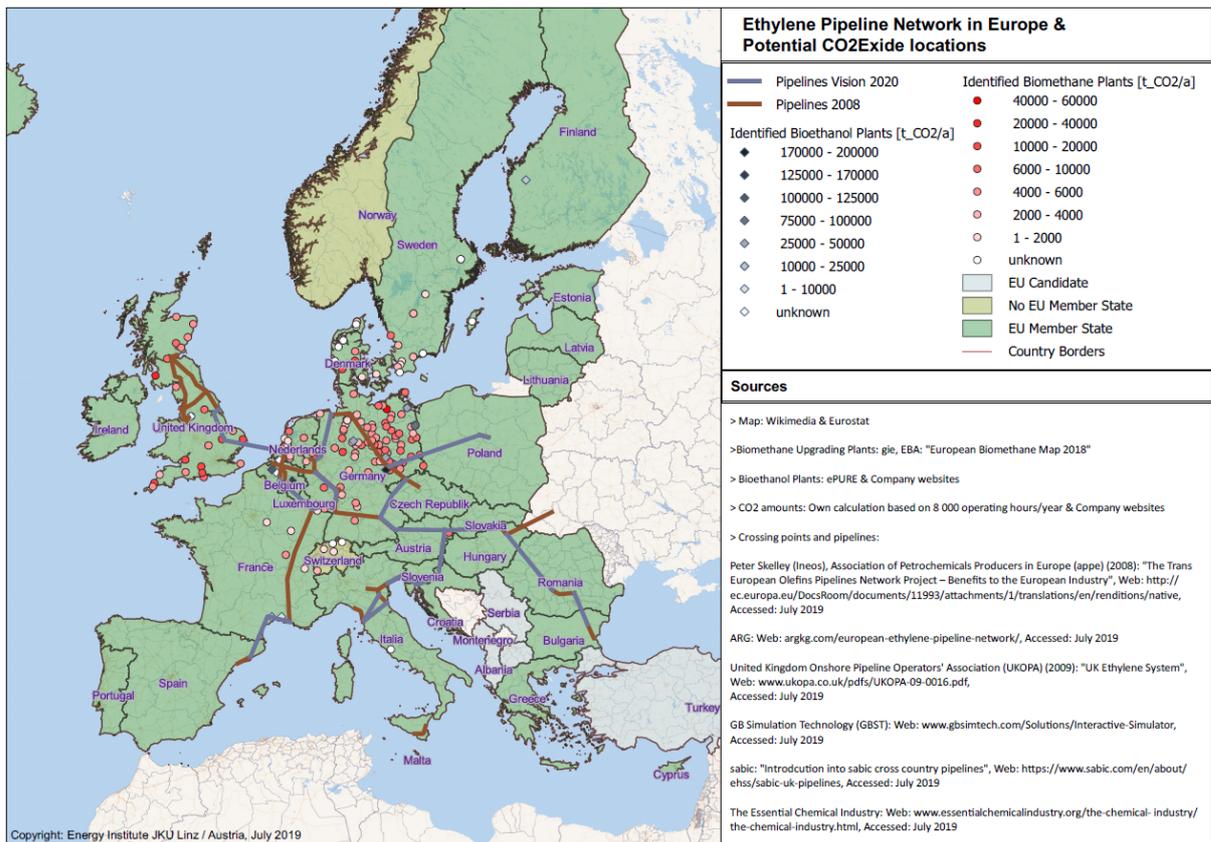
**Figure 3-5: Exemplary results of the GIS processing of ethylene pipelines across Europe as well as their crossing points and large chemical industry being related to ethylene (yellow triangles). No claim to completeness. Source: Energieinstitut based on [71–77].**

### 3.4.4 Matching CO<sub>2</sub> and RES sources

The CO<sub>2</sub> and RES data were displayed on a map of Europe. Different layers for bioethanol, biomethane, PV plants (= < 1 MW) and onshore wind farms (1 to 5 MW and > 5MW) were used. The data were color-coded and symbolized according to amount of CO<sub>2</sub> (in t/a) or power capacity (in MW) and type of data (CO<sub>2</sub> from bioethanol, CO<sub>2</sub> from biomethane, wind power, PV power).

Since it is easier to transport renewable electricity via the existing power grids to CO<sub>2</sub> sources and because there are much more RES sources than CO<sub>2</sub> sources, the matching was done the following way:

PV and wind farms were selected by their location within a 5 km radius around each CO<sub>2</sub> source. For some CO<sub>2</sub> sources, more than one RES source within 5 km range is available. In the next step, the amount of locally produced renewable energy compared to the available CO<sub>2</sub> amount was analyzed for each match. As can be seen from Figure 3-6, approx. 175 locations were identified that offer biogenic CO<sub>2</sub> and renewable energy within close proximity.



**Figure 3-6: Biomethane upgrading (162) and bioethanol (13) plants with PV/wind farms within a 5 km range available. Also, ethylene pipelines are displayed. Source: Energieinstitut based on [66,68,71–77] and specific company websites.**

Lastly, three locations across Europe were chosen for more detailed case studies. In this final selection also the proximity to pipelines/large industrial facilities played a crucial role. The three chosen locations are the following, more information can be found in section 4.1.3.4:

- Bruck an der Leitha, Austria
  - Biomethane plant
  - Wind power
  - Refinery and steam cracker Schwechat
- Zerbst, Germany
  - Biomethane plant
  - Wind + PV power
  - Refinery Leuna
- Isle of Wight, United Kingdom
  - Biomethane plant
  - PV power
  - Refinery Fawley (on mainland)

### **3.4.5 Limitations of the GIS-based analysis**

As the GIS analysis is based on data, its accuracy relies on the quality and completeness of the datasets used. Data validation and crosschecking was carried out as much as possible via desk research, however, no claim for completeness can be given. As the used data sets list producing facilities, they are subject to constant change, as some power plants as well as biomethane upgrading and bioethanol plants might be shut down or newly erected in the course of time. For example, the basic assessment for biomethane plants was carried out in 2018 and 2019 in course of WP2 – the available datasets from the European Biomethane Map [66] then listed 483 upgrading plants across Europe. In 2020 a new version was published, which already listed 729 [67]. Also capacities and production rates are likely to change over time, furthermore, information on “production capacity” and “production rate” is not always clearly declared depending on the data source. Lastly, data availability per country is likely to vary a lot as well, i.e. in some countries presumably more power plants and CO<sub>2</sub> sources exist than could be identified.

In some cases, the location of the power plants and CO<sub>2</sub> sources was not available via coordinates but identified based on their location near cities and/or the urban areas to which they are assigned to. Especially urban areas possibly have a diameter of well over 10 km, and/or smaller local communities might be declared as the city to which they belong in some datasets. Consequently, the location of various plants is not accurate, but sufficient for an approximate analysis of the RES and CO<sub>2</sub> potential by a perimeter query.

Taking into account the European efforts for climate change mitigation, we assume that the number of “ideal” sites (biogenic CO<sub>2</sub>, local RES) for CO<sub>2</sub>EXIDE (or renewable CCU plants generally) is likely to increase significantly within the next years. Regular tracking and assessing of the change in potential seems reasonable for further R&D activities.

## 4 TECHNO-ECONOMIC ASSESSMENT

### 4.1 Scope of the study

The techno-economic assessment aims to identify and project the economic performance of the CO<sub>2</sub>EXIDE process chain in a technically feasible industrial implementation. Therefore, typical economic indicators, such as product generation cost, net present value (NPV), and payback time, are evaluated. Due to the early stage of development of the technology (TRL 3-4) an according process evaluation and optimization based on actual implementations in relevant industrial environment is not possible. Thus, the development of the technology toward an industrial scale-up has to be anticipated based on yet available data, expert elicitation, consideration of individual component maturities and relevant literature review. Additionally, the economic impacts of technology scale-up, both in numbers and individual scale, potential by-products and regulatory measures – compared to fossil competitive products – have to be considered in an appropriate manner. This is an essential and integral part of the techno-economic assessment of emerging renewable processes with the scope to identify technical and economic bottlenecks in an early development stage. In consequence, these results allow to assess the techno-economic feasibility of the CO<sub>2</sub>EXIDE process chain and support the implementation of mandatory measures for the technology to be viable in future for the renewable production of high value chemicals.

#### 4.1.1 Fossil product benchmarks

As benchmark products, fossil-based ethylene oxide and procurers are considered. Production processes of these bulk chemicals are State of the Art (SOTA), i.e. TRL 9. Up to now, the SOTA production processes for ethylene oxide usually consist of direct oxidation where ethylene, oxygen and a recycle gas are mixed together in a catalytic reactor [4,78], resulting in ethylene oxide, CO<sub>2</sub> and water [4]. The most common process to produce ethylene is steam cracking of gas, other hydrocarbons or naphtha, i.e. a fraction of crude oil distillation. [79]

According to Plastics Europe [80], approx. 9 % of production costs accounted to energy consumption as of 2012, in some extreme cases energy input is responsible for about 75 % of production costs, with a reduction of average specific energy needs of 30 % compared to 1990. In October 2019 for the German chemical industry the 2050 roadmap [79] was published, looking i.a. into the future development of steam cracking products (HVC, High Value Chemicals) such as ethylene. According to this study, the following benchmarks for fossil HVC were derived:

Taking into account an average energy input of 4.582 MWh/t<sub>HVC</sub><sup>2</sup> and CO<sub>2</sub> emissions of 0.87 t<sub>CO2</sub>/t<sub>HVC</sub> (conventional cracker) resp. 2.22 t<sub>CO2</sub>/t<sub>HVC</sub> (electrical cracker in 2020), the total specific production cost amount to approx. 820 €/t<sub>HVC</sub> (conventional cracker) and 930 €/t<sub>HVC</sub> (electrical cracker, 2020). Consequently, for the conventional cracker, energy cost account for approx. 235.38 €/t<sub>HVC</sub><sup>3</sup> (28.7 %) and CO<sub>2</sub> emission-cost amount to 21.75 €/t<sub>HVC</sub> (2.65 %). For the electrical cracker, energy cost account for approx. 183.3 €/t<sub>HVC</sub><sup>4</sup> (19.7 %) and CO<sub>2</sub> emission-cost amount to 55.5 €/t<sub>HVC</sub> (5.97 %).<sup>5</sup> However, it has to be noted that the high CO<sub>2</sub> emissions of the electrical cracker (new technology) compared to the conventional cracker derive solely from the German electricity mix in 2020 and are reduced to 0 in the long-term scenario until 2050.

The aforementioned key figures will be taken as a benchmark of the CO<sub>2</sub>EXIDE process. However, since the target product of the investigated process is ethylene oxide, additional costs, energy inputs and emissions have to be considered for the fossil benchmark (conversion from ethylene to ethylene oxide).

#### **4.1.2 Reference unit**

The reference unit (RU) for the TEA is 1 kg of ethylene oxide (C<sub>2</sub>H<sub>4</sub>O) produced from ethylene (C<sub>2</sub>H<sub>4</sub>) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) that are intermediates produced from carbon dioxide (CO<sub>2</sub>) and water (H<sub>2</sub>O) in the electrocatalytic CO<sub>2</sub>EXIDE process. All specific cost assessments, such as the levelized costs of product (LCoP), are related to this reference unit. This process is described in literature [78,81] with large industrial scale simulations and TEA/LCA conducted. In terms of realization, the concepts was proven on laboratory scale at least.

---

<sup>2</sup> Conversion from 16.5 GJ/t<sub>HVC</sub> taken from [79].

<sup>3</sup> Assumption: Energy demand covered by oil/ gas with energy price 98 \$/barrel. Assuming 1.20 \$ = 1.00 € 158.9873 l/barrel and 10 kWh<sub>LHV</sub>/l, an average energy price of 5.137 ct/kWh<sub>LHV</sub> is calculated. Assumption based on data from [79].

<sup>4</sup> Calculated based on data from [79].

<sup>5</sup> Assuming 4 ct/kWh<sub>el</sub> (neglecting taxes, levies and CO<sub>2</sub>-emission-prices) and 25 €/t<sub>CO2</sub> [79].

**Table 4-1: Characteristics of polymer precursors (ethylene, ethylene oxide) under consideration and potential subsequent ethylene glycols as well as hydrogen peroxide. Source: adapted from [80,82]**

Precursor name	IUPAC name (for mixtures systematic name)	CAS number	Chemical formula
Ethylene	Ethene	74-85-1	C <sub>2</sub> H <sub>4</sub>
Ethylene oxide	Oxirane	75-21-8	C <sub>2</sub> H <sub>4</sub> O
Monoethylene glycol	Ethane-1,2-diol	107-21-1	C <sub>2</sub> H <sub>6</sub> O <sub>2</sub>
Diethylene glycol	(2-Hydroxyethoxy)ethan-2-ol	111-46-6	C <sub>4</sub> H <sub>10</sub> O <sub>3</sub>
Triethylene Glycol	2-[2-(2-Hydroxyethoxy)ethoxy] ethanol	112-27-6	C <sub>6</sub> H <sub>14</sub> O <sub>4</sub>
Hydrogen peroxide	Peroxol	7722-84-1	H <sub>2</sub> O <sub>2</sub>

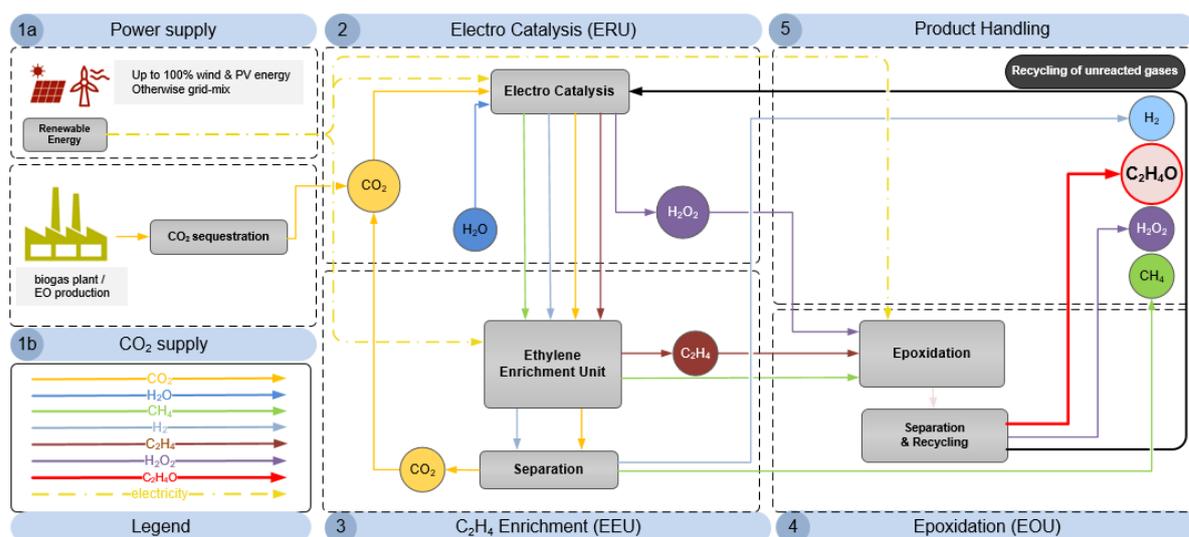
As a conventional reference technology, the oxidation of steam-cracked ethylene with oxygen or air to ethylene oxide via silver catalysts is taken. This process is SOTA in industry and is operational at TRL 9.

#### 4.1.3 Boundary conditions and application scenarios

##### 4.1.3.1 Technology description CO<sub>2</sub>EXIDE

The CO<sub>2</sub>EXIDE technology is a Carbon Capture and Utilization (CCU) and Power-to-X (PtX) technology that enables the utilization of excess electricity from volatile renewable energy resources such as photovoltaics or wind power and the mid-/long-term storage of carbon dioxide (CO<sub>2</sub>). The overall purpose is to produce renewable, sustainable base chemicals to replace usually fossil-based chemicals (such as ethylene (C<sub>2</sub>H<sub>4</sub>), **ethylene oxide (C<sub>2</sub>H<sub>4</sub>O)** and ethylene glycol) in the production chain of various materials and products.

Ethylene and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) are produced from water (H<sub>2</sub>O) and CO<sub>2</sub> via an electrocatalytic reaction unit (see Figure 4-1, step 2). In the next step, these two intermediates are enriched and reacted to synthesize to ethylene oxide (see Figure 4-1, step 3a, 3b and 5), which can further be reacted in excess water (hydrolysis) to yield ethylene glycol [83,84]. Side products from step 2 can be recycled via combustion to CO<sub>2</sub> and water (step 4) and fed back to the electro catalysis or valorized as marketable products.



**Figure 4-1: Schematic overview of analyzed CO<sub>2</sub>EXIDE process with on-site waste-product recycling, cascade synthesis to ethylene oxide and optional side product valorization. Source: Energieinstitut.**

For the CO<sub>2</sub>EXIDE demonstrator an enrichment unit for ethylene was developed. Depending on the technological development and scale-up, it is possible that either no enrichment at all or ethylene and hydrogen peroxide enrichment is needed, depending on the amount of side products produced in the electro catalysis. As it is more likely and realized in the demonstrator in WP 6, the ethylene enrichment unit is included in order to evaluate the influence on the overall performance of the process.

Also dependent on the technological development is the necessity of an on-site recycling unit of side products. This strongly depends on the amount, kind and purity of the side products. E.g. if a high-value fuel such as renewable methane is produced in considerable amounts, internal recycling might not be the best solution. At the current status, the external side product valorization especially for hydrogen and methane is anticipated via the existing natural gas grid. However, if considerable amounts of various side products (hydrocarbons, hydrogen etc.) are produced in future scale up, their on-site combustion or recycling into the electro catalytic process and probably also the utilization of generated waste heat could be of potential interest for further assessment. Also, the combustion unit is probably needed to fulfill environmental standards as potential hazardous chemicals cannot be vented.

#### 4.1.3.2 System boundaries

For the TEA similar to the LCA (cf. Deliverable D7.2) a Cradle-to-Gate scenario is assumed, including the processes of CO<sub>2</sub> sequestration, electricity generation, water supply system and transport of the final product ethylene oxide. Cost factors are attributed in order to reflect the source of material and energy inputs.

There are three main **inputs** into the system:

- a. Electrical energy

Electrical energy is supplied, either by purchasing electricity from the grid or from a local RES plant, such as a wind park or a PV plant. The RES technology is not included into the TEA, an average energy price based on energy availability is calculated to represent the assessed source.

b. Carbon dioxide (CO<sub>2</sub>)

The CO<sub>2</sub> feedstock is supplied by a nearby biogenic stationary industrial process, e.g. via a direct line or short road transport. The CO<sub>2</sub> separation technology and process is not included in the TEA, though a specific CO<sub>2</sub> price, depending on the CO<sub>2</sub> source is considered (cf. also sensitivity analysis) covering the potential capture costs.

c. Water (H<sub>2</sub>O)

Water is supplied via the local water network, its costs are considered according to local standards for each case study resp. EU average for the benchmark system.

For the **outputs** there are two options, as either the intermediate products ethylene (C<sub>2</sub>H<sub>4</sub>) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) or the subsequent intermediate ethylene oxide can be looked at, as they are the main products of the newly developed CO<sub>2</sub>EXIDE process. Since the CO<sub>2</sub>EXIDE project aims on the development of a process to produce sustainable ethylene oxide, the latter option is chosen for this TEA.

Alternatively, also the conversion of ethylene oxide to ethylene glycol could be taken into account. However, as this last conversion step is either SOTA and identical to the fossil-based production chain or not fully developed to be assessed, this last step will be neglected here and is out of the scope of the study.

#### 4.1.3.3 Generic case

For the generic case, assumptions are aligned with the virtual demonstrator (D7.1) in terms of 2030 production capacity, faraday efficiencies and voltage efficiency.

The hourly CO<sub>2</sub> input (without recycled amount) is approx. 394 kg/h, this value corresponds with the average CO<sub>2</sub> available by the biomethane upgrading plant Bruck an der Leitha/Austria, which served as the exemplary CO<sub>2</sub> source in D7.1. The single pass conversion rate of CO<sub>2</sub> in the ERU is approx. 19 % in the 2030 case, surplus CO<sub>2</sub> is recycled. I.e., the total CO<sub>2</sub> input of the ERU is about 2,031 kg/h. For the 2040 scenario, a single pass conversion rate of 50 % was assumed.

In terms of power demand of the ERU, 11.67 MW<sub>el</sub> were considered based on 36 % total voltage efficiency and 500 mA/cm<sup>2</sup> current density as well as the available CO<sub>2</sub> amount, i.e. theoretical ethylene oxide capacity. For the 2040 case, an increased voltage efficiency of 80 % was assumed. For the electricity input, an average grid-mix electricity price was assumed.

The Faraday efficiencies throughout all scenarios were kept constant, as a change in FE<sub>C<sub>2</sub>H<sub>4</sub></sub> would cause decreased FEs of the side products and hydrogen peroxide. As no projection for the 2040 FEs is available, the conservative assumption was made that the FEs stay constant. For the ethylene oxide reaction resp. epoxidation unit (EOU), Ghanta et al. [78] was taken as

a reference, considering specific electrical energy, steam and cooling water demands per kg ethylene oxide as well as conversion efficiencies. Assumptions concerning EOU parameters were kept constant for all scenarios, as already for the 2030 scenario rather high efficiencies according to [78] were considered.

#### **4.1.3.4 Boundary Conditions - Case Studies**

Beside the evaluation of a generic implementation of the CO<sub>2</sub>EXIDE process at an industrial scale, three national case studies are considered. These case studies focus on the local availability of the basic resources for the process, i.e., renewable electricity and CO<sub>2</sub>, and mainly differ in type and amount of these. Therefore, the investigated application scenarios are described in detail in the following subsections.

##### **4.1.3.4.1 Bruck an der Leitha – Austria – Benchmark plant**

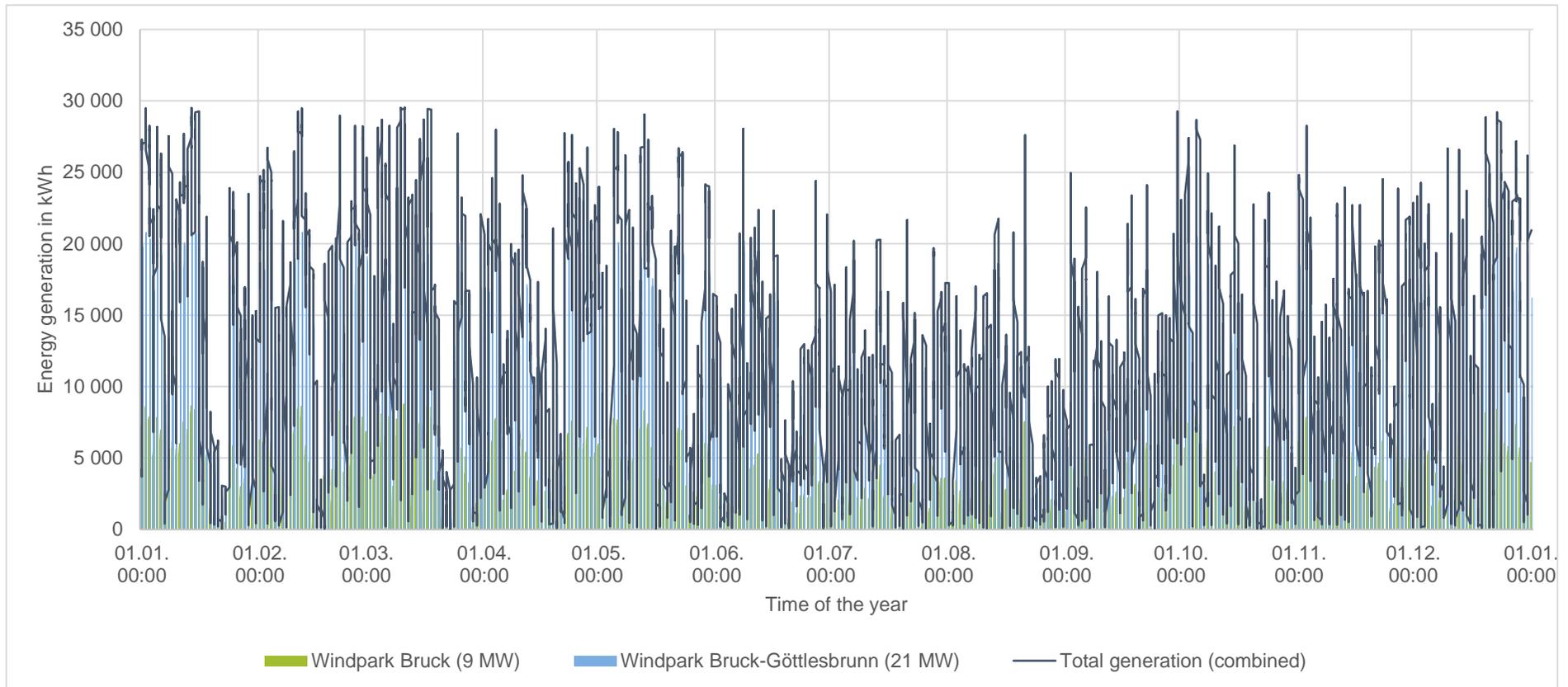
The Austrian case study was evaluated for the location Bruck an der Leitha. As mentioned before in 4.1.3.3, it also serves as the generic benchmark plant, as the generic TEA is based on the results from CO<sub>2</sub>EXIDE report D7.1. The location provides access to biogenic CO<sub>2</sub> from a local biogas plant with biomethane upgrading and thus an existing separation of CO<sub>2</sub>. The current production capacity of the biogas plant is stated with 500 m<sup>3</sup> of biomethane per hour [66]. This would result in a theoretical feedstock potential of 5,280 t CO<sub>2</sub> – assuming a CO<sub>2</sub> content of 40 %-vol. and 8,000 full load hours of operation per year. However, an on-site investigation by the project partner AXIOM revealed an actual potential of about 3,370 t<sub>CO2</sub>/a, which was then used for the following case-specific calculations.

For the renewable power supply two spatially close wind farms were identified. These wind farms, both within a distance of 7 km, have an installed capacity of about 30 MW in total. A simulation of the annual production based on historic weather data suggests an annual renewable energy production of about 96.3 GWh/a (www.renewables.ninja, [85]). Since additional data on annual energy generation is available from the plant operator [86,87], these values are used for the subsequent analyses, even though they state an up to 70 % lower annual production (approx. 66 GWh/a in total). This discrepancy is potentially due to planned and unplanned shutdowns of the wind farms throughout the year and unconsidered inefficiencies in the simulations.

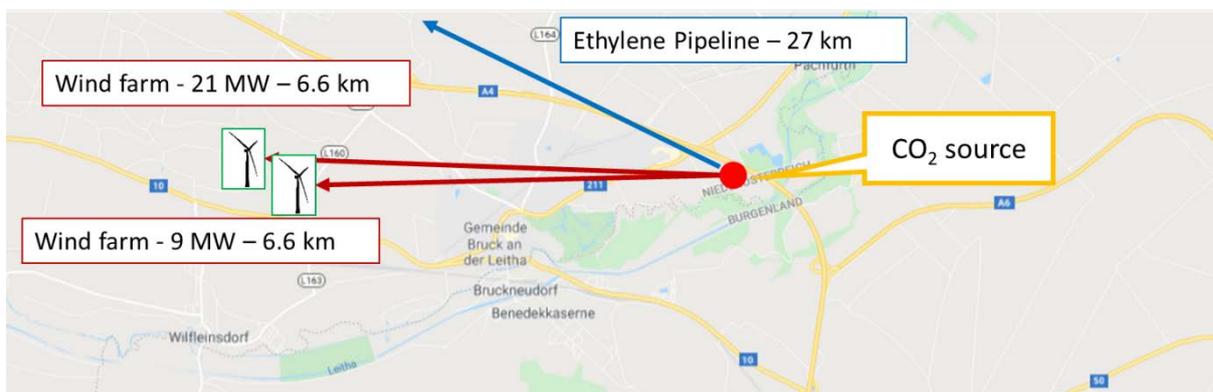
In addition to the local supply opportunities, the Austrian location also lies in relatively close range to chemical industry (about 26 km), including the beginning of an intra-national ethylene pipeline (see Figure 4-3).

**Table 4-2: Overview of CO<sub>2</sub> and power sources in Bruck an der Leitha, Austria.**  
Sources: [66,69,70,85–89]

Information on CO <sub>2</sub> -source		Matched power plants	Wind power	
Plant name	Biogasanlage Bruck/Leitha		Bruck an der Leitha (Windpark Bruck)	Bruck an der Leitha - 2 (Bruck-Göttlesbrunn)
Coordinates	48.031866, 16.821901	plant ID QGIS	48.033853, 16.726330	48.033863, 16.726330
Commissioning Year / Start of Operation	2004 (2014: biomethane upgrading)	year	2000	2015
Substrate	vegetable + animal residues (+ interim crops)	[t/a]	9,488	9,489
Separation Technology	gas pre-treatment + three-stage membrane system			
Biomethane Feed-in Capacity [m <sup>3</sup> /h]	500	Installed Power [MW]	9	21
CO <sub>2</sub> amount calculated [t/a]	5 280	Annual energy generation (simulated) [MWh/a]	21,101	75,234
CO <sub>2</sub> amount according to AXIOM [t/a]	3,366	Annual energy generation (literature) [MWh/a]	15,000	51,000



**Figure 4-2: Individual and total power generation of the RES considered in the Austrian case study. Data source: simulated with Renewables.Ninja [85] based on wind farm data from VERBUND [86,87]**



**Figure 4-3: Location of the biomethane plant Bruck/Leitha and wind farms in close proximity. Additionally, an ethylene pipeline crossing Austria is located in 27 km distance in Schwechat/Vienna. Sources: Energieinstitut based on Google Maps & input data: compare Table 4-2.**

#### **4.1.3.4.2 Zerbst – Germany**

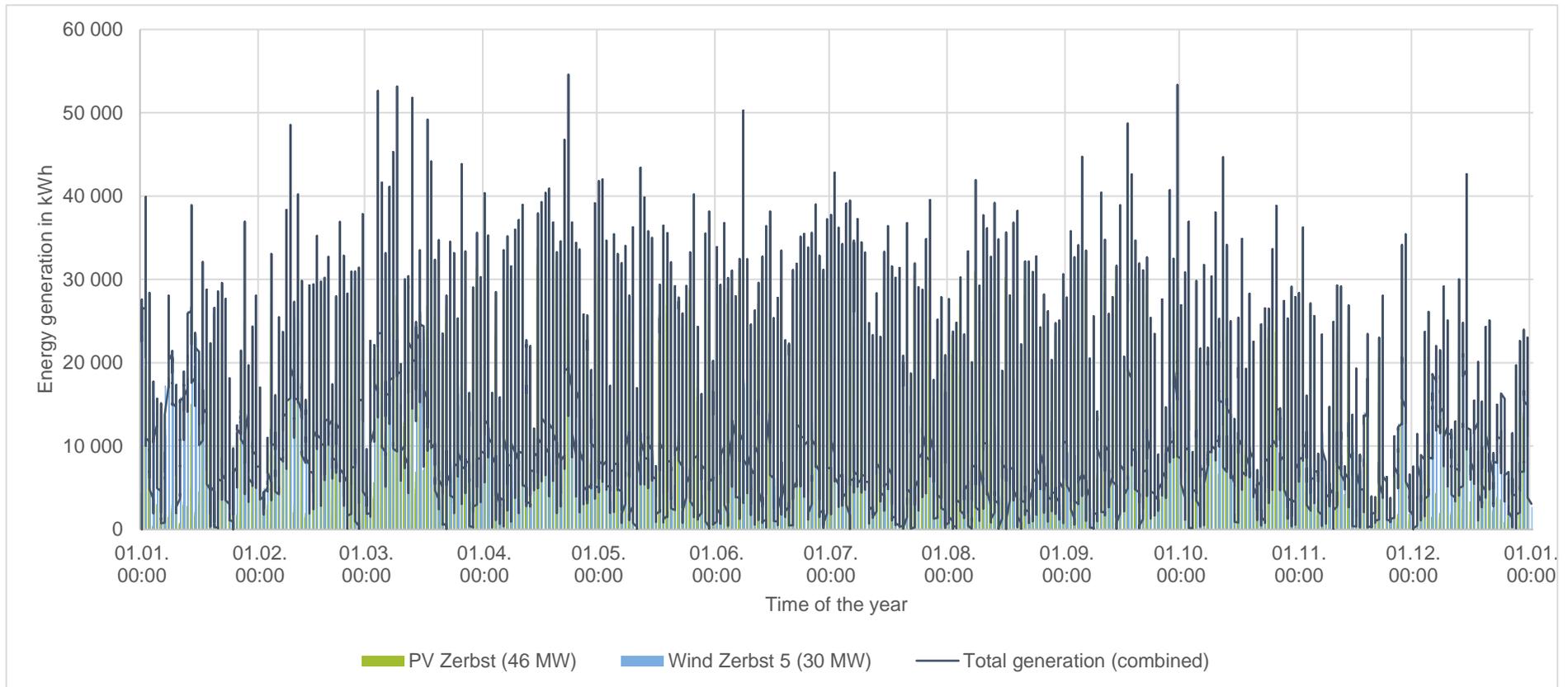
For the German case study, the Energiepark Zerbst, an energy model park in the northeast of Germany, was identified as a considerable option in the GIS-based location analysis. The location provides capacities of solar PV and wind power, as well as a biomethane plant as source for the CO<sub>2</sub> feedstock. According to the available literature data, the biomethane plant provides an annual biomethane production capacity of 770 m<sup>3</sup>/h [66]. Presuming the same conditions as for the Austrian case study – a CO<sub>2</sub> content in the biogas of 40 %-vol. and 8,000 full load hours of operation per year – the theoretical CO<sub>2</sub> resource potential for the location would relate to approx. 8131 t<sub>CO2</sub>/a.

The installed PV capacity at Zerbst is stated with 30 MW<sub>peak</sub>. Performing a simulation of the expectable PV generation for the available location data using PVGIS [90], the annual electric energy production would reach about 52 GWh/a. In addition, the available energy production from wind with an installed capacity of 46 MW were calculated to be about 57.7 GWh/a. Since these simulations were performed using Renewable.Ninja [85], showing significant differences to the actual generation for the Austrian case study, similar uncertainties can be expected here. Though, due to the lack of more reliable data, these simulated generation profiles are used for the subsequent evaluations.

Table 4-3: Overview of CO<sub>2</sub> and power sources in Zerbst, Germany.

Sources: [66,69,85,90–94]

Information on CO <sub>2</sub> -source		Matched power plants	Wind power	Solar power
Plant name	Energiepark Zerbst		Zerbst 5 (Windpark Zerbst)	Zerbst
Coordinates	52.003302, 12.133536	Plant ID QGIS	51.984869, 12.119544	51.998757, 12.134478
Commissioning Year / Start of Operation	2014	[year]	2015	2011
Substrate	Energy crops	[t/a]	78,129	78,124
Separation Technology	Water scrubbing			
Biomethane Feed-in Capacity [m <sup>3</sup> /h]	770	Installed Power [MW]	30	46
CO <sub>2</sub> amount calculated [t/a]	8,131	Annual energy generation (simulated) [MWh/a]	57,658	52,000
CO <sub>2</sub> amount literature [t/a]	n/a	Annual energy generation (literature) [MWh/a]	n/a	n/a



**Figure 4-4: Individual and total power generation of the RES considered in the German case study. Data source: wind power simulated with Renewables.Ninja [85], PV power simulated with PVGIS [90] based on wind and solar farm data from [91–94]**



**Figure 4-5: Location of the biomethane plant Zerbst within Energy Park Zerbst and the close-by wind farm and solar farm, which are also part of Energy Park Zerbst. Source: Energieinstitut based on Google Maps & input data:**

#### **4.1.3.4.3 Isle of Wight – United Kingdom**

On the Isle of Wight a considerable location for a potential implementation of the CO<sub>2</sub>EXIDE process was found in the United Kingdom. The location provides an existing biomethane plant as potential source of biogenic CO<sub>2</sub>. The theoretical potential for this feedstock material, given the same conditions as for the other case studies of 40 %-vol. of CO<sub>2</sub> content in the biogas and 8,000 full load hours of operation per year, would be about 6,300 t<sub>CO2</sub> per year. Available literature on the upgrading technology [95] states slightly higher values of 6,900 t<sub>CO2</sub>/a mainly based on higher CO<sub>2</sub> content of 45 %-vol. in the raw biogas.

The location on the Isle of Wight has several PV power plants in close proximity to the CO<sub>2</sub> source, which could serve as source for renewable electricity. For the case study 4 individual PV plants were considered within a range of 5.5 km around the biogas plant. The individual peak capacities reach from 4.8 to 10.6 MW, summing up to 28.7 MW in total. Due to the lack

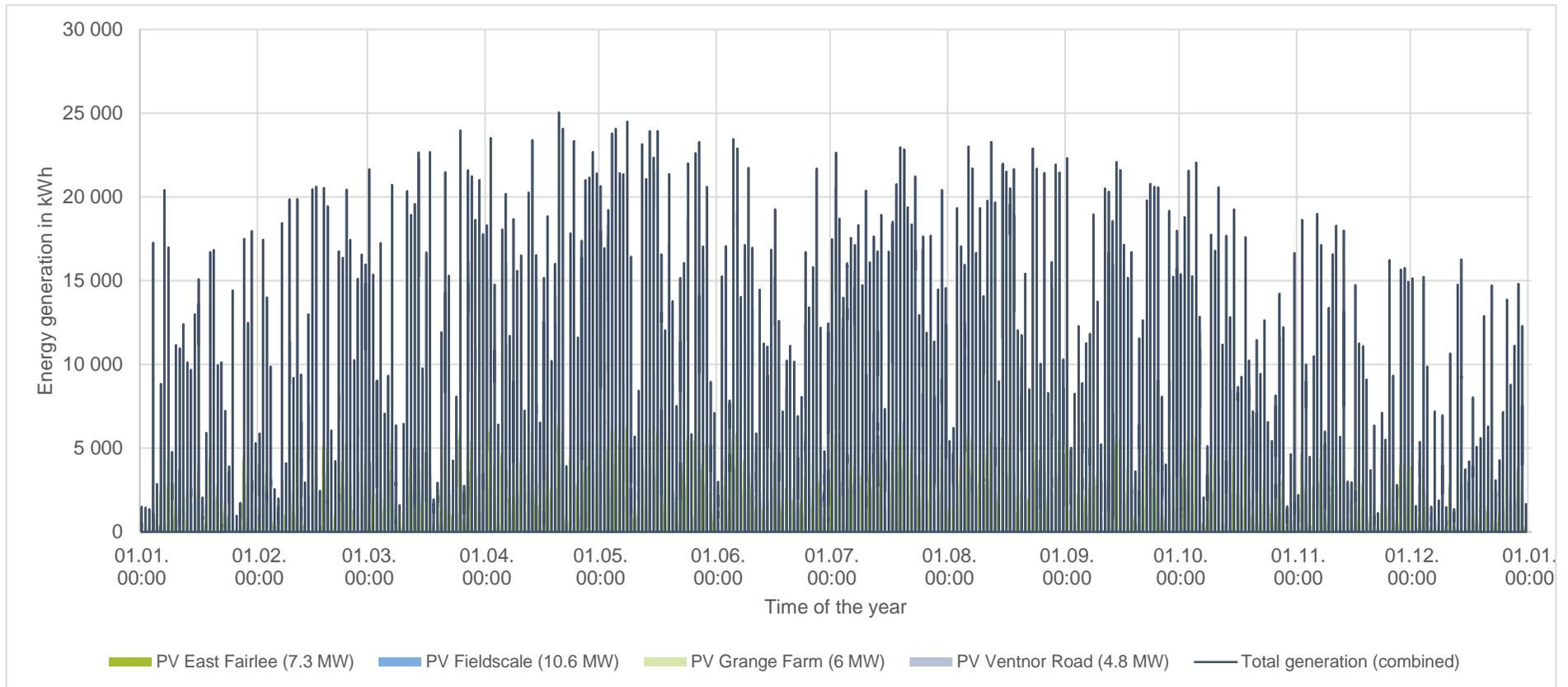
**CONFIDENTIAL**

of dedicated production data, the expected annual energy generation was again simulated for the location using PVGIS [90]. With an amount of approx. 27 GWh per year, the resulting power supply potential is significantly lower than in the other case studies.

In addition to the local resources, the availability of a sea port in a distance of about 10 km could provide an additional benefit in the consideration of the location for a potential future implementation of the CO<sub>2</sub>EXIDE process.

**Table 4-4: Overview of CO<sub>2</sub> and power sources on the Isle of Wight, United Kingdom. Sources: [66,69,90,95–98]**

Information on CO <sub>2</sub> -source		Matched power plants	Solar power			
Plant name	Gore Cross		East Fair-lee	Fieldscale	Grange Farm	Ventnor Road Solar Park
Coordinates	50.675146, -1.253390	Plant ID QGIS	50.715837, -1.274390	50.657023, -1.235434	50.712930, -1.261002	50.641604, -1.199894
Commissioning Year / Start of Operation	2014/2015	[year]	2015	2016	2015	2013
Substrate	Energy crops	[t/a]	20,008	23,035	26,687	73,468
Separation Technology	Membrane technology					
Biomethane Feed-in Capacity [m <sup>3</sup> /h]	580	Installed Power [MW]	7.3	10.6	6	4.8
CO <sub>2</sub> amount calculated [t/a]	6 336	Annual energy generation (simulated) [MWh/a]	6 987	9 769	5 742	4 640
CO <sub>2</sub> amount literature [t/a]	6 900	Annual energy generation (literature) [MWh/a]	n/a	n/a	n/a	n/a



**Figure 4-6: Individual and total power generation of the RES considered in the UK case study. Data source: PV power simulated with PVGIS [90] based on solar farm data from [96–98]**



**Figure 4-7: Location of the biomethane plant Gore Cross close to Arreton and the close by solar farms. The port of the Isle of Wight is approx. 10 km away. Approx. 20 km away on the mainland in Fawley, near Southampton, the United Kingdom's largest conventional refinery is located. Sources: Google Maps, input data: compare Table 4-4 and ExxonMobil [99], illustration: Energieinstitut.**

#### **4.1.4 Analysis of RES availability and quality for the case studies**

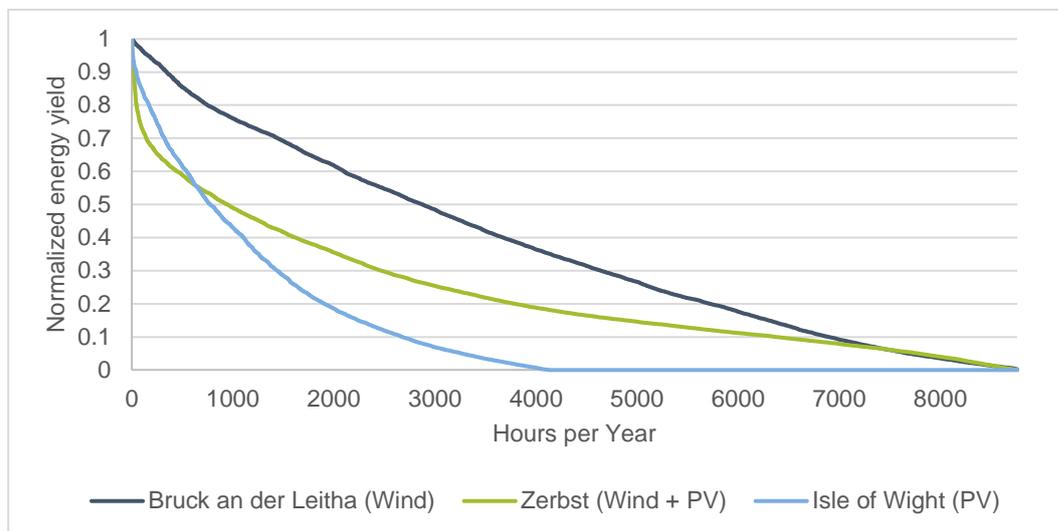
Since RES like wind or PV are rather volatile in their production, these characteristics are relevant for the operation of future implementations of the CO<sub>2</sub>EXIDE process at the evaluated locations. The results provided in Table 4-5 show that the type of energy generation has a significant impact on the temporal availability of electricity for the CO<sub>2</sub>EXIDE process. Comparing the Austrian (Bruck/Leitha) and UK (Isle of Wight) case study with similar installed RES capacities of about 30 GW, the former, which is only using wind power, is able to provide electric energy throughout the whole year, whereas the latter, relying on PV only, has actually no production for 53 % of the year is solely relying on the PV capacity. Furthermore, the total energy generation is about 3.5 times higher in the Austrian scenario valorizing the local wind production. Though the hybrid supply (PV + wind) in the German case study prevents hours of

no electricity production, the total and average generation over the year are just about 10 % higher compared to the Austrian case, despite 2.5 times higher installed capacities.

**Table 4-5: Overview of the simulated energy production for the combined RES considered in the three case studies**

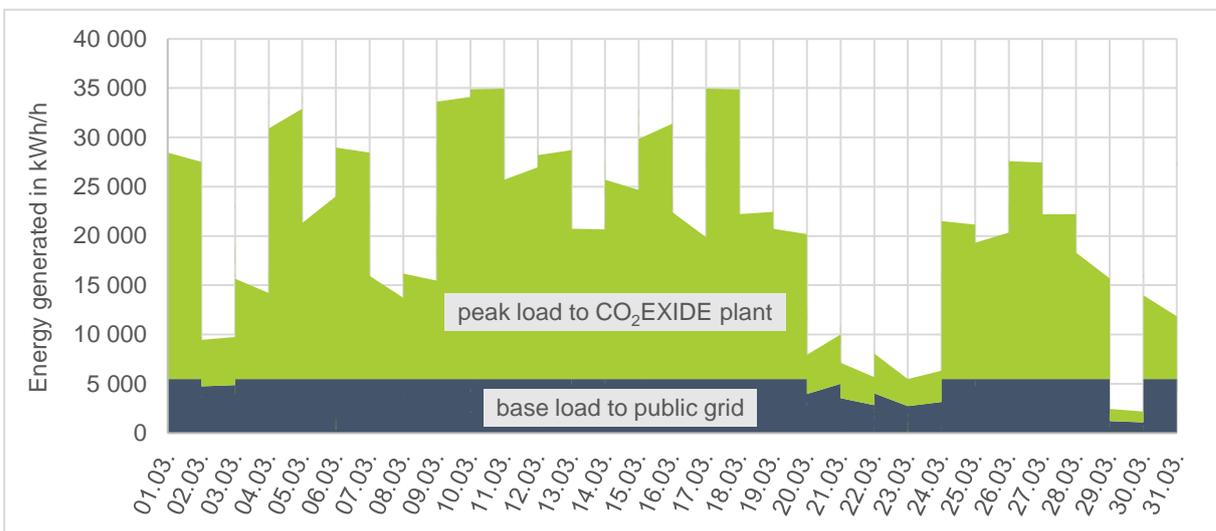
	Unit	Case study - Bruck/Leitha	Case study - Zerbst	Case study - Isle of Wight
<b>Cumulated installed RES capacity</b>	<b>MW</b>	<b>30</b>	<b>76</b>	<b>28.7</b>
<b>Total energy generated</b>	<b>MWh</b>	<b>96,344</b>	<b>109,659</b>	<b>27,138</b>
<b>Average energy generated</b>	<b>kWh/h</b>	<b>10,998</b>	<b>12,518</b>	<b>3,089</b>
<b>Share of hours with production of 0 kWh</b>	-	<b>0%</b>	<b>0%</b>	<b>53%</b>
<b>Share of hours with production &lt; 100 kWh</b>	-	<b>0%</b>	<b>0%</b>	<b>54%</b>
<b>Share of hours with production &lt; 10% of average</b>	-	<b>9%</b>	<b>5%</b>	<b>56%</b>
<b>Share of hours with production &gt;= average</b>	-	<b>45%</b>	<b>38%</b>	<b>28%</b>

Figure 4-8 confirms these calculations showing the normalized load duration curves for the renewable energy supply potentials in the three scenarios. It can be seen that the achieved power generation is well above 35 % of the nominal capacity for about 4,000 hours during the year in the Bruck/Leitha wind-only scenario. In comparison, the solely PV-based scenario at Isle of Wight can exhaust its capacity only for a few hours of the year. As a result of the intermittency only 50 % of the peak capacity is available for less than 1,000 hours – and at all electricity production is only available for about 4,000 hours of the year.



**Figure 4-8: Load duration curves for the RES at the three case studies. Source: Energieinstitut based on simulation with renewables.ninja.**

The former analyses of the individual power supply profiles showed that the direct utilization of electricity production from RES requires an appropriate flexibility of the downstream PtX process. However, this could partially be mitigated by the integration of intermediate electricity storage capacities to deburr the supply profiles for the electrochemical conversion process. Additionally, PtX processes are often suggested to be operated in a grid-supportive manner, such as balancing or peak shaving. Therefore, it could be presumed that available base load from the power generation is supplied to the grid, and thus only volatile shares of the production are used by the nearby CO<sub>2</sub>EXIDE plant (exemplarily shown in Figure 4-9). However, due the yet uncertain operational characteristics of the electrochemical conversion and downstream synthesis processes in terms of dynamicity and flexibility an according supply profile was not evaluated. Furthermore, potential economic benefits on energy supply costs for grid-supportive operation could not be estimated. Thus, these types of operation were not considered for the techno-economic assessment.



**Figure 4-9: Exemplary grid-supportive power generation and supply profile for one month at the location in Bruck an der Leitha. Source: Energieinstitut based on simulation with renewables.ninja.**

## 4.2 Indicators and Methods TEA

### 4.2.1 Literature research

For the TEA, various data are needed as input for the models and comparative analysis. For example, such data can be statistical data on energy and resource inputs, product benchmarks, technology efficiency, lifetime and cost data. Those data are taken from/based on literature, some of the input data also derive from the CO<sub>2</sub>EXIDE project directly, especially from the virtual demonstrator (D 7.3).

### 4.2.2 Evaluated techno-economic indicators

To assess the techno-economic performance of the CO<sub>2</sub>EXIDE process a predefined set of indicators was evaluated for the investigated application scenarios: Net Present value (NPV), Payback time (PBT) and Levelized Costs of Product (LCoP).

#### 4.2.2.1 Net present value (NPV)

The net present value (NPV) is a common metric in the dynamic evaluation of investments. It represents the sum of all – today's and future – cash flows of an investment discounted to the present. Therefore, it accumulates all expenditures and proceeds that are expected to occur during the operation of the plant in the considered observation period.

For the calculation of the NPV a linear depreciation was presumed, which means that CAPEX are meant to be uniformly distributed over the whole observation period. Therefore, the NPV after  $N$  periods (years), with a given interest rate  $i$  is defined as follows:

$$NPV(i, N) = \sum_{t=0}^N \frac{R_t}{(1+i)^t} \quad \text{Eq. 1}$$

with:

- $t$  ... time of the cash flow
- $N$  ... total number of periods
- $R_t$  ... cash flow at time  $t$
- $i$  ... interest rate

For the total cash flows  $R_t$  in Eq. 1, expenditures (costs) are represented as negative values and include, besides fixed costs (CAPEX and OPEX), the annual costs for feedstock materials and energy inputs. Contrary, potential revenues from product and by-product sales are represented as positive values. Consequently, a  $NPV > 0$  means that the considered investment would add value to an according operator and thus support a positive investment decision. On the other hand, a  $NPV < 0$  would represent an overall negative added value (subtract value) for the operator and thus be a factor against the investment. For the calculation of the present values

#### 4.2.2.2 Payback time (PBT)

The (static) payback time (PBT) is a simple indicator to estimate the time of operation, which would be necessary for the plant to be profitable in total. Therefore, for a static evaluation the average payback time is simply defined by dividing the overall investment costs by the total of annual costs and proceeds:

$$PBT = \frac{I}{\sum c + \sum r} \quad \text{Eq. 2}$$

with:

$I$	...	total investment costs (CAPEX)
$\sum c$	...	total annual costs
$\sum r$	...	total annual revenues

Generally, the shorter the payback time, the more profitable is the operation of the plant and the earlier a net profit is generated from operating it. Consequently, a long payback time may have a negative impact on the investment decision, whereas a negative value would indicate a non-profitable operation of the plant, independent of the overall time in operation.

#### 4.2.2.3 Levelized Costs of Product (LCoP)

To estimate potential production costs for the products generated in the CO<sub>2</sub>EXIDE process an appropriate specific indicator, denoted as *levelized costs of product* (LCoP), was calculated, comparable to similar evaluations done in other PtX assessments, such as [9]. A similar approach is commonly used when evaluating costs of electricity production named as *levelized costs of electricity* (LCoE) [100].

$$LCoP = \frac{-A + \sum_i C_{var,i}}{M_{out}} \quad \text{Eq. 3}$$

The assessment considers a full year of operation in which the total annual costs are calculated using the annuity method [101]. In Eq. 3,  $A$  represents the annuity of the fixed total annual payments such as capital- and operation-related (e.g., insurance and maintenance) costs.  $C_{var}$  represents variable costs and revenues that are dependent upon the corresponding material and energy streams and thus related to the annual time of operation and potential variable load conditions such as part-load efficiencies. These include the demand-related costs for resources such as electricity, CO<sub>2</sub>, and water, and they also include potential by-product sales.  $M_{out}$  is the total annual product mass related output of the process.

Capital-related annuity considers the investment costs of the main equipment of the CO<sub>2</sub>EXIDE plant. Additionally, it includes future costs for the expected replacement of individual components within the set observation period. It is defined as:

$$A_C = (I_0 + I_1 + \dots + I_n - R) \cdot a \quad \text{Eq. 4}$$

where  $I_0$  is the initial investment cost, and  $I_1 \dots I_n$  represents the first to  $n^{\text{th}}$  replacement investment.  $R$  represents the residual value of the plant at the end of the observation period. The

cash values of the replacement investments and residual value are calculated considering the interest rate factor  $q = 1 + i$  (where  $i$  is the interest rate) and the presumed depreciation period  $T_N$ :

$$I_n = \frac{I_0}{q^{n \cdot T_N}} \quad \text{Eq. 5}$$

$$R = I_0 \cdot \frac{(n + 1) \cdot T_N - T}{T_N \cdot q^T} \quad \text{Eq. 6}$$

The annuity factor  $a$  in Eq. 4 is calculated based on the interest rate factor and observation period:

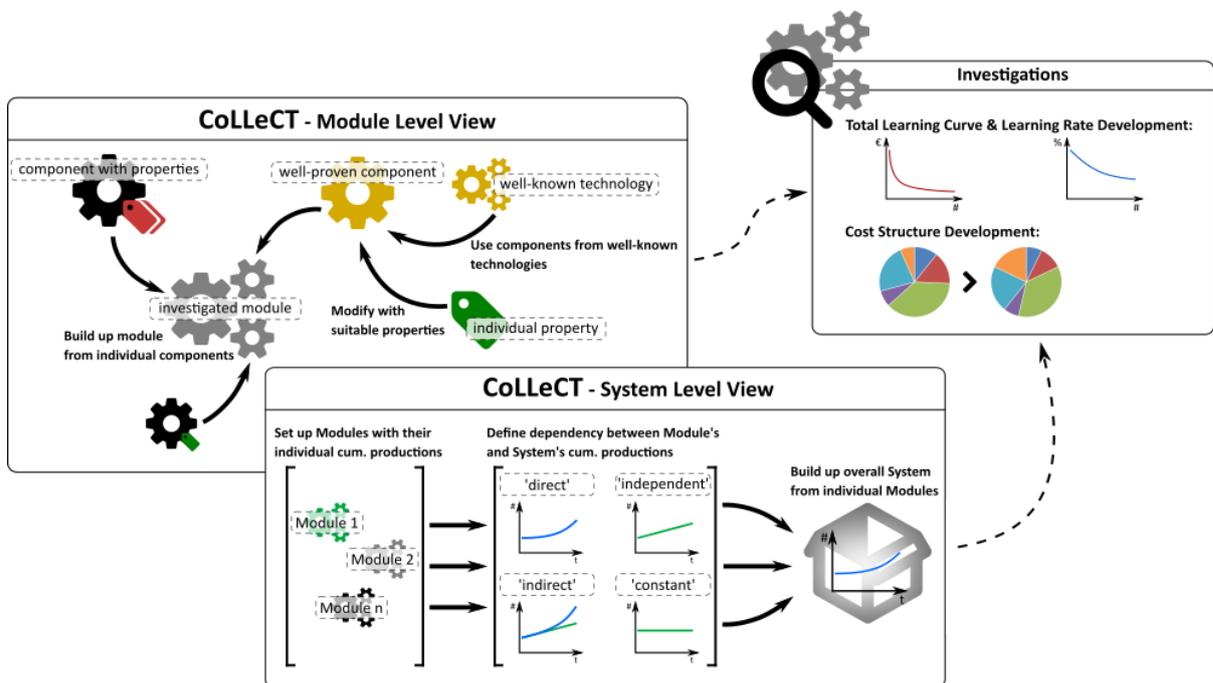
$$a = \frac{q^T \cdot (q - 1)}{q^T - 1} \quad \text{Eq. 7}$$

As only investment costs for the main equipment are directly included in the capital-related annuity, additional costs that arise such as those for engineering, construction, and commissioning of the plant were considered in the form of appropriate overhead factors [102].

The annuity of operation-related costs (maintenance and insurance) was considered as a fixed factor related to the initial investment  $I_0$  and was likewise provided with the annuity factor  $a$ .

#### **4.2.3 Learning curve model CoLLeCT**

The calculation model CoLLeCT (Component Level Learning Curve Tool) allows to determine learning curves for technologies on a low TRL. Therefore, the evaluation of learning curve effects is done by consideration of learning rates for individual components and properties specific to the investigated technology. By this disaggregation approach, it is possible to compare learning rates between different technologies with similar materials and manufacturing processes. Hence, the requirement for high production volumes to assess actual learning rates for the technology is significantly reduced. In addition, the modular approach allows to integrate common peripheral components into the analysis since direct and indirect learning effects, which are generated by spillover from concurrent usage applications, can be investigated independent from the main technology. In this context, also changes in the overall cost structure can be analyzed and thus potential leverages for cost reduction may be discovered in an early technology maturity level.



**Figure 4-10: Illustration of the learning curve assessment process using CoLLeCT**

Even though such an assessment using CoLLeCT approach requires – dependent on the chosen grade of modularization – a proper knowledge of the component and cost structure as well as according individual learning rates, the share of technology-specific components is usually low. Hence, component learning rates can often be derived from established technologies. Consequently, the generation of broader-based data pool and thus the spectrum of assessable technologies is considerably improved.

Apart from technological learning effects that solely relate to the gain of expertise by increase of the cumulative volume of produced (or installed) units, cost reductions through a scale-up of the individual unit capacities is a relevant factor for the assessment of future implementations. In this context, the disaggregated structure of the CoLLeCT approach allows to consider these economies of unit scale more specific. Since main components are already known, appropriate scaling factors can be applied individually instead of using a common scale factor (e.g., 0.6, acc. to the “six-tenth-factor rule” [102]). Since appropriate scaling effects for common plant components are widely available – e.g., from former experience, literature, chemical engineering analysis – the modular CoLLeCT approach helps to increase the accuracy in assessing costs for different plant scales.

A detailed description of the model and its application on power-to-gas technologies can be found in relevant publications [9,103].

## 4.3 Input data inventory

### 4.3.1 General input data

Due to the fact that the CO<sub>2</sub>EXIDE technologies and processes are still in an early development stage, technical and economic characteristics for an implementation at industrial scale were only partially derivable from the actual project results. Most of the presumptions and projections made for future plant performances were based on the results delivered from the virtual demonstrator (see Deliverable D7.1). To cover these parameters, additional literature data was exploited where available from similar process evaluations, experimental studies and techno-economic assessments. The according references are stated in the appropriate sections and parameter tables.

Since especially cost data available in literature is subject to permanent change related to conversion rates between different currencies and inflation, a normalization of all used cost data to current values was performed. The according conversion factors used are summarized in Table 4-6.

**Table 4-6: Calculation factors used for cost conversion between sources of different currencies and publication dates**

Conversion	Factor
<b>Currency</b>	
USD to EUR (2010)	0.755
USD to EUR (2013)	0.779
USD to EUR (2018)	0.847
<b>Inflation</b>	
2010 to 2021	1.15
2013 to 2021	1.09
2018 to 2021	1.04

### 4.3.2 Technical parameters and assumptions

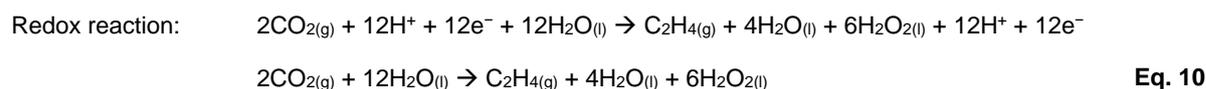
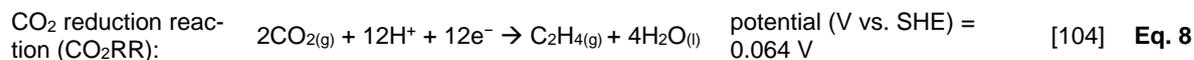
#### 4.3.2.1 Electrochemical reactor unit (ERU) specifications

The electro catalysis with a low TRL of 3-4 is the core technology of the CO<sub>2</sub>EXIDE process and the TEA. The process bases on common water electrolysis technology with comparatively high TRL, therefore, the assumptions made base on experiences with techno-economic assessments of PtX projects with a TRL of 8 to 9.

The electrocatalytic reactor consists of two parallel half cells, containing the cathode chamber (oxidation, ethylene production) and anode chamber (reduction of water to hydrogen peroxide). Each chamber is supplied with an electrolyte solution, in this case KHCO<sub>3</sub> at different concentrations. The cathode of the demonstrator setup consists of copper sputter deposited on a Freudenberg gas diffusion layer (Cu/GDL), while the anode is composed of boron-doped diamond / niobium electrode (BBD/Nb). The chambers are separated by a membrane, various

membranes have been tested, for the demonstrator a commercially available Nafion membrane was chosen. The overall cell design is comparable to commercially available hydrogen PEM cells.

The following half-cell reactions (Eq. 8, Eq. 9) shall take place, leading to the overall combined reaction according to Eq. 10 :



Taking into account thermodynamic principles (operating temperature of the cell i.a.), the theoretical cell potential is therefore  $1.760 \text{ V} - 0.08 \text{ V} = 1.68 \text{ V}$ <sup>6</sup>, under real conditions, higher voltages apply as overpotentials due to cell resistances i.e., are needed. Furthermore, competitive reactions have to be prevented, such as oxygen evolution through water splitting at the anode or production of other hydrocarbons than ethylene at the cathode. Lastly, the chosen electrodes, catalysts and electrolytes influence the overall cell potential as well as the selectivity of reaction. In this sense also the current density is of utmost importance as it determines the theoretically possible amount of wanted products as well as the Faraday efficiency. [104–106]

For the demonstrator in the laboratory, current densities of 150 to 200 mA/cm<sup>2</sup> with 300 cm<sup>2</sup> active cell area are applied. The applied cell voltage reaches up to 10 V. In terms of overall energy efficiency, low voltages and high current densities in combination with high selectivity (= Faraday efficiency) of the target products are aimed at. Consequently, in the 2030 and 2040 scenarios lower voltages and higher current densities are assumed for future large-scale applications. For 2030, a voltage efficiency of 36 % is assumed (i.e. 4.67 V cell voltage), while in the 2040 scenario 80 % are assumed, i.e. 2.1 V cell voltage. For the current density, 500 mA/cm<sup>2</sup> are applied for 2030 and 2040, the value is varied in the sensitivity analyses.

The electrical power input was calculated based on the cell voltage, which derives from the theoretical voltage and the voltage efficiency on one side, on the other side the current, i.e. electrons needed to convert CO<sub>2</sub> and water to the various electrocatalytic products was considered via the FE of ethylene, based on Jouny et al. [104] See also following Eq. 11 on current calculation. The number of moles was calculated via mass flow and molar mass of ethylene.

---

<sup>6</sup> Written communication by Erhard Magori / Siemens via e-mail - 19.05.2021 / 15:26

Subsequently, power was calculated via  $P [W] = U [V] * I [A]$ . Additionally, via the current and a given current density, the active area of the ERU was calculated.

$$Q = \frac{z * n * F}{FE} \quad \text{Eq. 11}$$

with:

$Q$  = Charge passed, i.e. current  $I$  [A]

$z$  = number of required electrons to produce a given product [-]

$n$  = number of moles of given product [mol]

$F$  = Faraday constant [Coulomb/mol]

$FE$  = Faraday efficiency of given product [%]

Due to temperature sensitivity of the reactions and products (e.g. hydrogen peroxide decomposition), the overall cell and the electrolytes should be kept at max. 30 °C (cf. D6.5), i.e. at least one of the electrolytes has to be cooled to keep the overall cell temperature low. Additionally, to cooling, further improvements in energy efficiency can also lead to less cell heating, as energy losses in terms of heat might be reduced.

#### **4.3.2.1.1 Faraday Efficiencies (FE) (Selectivity)**

Recent literature reports faraday efficiencies for ethylene of up to 70 % mostly for half-cell assemblies against a reference electrode. At the same time, research on water oxidation reaction aiming on hydrogen peroxide as final product, reported FE of up to 70 % (ZnO @ 3 V vs RHE) as well, although most catalysts lead to lower FE at same voltage applied [107].

For this TEA, 48 % FE for the large-scale application scenario (year 2030 and 2040) are assumed for ethylene (cf. D7.1) as well as hydrogen peroxide.

Promising laboratory results were obtained in terms of stability of the BDD anodes in literature (see Table 4-7 and Table 4-8) as well as in the experimental work within the CO<sub>2</sub>EXIDE project. The project demands stability for roughly 1000 h which could not be verified empirically on a laboratory scale. However, in experiments which lasted up to 10 h no signs of degradation were obtained. Thus, an optimistic lifetime of 1000 hours was assumed.

**Table 4-7: Overview of electrocatalytic processes of CO / CO<sub>2</sub> to ethylene conversion according to literature. (1/2)**

Input stream	Output streams	Cell design	Electrodes / Catalysts / Membrane	Electrolyte	Cathodic FE [%]	Cell energy efficiency [%]	Current density / Cell voltage	Runtime [hours]	Year	Source
CO <sub>2</sub>	C <sub>2</sub> H <sub>4</sub> , Ethanol	Full cell	Cathode: GDEs covered with CuNP Anode: IrO <sub>2</sub> Catalysts: different CuNP catalysts Membrane: anion exchange membrane (Fumatech®)	1 M KOH	~ 27-46 (C <sub>2</sub> H <sub>4</sub> FE)*		-80 to -150 mA/cm <sup>2</sup> (C <sub>2</sub> H <sub>4</sub> partial current density)  -0.6 to -0.8 V vs RHE (cathode potential)	Up to 4	2016	[108]
CO <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	Full cell	Cathode: graphite/ carbon NPs/ Cu/ PTFE cathode Catalyst: NiFeOx oxygen evolution catalyst	7 M KOH		34 % full cell energy efficiency for conversion to ethylene	110 mA/cm <sup>2</sup> 2.4 V	1	2018	[109]
		Cathodic chamber against RHE	Cathode: graphite/ carbon NPs/ Cu/ PTFE		70 (C <sub>2</sub> H <sub>4</sub> FE)		55-70 mA/cm <sup>2</sup> (C <sub>2</sub> H <sub>4</sub> current density) -0.55 V vs RHE	150		
CO <sub>2</sub> @1 bar	C <sub>2</sub> H <sub>4</sub> , CO, H <sub>2</sub>	Various cell designs tested	Cathode: Cu-GDE, Nafion-bonded (pH ≈ 6.5) Anodic chamber: PEM-like design (pH ≈ 1.2) Membrane: Fumapem F14100 (Fumatech) CEM Catalysts: different silver/copper full metal electrodes / nanoparticulate GDEs	0.5 M K <sub>2</sub> SO <sub>4</sub> **	Up to 94 (C <sub>2</sub> H <sub>4</sub> current efficiency***)		300 mA/cm <sup>2</sup> (total) - 1.05 V vs RHE	n/a	2019	[110]
CO	C <sub>2</sub> H <sub>4</sub> (mainly)	GDE cell design	Cathode: Cu-GDE Anode: Ni Foam Membrane: PBI	1 M NaOH	65 (FE) 56 (single-pass-conversion rate of CO)		107 mA/cm <sup>2</sup> 2.59 V	4	2019	[111]
			Cathode: Cu-GDE Anode: Ni-coated Ti foam Membrane: Nafion	Anolyte: 1 M NaOH  No catholyte	72 (CO reduction) 43 (single-pass-conversion of CO)  [111] / Fig. 5E: 74 (FE CO reduction) 40 (FE C <sub>2</sub> H <sub>4</sub> )	24 (voltage efficiency CO to C <sub>2</sub> H <sub>4</sub> )	144 mA/cm <sup>2</sup> 2.32 V	24		

**Table 4-8: Overview of electrocatalytic processes of CO / CO<sub>2</sub> to ethylene conversion according to literature. (2/2)**

Input stream	Output streams	Cell design	Electrodes / Catalysts / Membrane	Electrolyte	Cathodic FE [%]	Cell energy efficiency [%]	Current density / Cell voltage	Runtime [hours]	Year	Source
CO	C <sub>2</sub> H <sub>4</sub> , Acetate	Flow electrolyte			68 (single-pass-conversion rate of CO)		107 mA/cm <sup>2</sup>	4	2019	[112]
		Membrane electrode assembly			43 (single-pass-conversion rate of CO)		104 mA/cm <sup>2</sup>	24		
CO <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>		Catalyst: ionomer bulk hetero-junction (CIBH) @ 60°C	7 M KOH	65-75 (FE C <sub>2</sub> H <sub>4</sub> )	46 +/-3 (cathodic energy efficiency)	1.34 A/cm <sup>2</sup> (partial current density of C <sub>2</sub> H <sub>4</sub> ) Approx. 3 V cell voltage (?)	60	2020	[113]
CO <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	membrane-electrode assembly	Cathode: PTFE electrode with N-aryl-dihydropyridine-based oligomer modified Cu (Cu-12) Anode: IrOx/Ti mesh Membrane: Sustainion®	0.1 M KHCO <sub>3</sub>	72 (C <sub>2</sub> H <sub>4</sub> FE)	20 (full-cell energy efficiency)	600 mA (stable current full cell) 3.65 V (full cell potential)	190	2020	[114]
		Cathodic chamber against RHE	Cathode: PTFE electrode with N-aryl-dihydropyridine-based oligomer modified Cu (Cu-12)	1 M KHCO <sub>3</sub>	72 (C <sub>2</sub> H <sub>4</sub> FE)		230 mA/cm <sup>2</sup> (partial current density C <sub>2</sub> H <sub>4</sub> ) -0.83 V vs RHE	n/a		
CO <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	Half-cell, experimental set up	Cathode: de-alloyed Cu-Al on PTFE	1 M KOH	80 +/-2 (C <sub>2</sub> H <sub>4</sub> FE)	34 +/-1 (C <sub>2</sub> H <sub>4</sub> power conversion efficiency, half-cell only)	400 mA/cm <sup>2</sup>	100	2020	[115]
				3 M KOH	70 +/-2 (C <sub>2</sub> H <sub>4</sub> FE)	52 +/-1 (C <sub>2</sub> H <sub>4</sub> power conversion efficiency, half-cell only)	150 mA/cm <sup>2</sup>			
				3 M KOH + 3 M KI	73 +/-4	55 +/-2 (C <sub>2</sub> H <sub>4</sub> power conversion efficiency, half-cell only)	150 mA/cm <sup>2</sup>	50		

PTFE – polytetrafluoroethylene  
 KOH – Potassium hydroxide  
 KI – Potassium iodide  
 GDE – gas diffusion electrode  
 CEM – cation exchange membrane  
 RHE – reversible hydrogen electrode

GDL – gas diffusion layer  
 CuNP – Copper nanoparticles  
 \* Continuous: volume fixed at 150 ml (recycled over complete course of experiment @ 30°C)  
 \*\* cf. [108]/Fig.5, Fig. 8  
 \*\*\* Setup e) with CU (cf. [108]/Fig. 8)

When it comes to the production of hydrogen peroxide, as one can gather from the presented literature data (see Table 4-9), a high current density tends to cause low faraday efficiencies and vice versa. Yet, it can be pointed out that a higher current also leads to higher production values of hydrogen peroxide. Selected examples of highest FEs are achieved with  $K_2CO_3$  which is too alkaline for hydrogen peroxide and furthers its degradation. Thus, an ideal system would employ a high faradaic efficiency, high current density and therefore high yields.

**Table 4-9: Overview of electrocatalytic processes to convert  $O_2$  or  $H_2O$  to  $H_2O_2$  according to literature.**

Input stream	Electrodes / Catalysts / Membrane	Electrolyte	Cathodic FE [%]	Current density / Cell voltage	Runtime [hours]	Year	Source
$H_2O$	BDD on Ti // Nafion	$KHCO_3$ , pH 8	28	120 mA/cm <sup>2</sup> 3.17 V	0.208	2020	[116]
$H_2O/O_2$	C-Cathode & BiVO <sub>4</sub> -Anode	2M $KHCO_3$	92	1.09 mA/cm <sup>2</sup> 1.7 V	5	2018	[117]
$H_2O/O_2$	PTFE Cathode & BDD Anode / $FeSO_4 \cdot 6H_2O$ /	pH 3.0	89.3	74 mA/cm <sup>2</sup> 0.4 kWh m <sup>-3</sup>	2.5	2019	[118]
$H_2O/O_2$	BDD	pH 3.0	89	1.28 mA/cm <sup>2</sup> 2.8 V	3	2013	[119]

#### 4.3.2.1.2 Conversion efficiency

Additionally to the selectivity, the single-pass conversion efficiency is also important in terms of overall energy efficiency. This is especially true for the  $CO_2$  conversion efficiency, as unreacted  $CO_2$  has to be separated from the gaseous ethylene and fed back to the cathode/ $CO_2$  storage (if any). In terms of educt recycling, for the anodic reaction single pass conversion is less determining as the overall reactions take place in aqueous solutions, i.e. unreacted water is recycled automatically due to electrolyte cycling. However, for both products, high concentration is relevant (i.e., ethylene in the product gas mixture and hydrogen peroxide in water) in order to decrease the energy input for product separation and product losses.

In order to enhance the  $CO_2$  utilization rate,  $CO_2$  recycling is considered in the ethylene enrichment unit and process integration into a biogas upgrading plant. In the TEA single-pass conversion rates for  $CO_2$  of approx. 19 % (incl. conversion to side-products) are considered (based on D7.1 virtual demonstrator balance, scenario 2030). According to literature up to 50 % (solely to ethylene) could potentially be realized in future, depending on the electrocatalytic CCU route [104].

At the same time, side-products might be formed as well, as these can aggregate in considerable amounts and be of value as well, some of them are considered in the TEA.

**Table 4-10: Characteristics of the electrochemical reactor unit**

Parameter	Unit	2030	2040	Notes
<b>Electric characteristics</b>				
Current density	A/cm <sup>2</sup>	0.50	0.50	
Voltage efficiency	%	36	80	
Cell voltage theoretical	V	1.68	1.68	
Cell voltage applied	V	4.67	2.10	calculated
Power demand	MW	11.67	5.25	calculated
<b>Efficiencies</b>				
Product selectivity cathode (FE C <sub>2</sub> H <sub>4</sub> )	%	48	48	
Conversion efficiency cathode	%	19	50	
Product selectivity anode (FE H <sub>2</sub> O <sub>2</sub> )	%	48	48	
Conversion efficiency anode	%	0.10	10	

#### 4.3.2.2 Ethylene enrichment unit (EEU) specifications

For the enrichment of the (intermediate) product ethylene, various technologies are available, such as physical absorption, pressure swing adsorption (PSA) and membrane separation, to name just a few. In CO<sub>2</sub>EXIDE the ethylene enrichment unit (EEU) is designed as a two-stage membrane separation unit, the main input is electricity to run the compressors (cf. D6.4). Also, a TRL of up to 9 can be assumed.

According to the 2030 scenario, approx. 6 kWh/kg<sub>C<sub>2</sub>H<sub>4</sub></sub> recovered are needed (including energy needed for separation of hydrogen and unreacted CO<sub>2</sub>, side product methane is considered to be separated in the EOU process). The value is used for the 2030 TEA scenario. For 2040 the energy demand is lower than 6 kWh, as recycled CO<sub>2</sub> volumes streams are lower due to higher single-pass conversion efficiencies. Table 4-11 shows the specific energy demand for ethylene separation alone and subsequent CO<sub>2</sub> recycling and hydrogen separation.

**Table 4-11: Characteristics of the ethylene enrichment unit (EEU)**

Parameter	Unit	2030	2040	Notes
Power demand EEU	kWh/kg C <sub>2</sub> H <sub>4</sub> recov.	3.37	3.37	Based on D7.1
Power demand H <sub>2</sub> /CO <sub>2</sub> separator	kWh/kg H <sub>2</sub> +CO <sub>2</sub> recov.	0.13	0.13	Based on D7.1
Ethylene recovery rate	%	76.77	76.77	Based on D7.1

The EEU also separates the unreacted CO<sub>2</sub> as well as other side-products from the ethylene. The separated streams then can be recycled on-site (especially CO<sub>2</sub>) resp. fed into the gas grid (methane, also hydrogen to some extent) or sold directly (hydrogen).

#### 4.3.2.3 Ethylene epoxidation unit (EOU) specifications

For the chemical synthesis of ethylene oxide (C<sub>2</sub>H<sub>4</sub>O), the anodic ERU intermediate hydrogen peroxide (in aqueous solution) is mixed with the gaseous cathodic intermediate ethylene. For the virtual demonstrator, it is assumed that the reaction is assumed to take place in a tube reactor, supported by catalysts (c.f. D7.1). Based on Ghanta et al [78], for future (2030 & 2040) large scale scenarios, ethylene single-pass conversion rates of 90 % and 99 %+ selectivity to ethylene oxide were assumed, also, unreacted ethylene is being recycled in [78]. Steam and electricity demand per kg ethylene oxide were also considered based on [78].

Ghanta et al. [78] describe that methanol is used as an additional solvent to water and is being recovered after the ethylene oxide separation. Furthermore, they consider small amounts of catalyst promoter. For the CO<sub>2</sub>EXIDE process however, we assume that the catalysts (and potential promoters) remain constant and without significant losses in quality in the epoxidation system, i.e., no additional process or flows are modelled that consider auxiliary materials for the epoxidation.

**Table 4-12: Characteristics of the epoxidation reactor**

Parameter	Unit	Value	Notes
Power demand	kWh/kg C <sub>2</sub> H <sub>4</sub> O	0.339	based on [78]
Steam demand	kg/kg C <sub>2</sub> H <sub>4</sub> O	0.740	based on [78]
Cooling water demand	m <sup>3</sup> /kg C <sub>2</sub> H <sub>4</sub> O	0.463	based on [78]
Selectivity to C <sub>2</sub> H <sub>4</sub> O	%	99	based on [78]
Conversion efficiency	%	90	based on [78]
Mass ratio H <sub>2</sub> O <sub>2</sub> /C <sub>2</sub> H <sub>4</sub> O	-	0.7721	stoichiometric
Mass ratio C <sub>2</sub> H <sub>4</sub> /C <sub>2</sub> H <sub>4</sub> O	-	0.6368	stoichiometric

#### 4.3.2.4 Technical maturity of the overall system

Finally, the maturity of the core components in the CO<sub>2</sub>EXIDE process and the downstream processes sum up to the overall TRL of the process. Under consideration of the individual components and their TRLs as well as the implied interactions in the complete process, the overall TRL of the investigated system is evaluated to be in the range of 4-5.

Since renewable electricity and CO<sub>2</sub> feedstock are basically considered as input materials and thus the according technologies are not in the scope of this TEA, their TRLs are not evaluated nor considered herein.

### 4.3.3 Economic parameters and assumptions

The economic parameters for the techno-economic evaluation are summarized in Table 4-13 below. The calculations of individual cost factors and interactions are described in the according following subsections.

**Table 4-13: Economic calculation parameters**

Parameter	Unit	2030	2040	Source
<b>General</b>				
Interest rate	%	3	3	assumption
Observation period	years	20	20	[120], based on overall plant lifetime
Deprecation period (for NPV calculation)	years	20	20	[120], based on overall plant lifetime
<b>OPEX</b>				
OPEX Maintenance	% of CAPEX	7	7	[121]
OPEX Insurance	% of CAPEX	1	1	[121]
Plant overhead	% of OPEX	50	50	[121]
<b>Electricity costs</b>				
Grid supply	€/MWh	35.6	35.6	[122], no projections for future grid electricity costs made
PV direct supply	€/MWh	55*	30	[123], SDS *2019 values used from the reference
Wind direct supply	€/MWh	55*	45	[123], SDS *2019 values used from the reference
<b>Feedstock costs</b>				
CO <sub>2</sub>	€/t	0	0	[7], lower range value for biogas upgrading
Water	€/m <sup>3</sup>	1.26	1.26	based on [104]
Cooling water	€/m <sup>3</sup>	0.019	0.019	based on [78]
Steam	€/kg	0.016	0.016	based on [78]
<b>Product Revenues</b>				
Ethylene	€/kg	0.75	1.50	based on [124]
Hydrogen Peroxide	€/kg	0.50	0.50	assumption
Ethylene Oxide	€/kg	1.50	3.00	assumption
Methane	€/kWh	0.05	0.15	based on [125] and [9] for renewable methane production in 2040
Hydrogen	€/kWh	0.10	0.08	based on [9] for renewable hydrogen production
<b>Additional</b>				
CO <sub>2</sub> ETS price	€/t	50	100	for 2030 actual prices are assumed, assumption for 2040

Crucial for achieving cost-competitiveness for the electrocatalytic CO<sub>2</sub> conversion on this route is low-cost CO<sub>2</sub> supply, as most activities related to CO<sub>2</sub> electrolysis operate with a pure CO<sub>2</sub> stream (development of impurity-tolerant catalysts capable of directly converting flue gas is an

urgent requirement). CO<sub>2</sub> prices in the European emissions trading scheme continue to rise. At the auctions in June, >50 €/t CO<sub>2</sub> were achieved. The rise has systemic, political and also speculative backgrounds. If a universal carbon tax on one-way carbon is introduced, “waste” carbon would suddenly become a valuable commodity.



**Figure 4-11: EU ETS carbon price development. Source: Energieinstitut based on [126]**

The ETS remuneration was considered in the TEA not via the utilized carbon dioxide input but via the fossil products substituted by the various products of the CO<sub>2</sub>EXIDE plant. The GWP potential of the substituted fossil products was modelled with GaBi 10.5 by Sphera ts modelling. Predefined processes by Gabi Sphera and Plastics Europe were used, see also Table 4-14 below.

**Table 4-14: Overview of fossil reference products and der GWP.**

GWP fossil reference products	Value	Unit	GaBi / Plastics Europe process
Ethylene	1.28	kg CO <sub>2</sub> eq./kgC <sub>2</sub> H <sub>4</sub>	EO via air / EU-28 / GaBi Sphera
Ethylene oxide (EO)	1.51	kg CO <sub>2</sub> eq./kgEO	Ethylene oxide via air DE / GaBi Sphera
Hydrogen peroxide	1.68	kg CO <sub>2</sub> eq./kgH <sub>2</sub> O <sub>2</sub>	DE: H <sub>2</sub> O <sub>2</sub> (100 %, H <sub>2</sub> from Steam cracker) / GaBi Sphera
Hydrogen	7.77	kg CO <sub>2</sub> eq./kgH <sub>2</sub>	RER: Plastics Europe H <sub>2</sub> from Steam reforming
Methane	0.578	kg CO <sub>2</sub> eq./kgCH <sub>4</sub>	DE: Methane / GaBi Sphera

### 4.3.3.1 CAPEX

In the following subsections the evaluation of projection of general capital expenditures (CAPEX) is described. These CAPEX include the direct costs for equipment purchase, reinvestments for expected replacements during the observation period and indirect costs that are not directly according to purchased equipment.

#### 4.3.3.1.1 Electrochemical reactor unit (ERU) costs

The electrochemical reactor unit (ERU) represents one of the main equipment that was developed during the CO<sub>2</sub>EXIDE project. Due to the novelty of this technology and the accordingly low TRL, the expectable CAPEX for an installation in an industrial environment at appropriate scale cannot be derived from the current demonstration scale. Thus, for the evaluation of the application scenarios targeting an implementation in the year 2030/2040, significant technological learning and scaling effects can be expected in relation to the current SOTA.

However, since a dedicated plant setup for an industrial implementation is yet undefined, suggested learning curve models (see section 4.2.3) cannot be applied directly. Therefore, references to existing evaluations for comparable technologies were considered. According to the technological similarities of the electrochemical cell used in the CO<sub>2</sub>EXIDE process and the proton exchange membrane (PEM) technology as a common representative for water electrolysis, recent cost development projections for the PEM electrolysis were used as calculated by Böhm, et al. [9]. For the system capacities relevant in the investigated implementation scenarios, 11.7 MW (2030) and 5.3 MW (2040), respectively, the modularized system costs as per Table 4-15 are calculated for PEM electrolysis in appropriate scales.

**Table 4-15: Modularized PEM water electrolysis costs and electrical characteristics in relevant system sizes. Based on [9]**

Year	Scale	Module	Costs in €/kW	Current density A/cm <sup>2</sup>	Cell voltage in V
2030	10 MW	<b>Overall system</b>	<b>542.6</b>	2.5	1.6
		<b>PEM Cell Stack</b>	<b>336.0</b>		
		<b>Power Electronics</b>	<b>122.2</b>		
		<b>Balance of Plant</b>	<b>84.3</b>		
2040	5 MW	<b>Overall system</b>	<b>274.7</b>	3.1	1.5
		<b>PEM Cell Stack</b>	<b>141.7</b>		
		<b>Power Electronics</b>	<b>83.5</b>		
		<b>Balance of Plant</b>	<b>49.5</b>		

To consider the impact of different reaction and conversion efficiencies between the two electrochemical processes in the scaling of the equipment costs, the costs for the electrocatalytic cell were transferred by taking the electrical characteristics of both technologies into account.

Thus, the costs of the cell stack module were converted to an area-related basis to be comparable. For the other modules listed in Table 4-15 they were presumed to be comparable as stated related to the electric capacity of the electrochemical cell. Thus, the specific ERU system costs were evaluated as summarized in Table 4-16 for the investigated future scenarios.

**Table 4-16: Specific CAPEX for the ERU considering learning curve and scaling effects using the CoLLeCT model**

Year	Scale (base)	ERU system costs		Current density in A/cm <sup>2</sup>	Cell voltage in V
		in €/kW	in €		
2030	10 MW	782.0	9,123,070 (11.7 MW)	0.5	4.67
2040	5 MW	745.0	3,911,046 (5.25 MW)	0.5	2.10

The results in Table 4-16 show that specific costs for the ERU are at a comparable level for both scenarios. Compared to the water electrolysis cell, it can be concluded from the slightly lower specific costs in 2040 that effects of technological learning (from produced units between 2030 and 2040) exceed the effects of downscaling (from 10 MW to 5 MW). Though, the expected decreasing power density of the ERU cell prevents an even more significant effect of the learning curve (related to the electric system capacity).

#### **4.3.3.1.2 Other main equipment**

Apart from the ERU, the ethylene enrichment unit (EEU) for the purification of the ethylene product stream and the epoxidation unit (EOU) for the synthesis of ethylene to ethylene oxide (incl. the separation of ethylene oxide and methane contents) represent the main equipment of the CO<sub>2</sub>EXIDE process. For the EEU, a similar concept was investigated by Jouny, et al. [104] for the product separation from different CO<sub>2</sub> electrolysis processes using pressure swing absorption (PSA). Comparable technologies were considered in a more recent techno-economic study for biogas upgrading [127], which was used as a reference for the estimation of the EEU CAPEX. To consider expected scaling effects an appropriate scaling factor of 0.7 according to Jouny, et al. [104] was used.

The CAPEX evaluation for an industrial scale EOU was based on the ethylene epoxidation section described and analyzed by Ghanta, et al. [78]. Due to the significantly higher plant capacity of the reference, the equipment costs stated by [78] were downscaled to the evaluated CO<sub>2</sub>EXIDE scenarios using common scaling factors for chemical reactors given in relevant literature (cf. Peters, et al. [121]). The resulting equipment costs considered for the EEU and EOU are summarized in Table 4-17.

**Table 4-17: Equipment costs for EEU and EOU**

Equipment	Costs in €		Reference scale	Scaling factor	Notes
	2030	2040			
EEU	3,411,513	2,232,133	250 m <sup>3</sup> <sub>in</sub> /h	0.7	based on [104,127]
EOU	1,547,841	1,828,734	22,600 kg <sub>out</sub> /h	0.55	based on [78,121]

#### 4.3.3.1.3 Replacement costs

For components that are expected to have a limited lifetime shorter than the presumed observation period for the TEA, additional costs for replacements will occur. In the present study these replacement costs were considered for the catalyst of the ERU, which is expected to degrade significantly in long-term operation. Hence, for the electrocatalytic stack share of the ERU costs (see section 4.3.3.1.1) a replacement every 7 years was assumed in accordance with Wenderich, et al. [120]. With the time of operation presumed in the general TEA of 8,000 full-load hours per year, this is also in line with the lifetimes of about 60,000 hours expected for PEM water electrolysis cell stacks in recent techno-economic studies [9]. Beside the ERU catalyst, the EEU is expected to have to be replaced after 15 years, according to the experiences within the CO<sub>2</sub>EXIDE project, and thus within the general observation period of 20 years.

All additional equipment is presumed to provide a lifetime equal to the observation period of the general TEA without planned costs for replacements. The cash values for the replacement costs are calculated according to VDI 2067, as described in section 4.2.2.3. A potential residual value of the equipment at the end of the observation period is considered as well. The resulting costs are listed in Table 4-18.

**Table 4-18: Costs for expected replacements of equipment during the observation period**

Equipment	Lifetime in years		Costs in €	
			2030	2040
ERU catalyst	7	Replacements total	9,897,300	9,902,235
		Residual value	-531,025	-531,290
EEU	15	Replacements total	2,189,721	1,432,721
		Residual value	-1,259,248	-823,919
<b>Total</b>			<b>10,296,747</b>	<b>9,979,748</b>

#### 4.3.3.1.4 Indirect costs

Up to this point only direct costs of purchase for the main equipment have been taken into account. Beyond that, additional costs for peripherals, construction and engineering will be relevant for an according implementation. These indirect costs have been considered by using

addition factors as common in chemical engineering and plant design literature, e.g. [121]. These addition factors are listed in Table 4-19.

**Table 4-19: Addition factors for indirect costs**

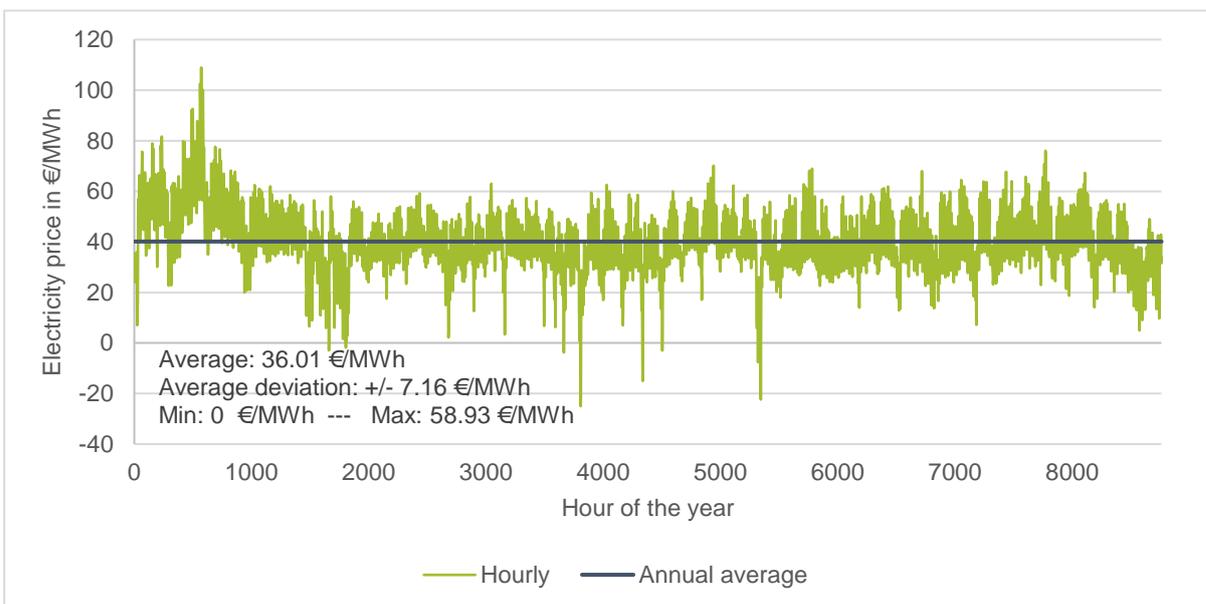
Cost factor	Addition (% of initial CAPEX)
Engineering & Supervision	20%
Construction	30%
Contingency	25%

#### 4.3.3.2 OPEX

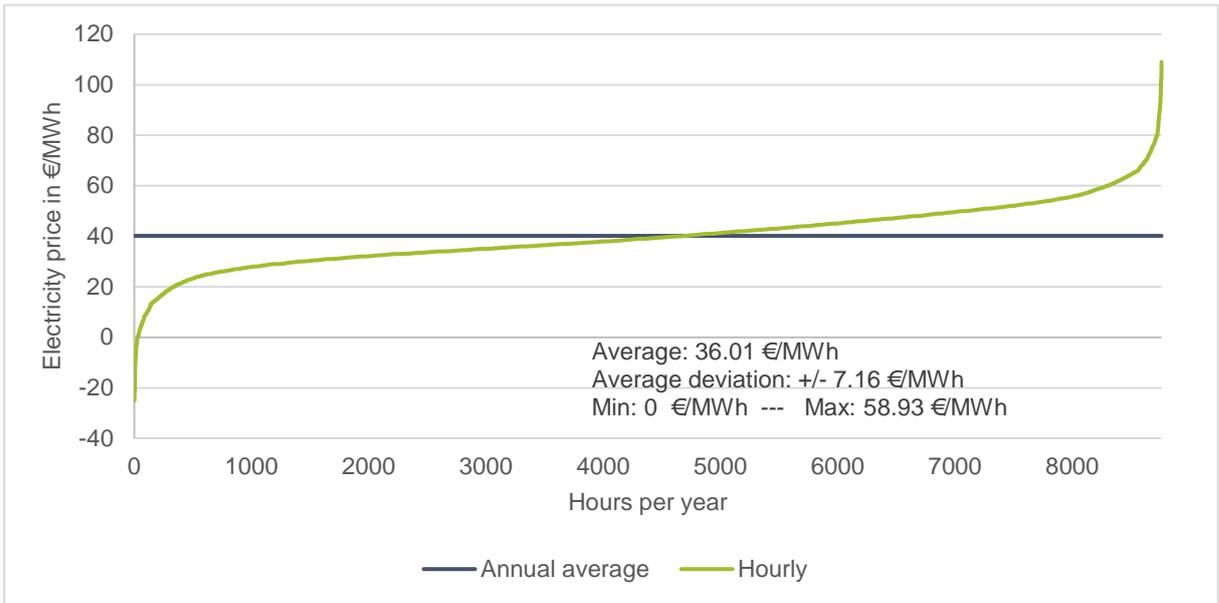
Operational expenditures (OPEX) cover the operation- and demand-related costs of the CO<sub>2</sub>EXIDE plant. The individual cost units are described in the following subsections.

##### 4.3.3.2.1 Electricity demand

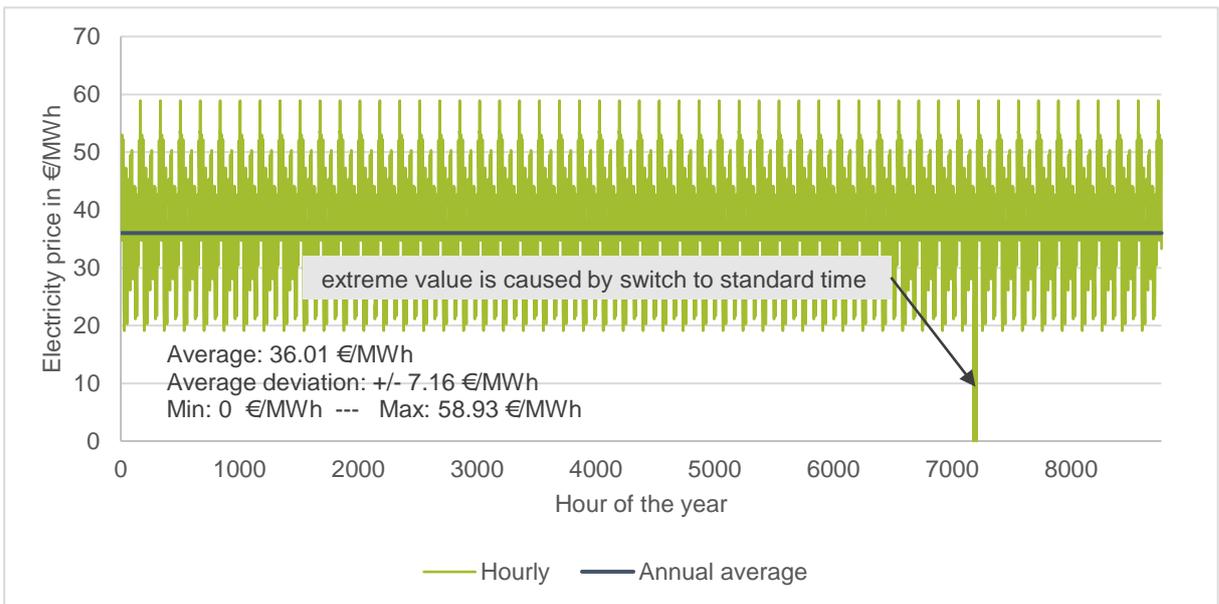
Due to the underlying electrochemical process, electric power is the major energetic resource required for the CO<sub>2</sub>EXIDE process. For the generic TEA scenarios electricity supply is supposed to be taken from the public grid. Therefore, historical spot market data from EXAA [122] was used to get an average price for grid electricity, see also Figure 4-12 to Figure 4-15.



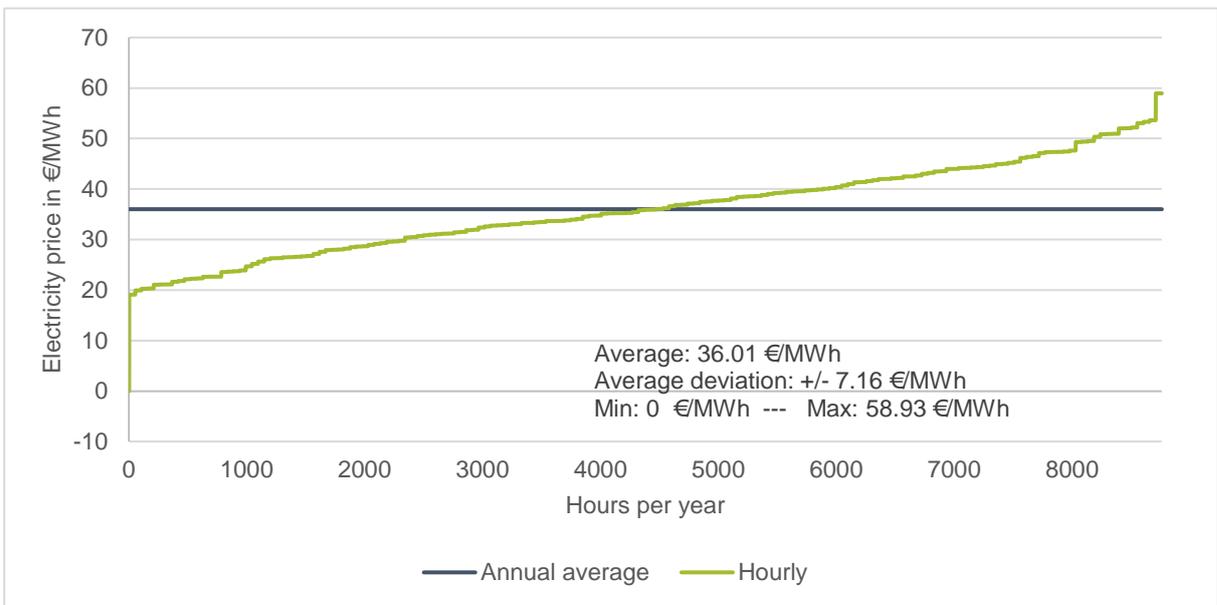
**Figure 4-12: Hourly EXAA grey electricity spot prices in the year 2019, unsorted. Energieinstitut based on [122]**



**Figure 4-13: Hourly EXAA grey electricity spot prices in the year 2019, sorted. Energieinstitut based on [122]**



**Figure 4-14: Hourly EXAA green electricity spot prices in the year 2019, unsorted. Energieinstitut based on [122]**



**Figure 4-15: Hourly EXAA green electricity spot prices in the year 2019, sorted. Energieinstitut based on [122]**

The Figure 4-12 to Figure 4-15 provide the prices for grey and, especially, green electricity at a European exchange platform (EXAA). What could envision in the last years is a trend to be continued: the prices for the volatile renewables are fluctuating and wind and PV provide already today the lowest marginal cost. The sorted prices on an hourly basis provide a window of opportunity for developing robust business cases for valorization process, not solely based on the few hours with negative prices, but with renewable electricity as a production commodity with the price curve pointing downwards. Nevertheless, this is actually still a rather synthetic option as far most all the production capacities are tied in individual contracts, PPAs (power purchase agreements).

For the direct supply from RES, as considered in the three comparative case studies, projected levelized costs of electricity (LCoE) for wind and PV in Europe, as suggested by relevant literature [100], were used. The actual values are listed in Table 4-13.

Note: Although EXAA offers designated green electricity at the spot market price, the data in Figure 4-14 demonstrate that there is apparently no trade based on it and that periodically recurring prices are not market-driven up to now. Despite this, the use of renewable electricity was preferred, i.e. the present analysis refers to the green electricity prices (Figure 4-15 to evaluate the influence of spot market prices. The electricity price was varied in the sensitivity analysis from -60 % to +60 % in order to cover the influence of future electricity price changes resp. current price changes.

With the use of public electricity grid infrastructure, also involved taxes and fees have to be paid. While these fees differ between countries and are partially still unclear for the integration

of power-to-X processes, the current Austrian legislation was used as a reference for all evaluated scenarios.

#### **4.3.3.2.2 Other material and resource costs**

Apart from electric energy some additional feedstock and materials are required in the CO<sub>2</sub>EXIDE process, above all CO<sub>2</sub> and water as the main feedstock for the electrochemical conversion. In all investigated scenarios CO<sub>2</sub> is presumed to be supplied from local biomethane plants. According to Rodin, et al. [7] the supply costs for CO<sub>2</sub> are ranging from 0–90 €/t with a tendency to single-digit values and are basically dependent on the separation technology. Furthermore, if the separation of CO<sub>2</sub> as part of biogas upgrading is presumed to part of the biomethane production and thus accompanying costs are allocated to that, the produced CO<sub>2</sub> could be valued as a waste stream, which is available free of charge. Consequently, the CO<sub>2</sub> feedstock costs are neglected within the present TEA.

Beside CO<sub>2</sub>, water is a major feedstock for the electrochemical conversion process. However, despite high throughput, an appropriate recycling and recirculation of waste water is presumed. Hence, the demand for fresh water is reduced and presumed to be available at moderate costs as suggested by Jouny, et al. [104]. In addition, the epoxidation process (EOU) requires steam and cooling water for operation. The according costs are considered with relation to the epoxidation process investigated by Ghanta, et al. [78]

The material and resource costs are summarized in Table 4-13.

#### **4.3.3.2.3 Fixed charges and overhead**

During normal operation of the plant recurring equipment maintenance and repair works can be expected and thus be considered within the ex-ante techno-economic assessment of the process. According to relevant literature of cost assessment of chemical plants, these annual maintenance and repair costs can be assumed in a range of 2–10% of the initial equipment cost in process industries, with 7% being a reasonable value [121]. In addition, the annual insurance costs for this kind of chemical plants can be presumed with about 1% of the fixed CAPEX [121].

However, all of the yet mentioned costs are more or less directly related to the production operation of the plant. However, along with those surrounding expenditures to ensure the functioning of the process may be expected. These additional costs are summarized as plant overhead costs, which can be estimated in a range of 50–70% of the total operational expenses (fixed charges) [121] and are thus considered as 50% of the fixed OPEX for maintenance, repair and insurance mentioned above.

## **4.4 Results and Discussion**

The results of the techno-economic assessment of the evaluated scenarios are presented and discussed in the following subsections. The main focus is on the generic scenarios with projected implementations in the years 2030 and 2040 based on the virtual demonstrator scaling

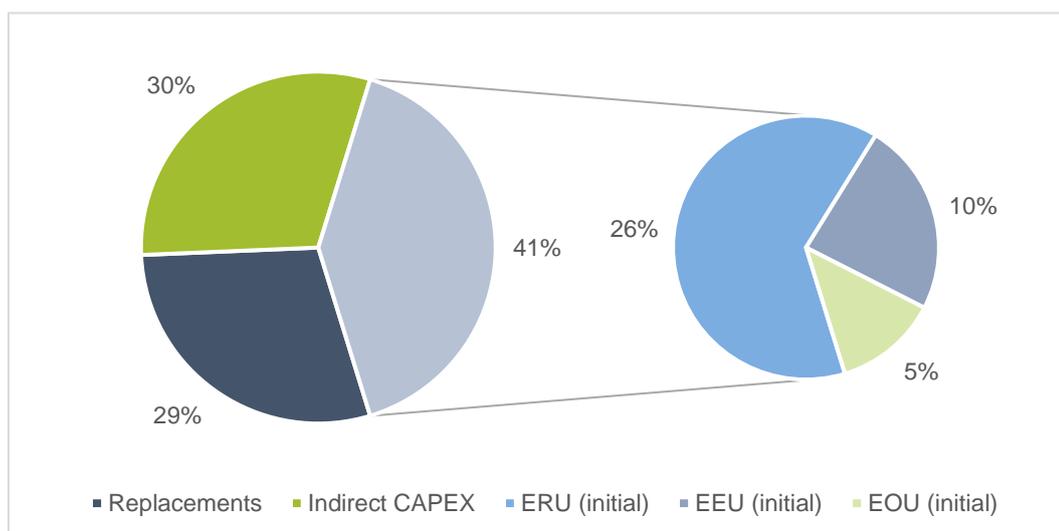
(D. 7.1) with the techno-economic performance and relevant impact factors analyzed. The three individual case studies for Bruck an der Leitha, Zerbst and Isle of Wight are discussed subsequently in comparison to the base scenarios.

#### 4.4.1 Base scenario

The generic base scenario describes the techno-economic assessment for the two plant capacities evaluated for the CO<sub>2</sub>EXIDE process for the according times of implementation, 11.67 MW for 2030 and 5.25 MW for 2040, respectively.

##### 4.4.1.1 Composition of cost shares

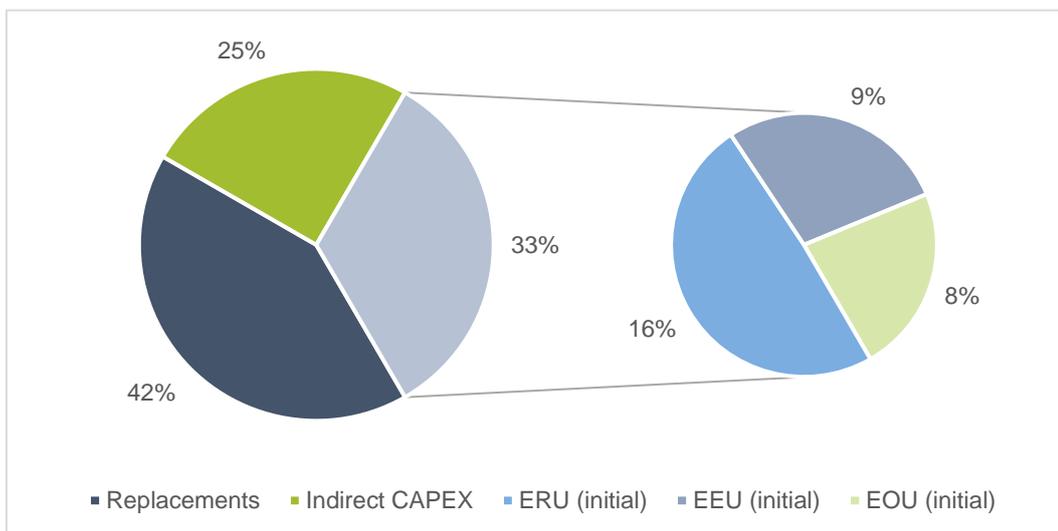
To identify individual potentials for cost reductions within the CO<sub>2</sub>EXIDE process, the different cost components were analyzed in detail. Looking solely on the investment costs for 2030, as shown in Figure 4-16, it can be seen that direct CAPEX, i.e., the initial purchase costs for main equipment, only account for about 41% of the overall CAPEX. Out of these direct CAPEX, the major part (ca. 63% of direct CAPEX) is allotted to the electrochemical reactor unit, while the remaining shares are assigned to EEU and EOU direct costs at a ratio of about 2:1. Thus, about 60% of the overall CAPEX are represented by indirect costs, such as engineering and construction, and expected replacements of the ERU and EOU equipment.



**Figure 4-16: Individual cost shares of CAPEX in the 2030 scenario. Source: Energieinstitut.**

For the 2040 scenario, these cost shares are evaluated to be changing as illustrated in Figure 4-17. As a consequence of the learning curve effects considered for the electrochemical reactor, its share of the overall CAPEX is reduced to about 16%. The additional scaling effects for the EEU reduce the direct investment share to about one third. In parallel, the absolute costs for replacements of the main equipment decrease insignificantly, whereby the allotted costs share is the most significant with >40%.

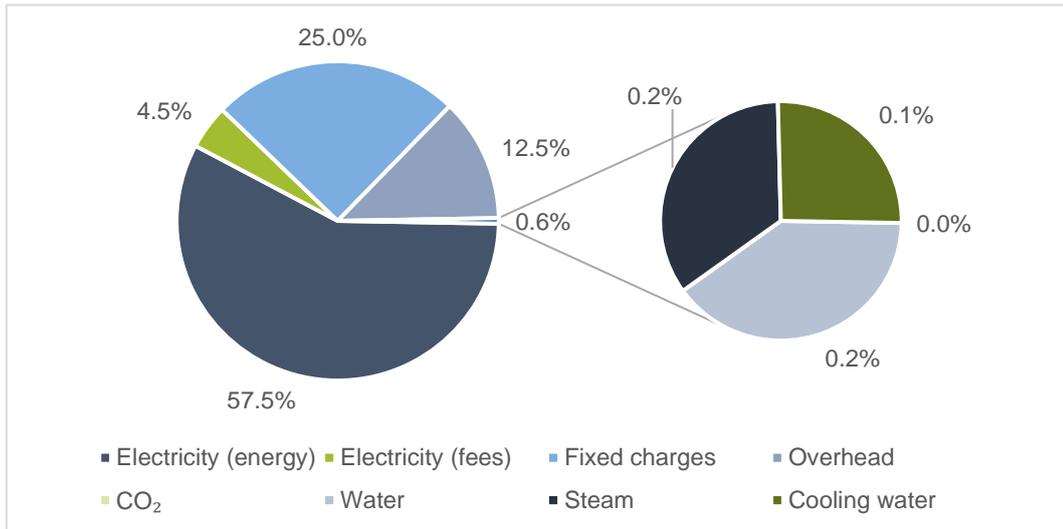
Altogether, the expected CAPEX for the generic scenarios are evaluated with about 35.4 Mio. € for 2030 and 23.9 Mio. € for 2040.



**Figure 4-17: Individual cost shares of CAPEX in the 2040 scenario. Source: Energieinstitut.**

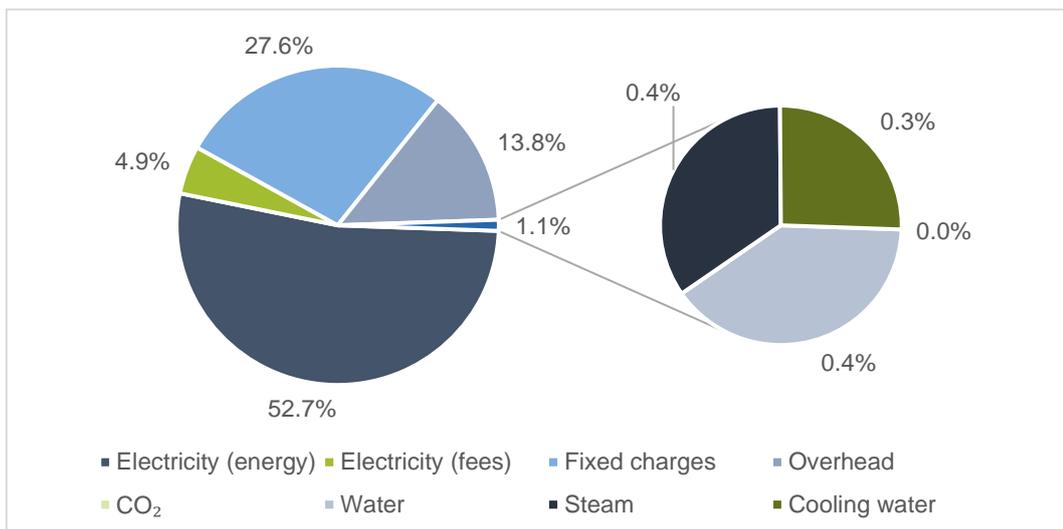
Beside CAPEX the operational costs (OPEX) for the process were analyzed. For the given plant capacity of 11.67 MW total OPEX of 18.1 k€/day were calculated in the 2030 scenario, excluding potential savings due to ETS paybacks. According to the half as high nominal capacity of the plant in the 2040 scenario, with about 5.25 MW input power, also the resulting OPEX are about halved to 9.1 k€/day. Considering ETS paybacks as part of the operational plant costs, the cost reduction is even more significant due to the expected increase of CO<sub>2</sub> certificate costs.

As Figure 4-18 shows for the year 2030, the major share of the OPEX is represented by the costs of electricity supply, which accounts for > 57 %. These energy costs are about to decrease significantly for the 2040 scenario (see Figure 4-19) due to the presumed improvement of the electric efficiency of the ERU, which basically effects the overall lower power demand and thus input capacity. Along with those, also the directly related tariffs and fees for electricity supply are reduced.



**Figure 4-18: Individual cost shares of OPEX in the 2030 scenario. Source: Energieinstitut.**

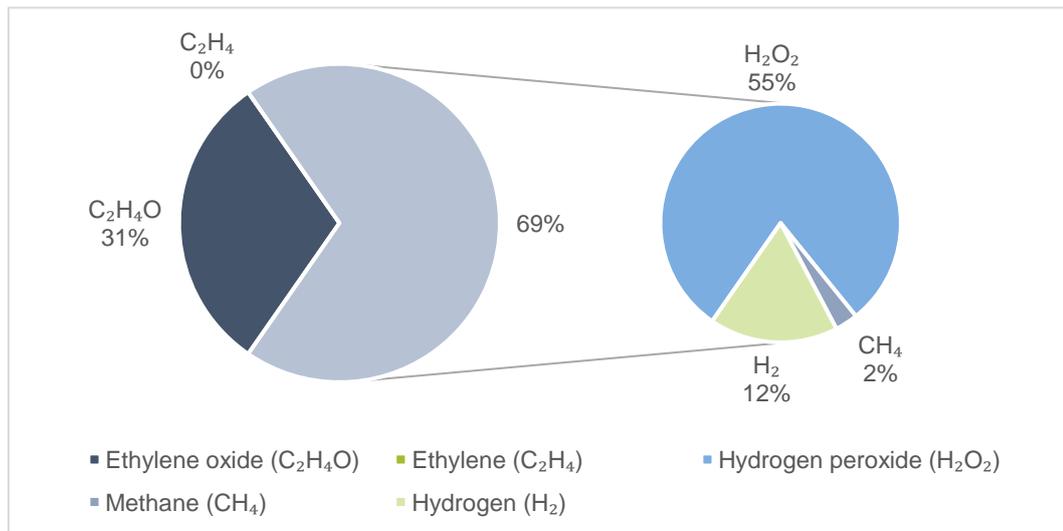
However, the costs share structure of the OPEX is not changing significantly despite decreasing electricity supply costs when comparing the 2030 and 2040 results. This is related to the aspect that the reduction of CAPEX, as discussed before, imply a reduction of the directly related OPEX summarized under *fixed charges* (operation & maintenance, insurance) and *overhead*. According to the unchanged production capacity of the 2030 and 2040 plant, the absolute costs for feedstock and raw materials (CO<sub>2</sub>, (cooling) water, steam) are not going to change between scenarios. Thus, only their (low) significance on the overall OPEX is slightly increasing.



**Figure 4-19: Individual cost shares of OPEX in the 2040 scenario. Source: Energieinstitut.**

#### 4.4.1.2 Product sale revenues

Apart from all costs, the proceeds generated from sales of ethylene oxide as the target product and the individual by-products, i.e., hydrogen, methane and hydrogen peroxide, are ultimately relevant for the economic efficiency of the plant/process. Given the presumed sale prices for these renewable value chemicals, about 4,450 €/day (2030) and 8,900 €/day (2040), respectively, could be achieved by the production and sale of ethylene oxide as the main product. However, assuming that hydrogen peroxide can be effectively separated and exploited, ethylene oxide could only be accountable for about 31 % (2030) and 46 % (2040), respectively, of the overall product and by-product proceeds, while 42–55 % are related to hydrogen peroxide sales.

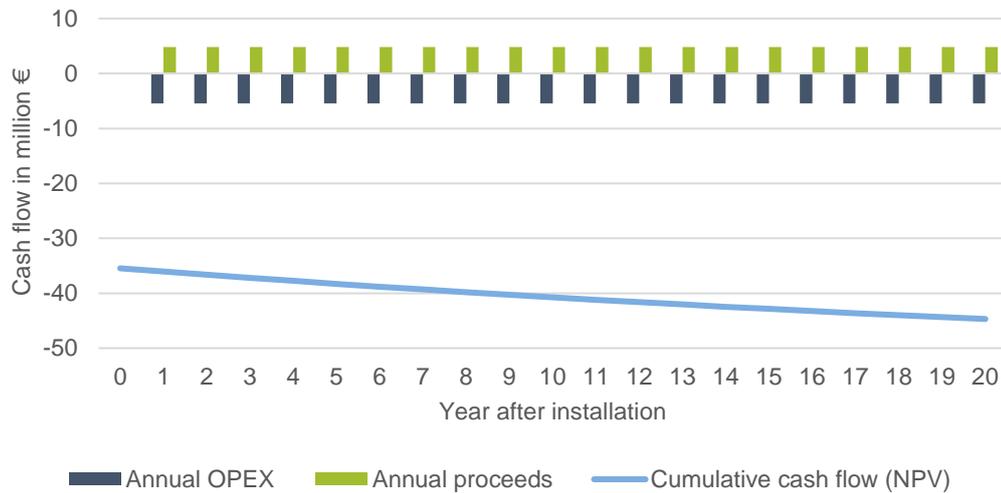


**Figure 4-20: Shares of the proceeds generated from product sales based on the 2030 scenario.**  
Source: Energieinstitut.

The other by-products, in particular hydrogen and methane, will have to compete with other renewable production methods for these products, such as water electrolysis and methanation, whereby their effective value will be dependent on these concurrent technologies (cf. [9]).

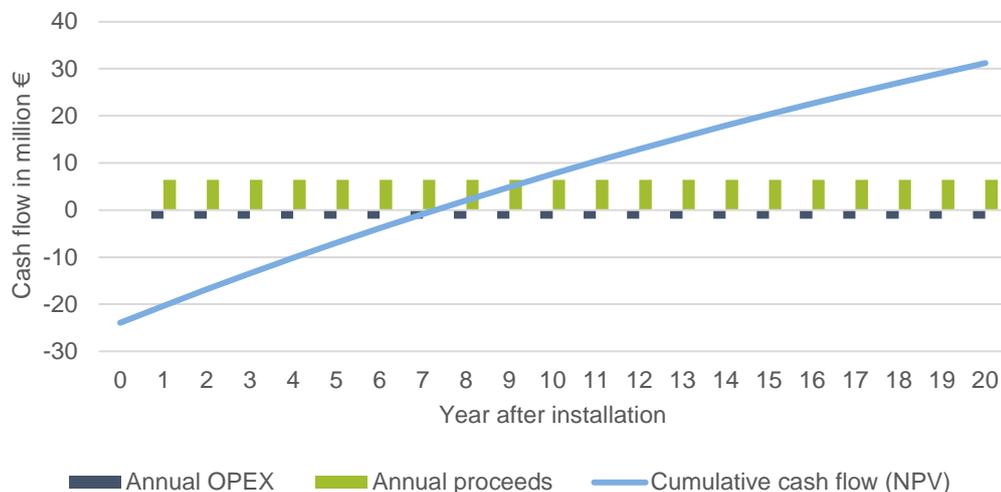
#### 4.4.1.3 Net present value (NPV) and payback time (PBT)

The development of cash flows and overall economic performance of the CO<sub>2</sub>EXIDE plant is discussed based on the net present value (NPV) and payback time (PBT). For the year 2030 scenario, the absolute annual profit is negative despite considering all potential by-product sales and savings from ETS certificates. Hence, the overall negative annual cash flow leads to a further decrease of the NPV starting from a negative value of -35.4 mio. € due to fixed CAPEX (all investments, incl. replacements discounted to the initial year). Consequently, the calculated PBT is also negative, which means that the plant is not getting profitable independent of the chosen depreciation period.



**Figure 4-21: Development of the net present value (NPV) in the generic scenario for 2030.**  
**Source: Energieinstitut.**

In the year 2040 scenario, the increased proceeds from higher value chemical prices exceed the simultaneously reduced operating costs that follow from reduced power demand and CAPEX-dependent fixed OPEX. Therefore, the NPV is increasing over the set depreciation period. With the additionally less negative starting value of approx. -23.9 mio. € based on the considered learning curve effects on CAPEX, the NPV reaches a positive value by year 5. A similar result is delivered by the static payback time analysis giving an expected PBT of just 3.3 years.



**Figure 4-22: Development of the net present value (NPV) in the generic scenario for 2040.**  
**Source: Energieinstitut.**

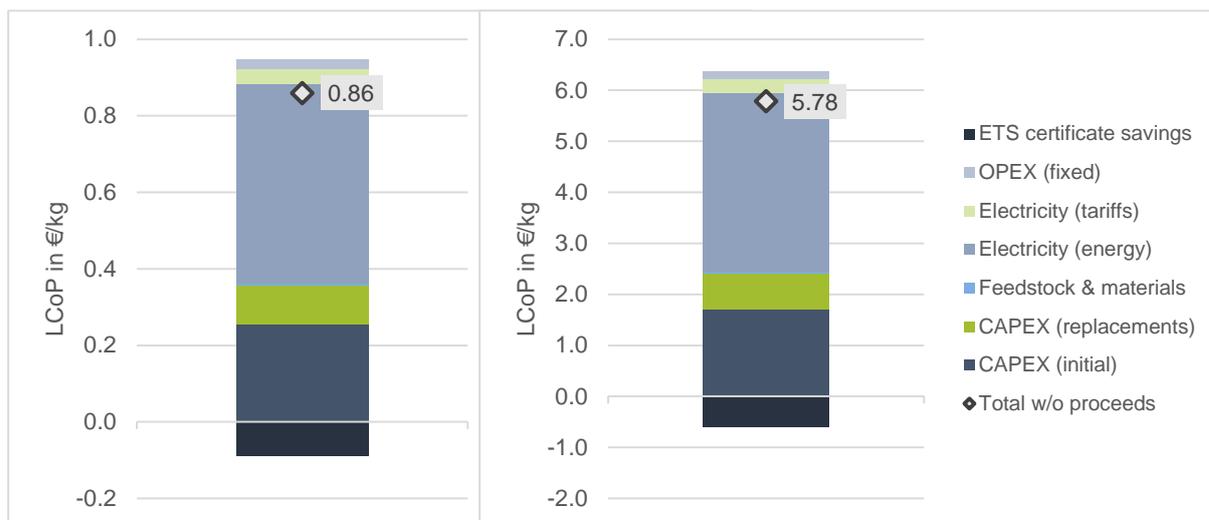
Based on these economic results it can be concluded that for a competitive operation of the CO<sub>2</sub>EXIDE process an according decrease of the operational costs is required, which is mainly

reached by an increase of electric efficiency of the electrochemical process. Hence, the reduced energy costs together with lower investment efforts could result in a process that is economically viable within an acceptable planning interval.

#### 4.4.1.4 Product generation costs (LCoP)

To evaluate the competitiveness to fossil-based ethylene-oxide production and allow to set reasonable selling prices for the renewable product, LCoP are a valuable indicator. Since the CO<sub>2</sub>EXIDE process generates significant amounts of valuable by-products the LCoP is calculated both, related to the overall product mass including by-products (H<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O<sub>2</sub>), and related solely to the mass of ethylene oxide as the main product.

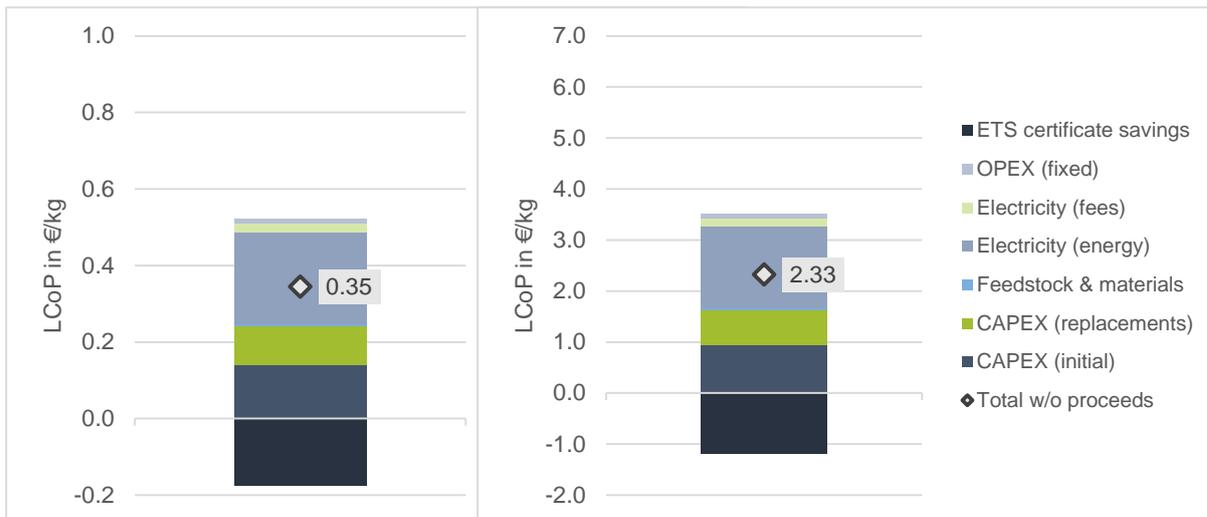
Given the results for the year 2030, as shown in Figure 4-23, the average production costs for all value chemicals generated in the CO<sub>2</sub>EXIDE process are at about 86 €-cent/kg, which would be within the range of the different considered product selling prices (see Table 4-13). However, assuming that by-products cannot be economically exploited and ethylene oxide is the only utilizable product, the related LCoP are at approx. 578 €-cent/kg ethylene oxide. Hence, according product prices would have to be significantly above current fossil-based competitive products.



**Figure 4-23: LCoP composition for the generic scenario in 2030 related to total products (left) and ethylene oxide only (right) without by-product sales. Source: Energieinstitut.**

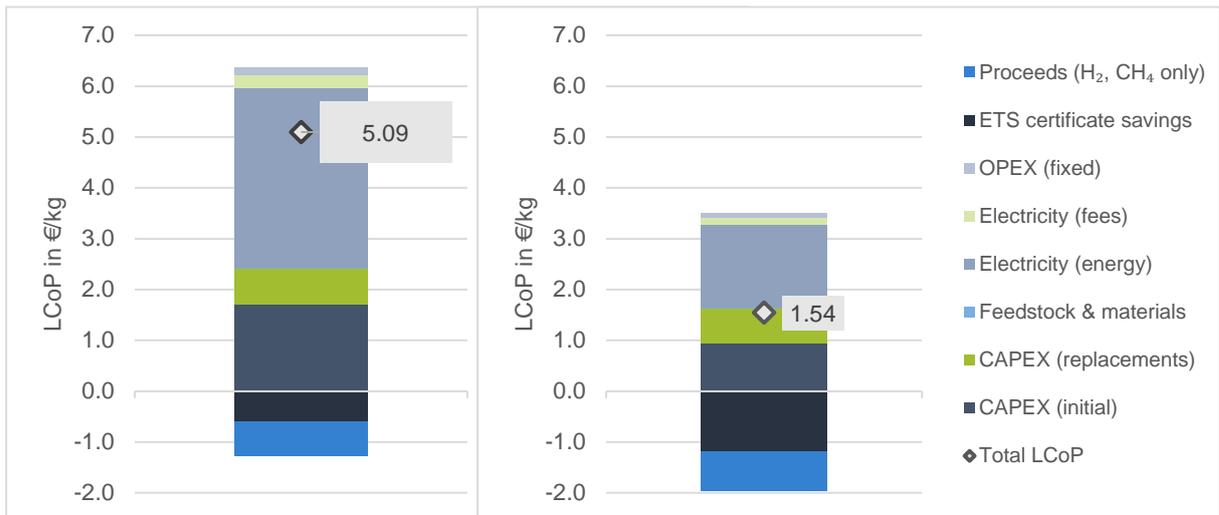
For the 2040 scenario, the reduced CAPEX and electricity demand lead to significantly lower product costs (see Figure 4-24). With about 35 €-cent/kg the average costs for all products are lower than the available prices for the fossil-based value chemicals ethylene-oxide, ethylene and hydrogen peroxide. For the main product alone, production costs of 233 €-cent/kg of ethylene oxide could be achieved. However, these calculations take significant paybacks for ETS

certificate savings (100 €/t CO<sub>2</sub>) into account. Without these paybacks, product costs would increase by 18 €-cent and 119 €-cent per kg product mass, respectively.



**Figure 4-24: LCoP composition for the generic scenario in 2040 related to total products (left) and ethylene oxide only (right) without by-product sales. Energieinstitut.**

If selling of by-products is considered as revenues in the production process of ethylene oxide, the ethylene oxide-related LCoP could be reduced further. Figure 4-25 shows the effective levelized production costs for ethylene oxide in the CO<sub>2</sub>EXIDE process, including the proceeds from selling renewable hydrogen and methane by-products. Due to the uncertainty according to the viable separation of hydrogen peroxide from the ERU anode output stream, according proceeds for this by-product were neglected in these results. Hence, the ethylene oxide-related production costs could reach a value of about 1.54 €/kg in the 2040 scenario, being competitive to current fossil-based products (cf. section 4.1.1).



**Figure 4-25: LCoP composition under consideration of by-product sales (without H<sub>2</sub>O<sub>2</sub>) for 2030 (left) and 2040 (right). Source: Energieinstitut.**

#### 4.4.2 Comparison of case studies

In comparison to the generic scenarios the three location-based case studies, Bruck an der Leitha, Zerbst and Isle of Wight, were evaluated. For these evaluations the same system capacities as presumed in the generic scenarios were used to maintain comparability. Based on these electric power requirements, the achievable full-load hours of operation for the given renewable power supply potentials at the three locations were calculated on an hourly basis considering actual usage capacities. The electricity supply costs were weighted according to the levelized costs of electricity (LCoE) presumed for the individual types of power generation ([100], see Table 4-13).

Related to that, the according CO<sub>2</sub> demands for the given plant capacities show that basically all three locations are able to provide enough renewable CO<sub>2</sub> from the local biogas production to serve the CO<sub>2</sub>EXIDE process. In contrast, the biomethane plants on the Isle of Wight and in Zerbst would provide 6.7–9.4 and 2.8–3.5 times, respectively, the required amount of CO<sub>2</sub> and thus the potential for an extended capacity. Hence, the CO<sub>2</sub> supply does not represent a bottleneck in these scenarios.

Additionally, for the two case studies, Bruck/Leitha and Zerbst, that provide electric power from local wind farms, the annual energy generation is high enough to achieve a high number of annual full-load hours (> 5,500 h/a in 2030 and > 7,000 h/a in 2040) – comparable to the generic scenarios. However, this presumes that the process allows for an appropriately dynamic operation or the availability of an intermediate electricity storage to deburr to power supply profile. For the solely PV-based power-production in the Isle of Wight case study the CO<sub>2</sub>EXIDE plant can only be operated for a limited amount of annual full-load hours. Though, this can

be improved in the 2040 scenario according to the expected efficiency improvements and the thus reduced power demand.

**Table 4-20: Comparative TEA results for the considered case studies dependent on the available electricity production**

Parameter	Unit	2030			2040		
		Bruck/ Leitha	Zerbst	Isle of Wight	Bruck/ Leitha	Zerbst	Isle of Wight
<b>Operation</b>							
Potential FLH <sup>1)</sup>	h/a	5,864	6,150	1,959	7,170	7,745	2,742
CO <sub>2</sub> demand	t/a	2,198	2,305	734	2,688	2,903	1,028
Electricity costs (weighted)	€/MWh	55	55	55	30	37	45
<b>Economic results</b>							
Payback time	years	-14.3	-14.3	-14.6	3.7	3.5	16.6
LCoP <sup>2)</sup>	€/kg product	1.29	1.26	2.38	0.34	0.36	0.92

<sup>1)</sup> Potential full load hours based on the hourly available electricity production in relation to ERU capacity

<sup>2)</sup> Related to overall product mass (incl. by-products) without proceeds from by-product sales

For the techno-economic comparison of the case studies, the calculated payback time and LCoP were considered. As summarized in Table 4-20, the evaluated payback times are negative for all three case studies as expected according to the previous results for 2030 in the generic scenario. Thus, no profitable operation is expectable for an implementation in 2030. For the 2040 time horizon, the potential locations in Bruck/Leitha and Zerbst perform similar to the generic scenario with short payback times of 3.5 to 3.7 years. In relation to the presumed depreciation period of 20 years the location on the Isle of Wight also may reach profitability with a payback time of about 17 years. Based on the levelized product costs (LCoP), which are represented in Table 4-20 as average according to the overall product mass (incl. by-products), all case studies revealed higher costs than the generic scenario for 2030, which results from the higher electricity supply costs and the low annual load for Isle of Wight. For the year 2040 the location in Bruck an der Leitha achieves even lower production costs than the generic scenario due to the presumably low electricity costs for wind production. The higher costs for PV an the still low load in 2040 lead to an LCoP being about 2.6 times higher for the Isle of Wight compared to the generic scenario.

In a nutshell, a full-year operation (>8,000 h) of the CO<sub>2</sub>Exide plant based on locally produced renewable energy is not possible at any of the three locations without additional energy storage. In the case that energy storage is considered however, the operation of the CO<sub>2</sub>Exide plant in order to stabilize the electricity grid is questionable, as this role could be taken over completely by storage systems. Another possibility is to reduce the operating hours of the CO<sub>2</sub>Exide plant based on the availability of local renewable energy. Consequently, the yearly production rate of ethylene oxide is drastically reduced, while CAPEX and partially also OPEX

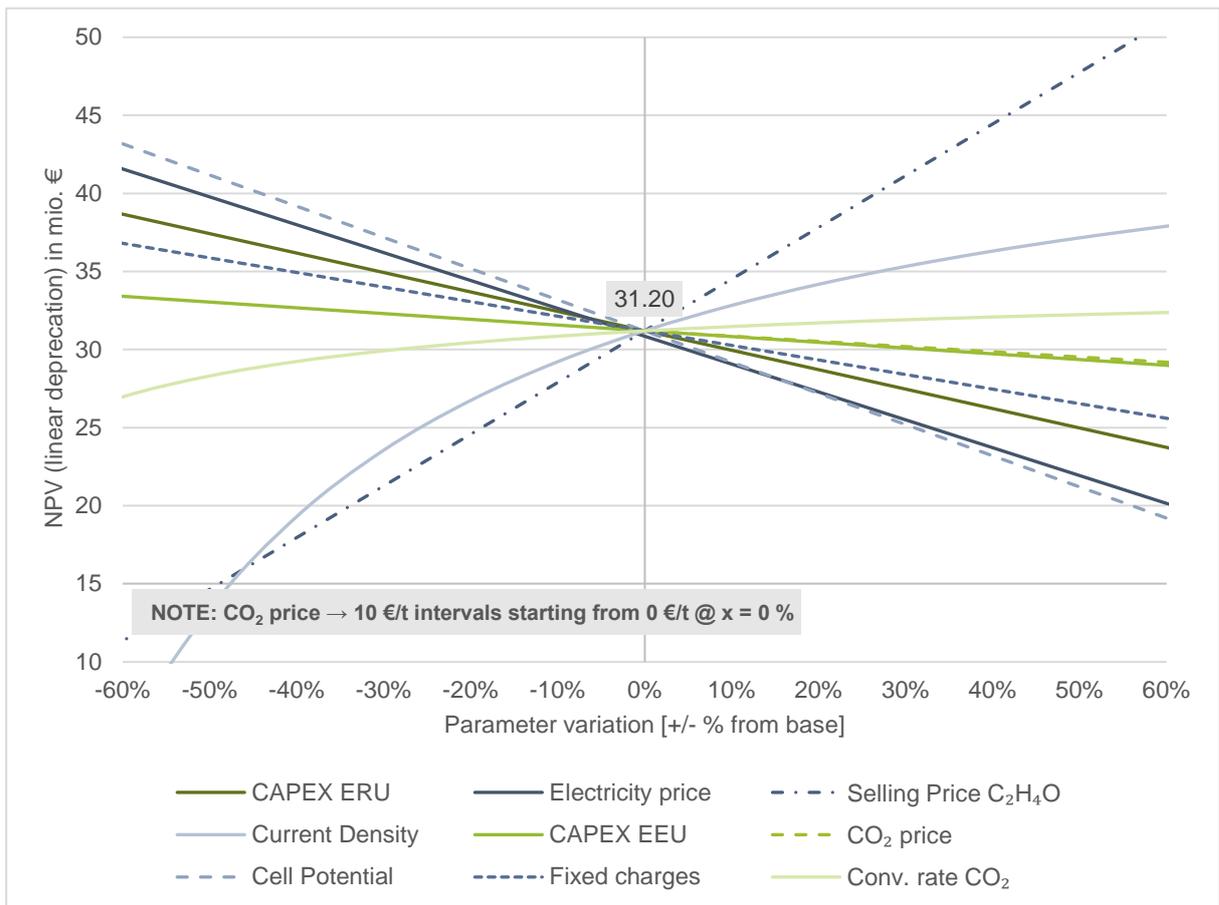
(such as fixed charges) stay the same. I.e., the overall profitability of the plant is reduced significantly. This raises the question, which incentives could lead to advantageous operation of the CO<sub>2</sub>EXIDE plant for the electricity grid? Reduced electricity prices for example could reduce the OPEX but the difference in price presumably cannot be compensated by the power plant nor grid operators, i.e. public subsidies might be needed. On the other hand, the achievable selling price of renewable ethylene-oxide and associated green premium market prepositions are expected to have the major impact on the overall competitiveness of the process.

#### **4.4.3 Uncertainty and sensitivity analysis**

To estimate the impact of individual calculation parameters on the evaluated indicators a sensitivity analysis was performed by varying selected impact factors for the 2040 scenario.

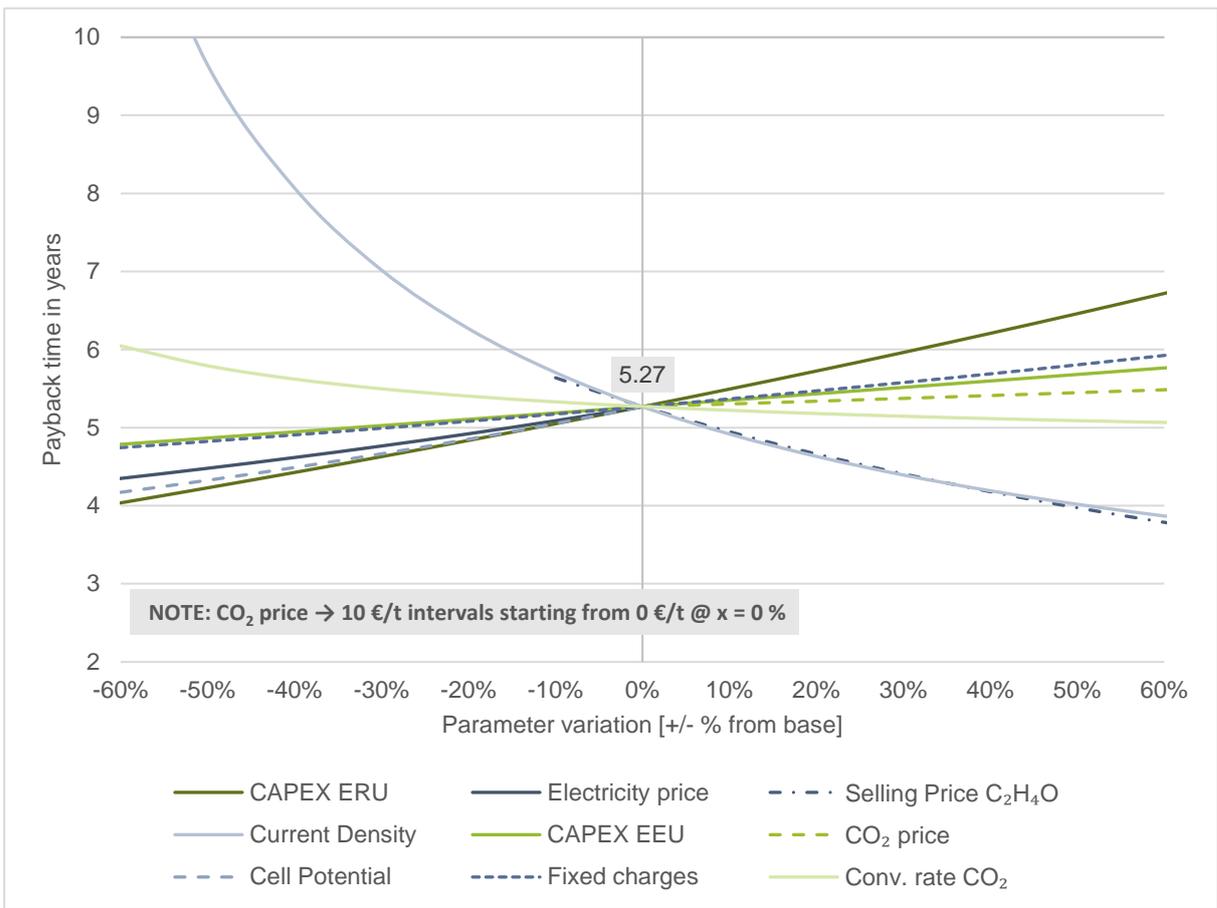
##### **4.4.3.1 Sensitivity of plant profitability**

The sensitivity analysis for the net present value (see Figure 4-26) and payback time (Figure 4-27) calculations particularly show the high – and non-linear – impact of the presumed current density of the CO<sub>2</sub>EXIDE process (cf. section 4.3.2.1). Hence, to maintain the calculated economic performance of the process, it has to be ensured in the further process development, that current densities are rather increased. Equally important are the cell voltage and the voltage efficiency respectively. A corresponding, but less significant, behavior can be observed for the CO<sub>2</sub> conversion rate of the ERU cell.



**Figure 4-26: Sensitivity of net present value (NPV) to individual parameter variation. Source: Energieinstitut.**

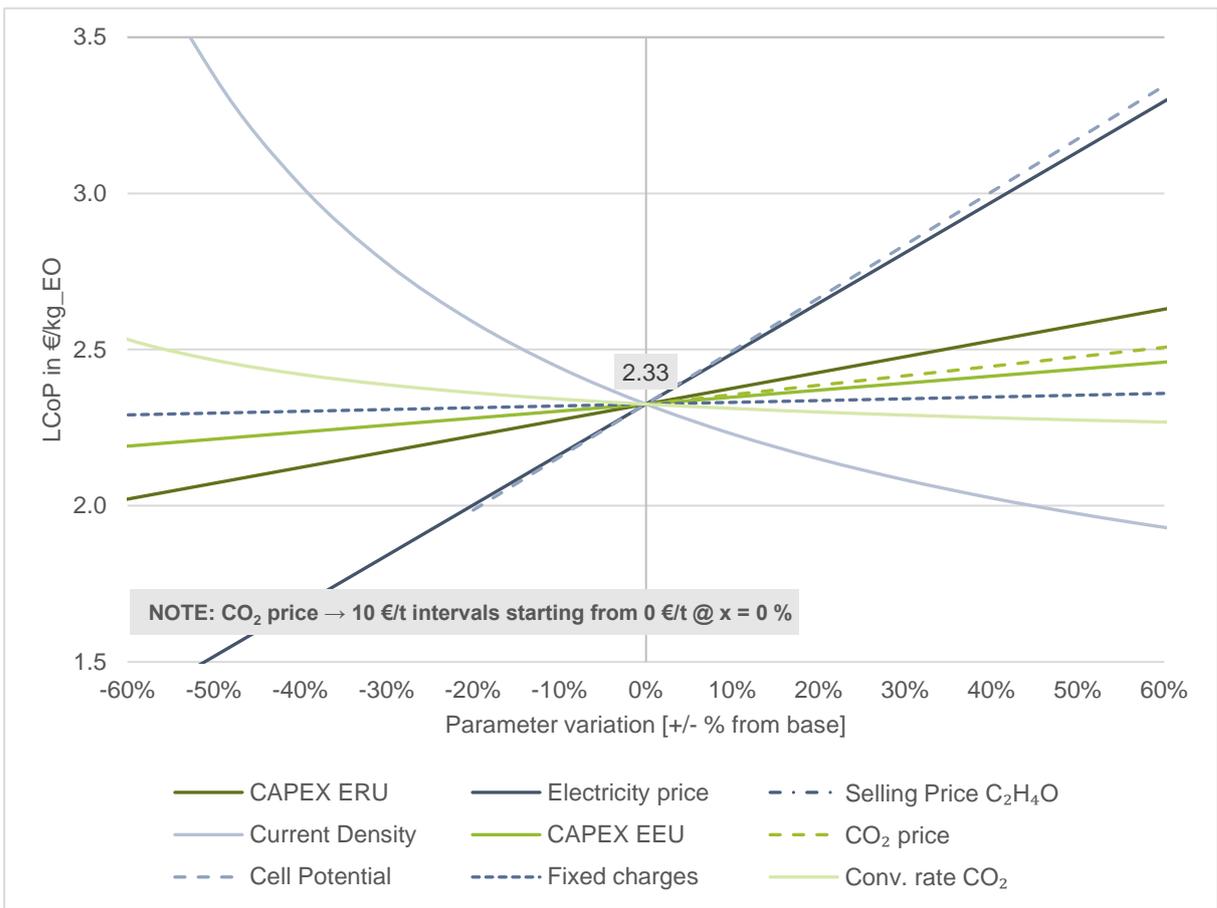
The most significant impact according to direct CAPEX and OPEX are related to investment costs for the ERU, the CAPEX-related fixed charges, and, as expected, the electricity costs as the main input costs and major cost factor in the calculation (cf. Figure 4-18 and Figure 4-19). However, in the end the achievable selling price for ethylene-oxide as a renewable value-chemical is expected to have the major impact on the overall competitiveness of the process.



**Figure 4-27: Sensitivity of payback time (PBT) to individual parameter variation. Source: Energieinstitut.**

#### 4.4.3.2 Sensitivity of product costs

As expected, the sensitivity analysis for the production costs in Figure 4-28 shows a similar behavior as those for NPV and PBT. The electricity price and cell potential tend to have the highest effect on the resulting product costs, given an equal relative change of the parameter. In contrast, the impact of a variation of the fixed charges (OPEX for maintenance, insurance, etc.) is neglectable. Basically, the impact of OPEX- and CAPEX-related parameters and cost factors can also be estimated according to their individual cost shares on the overall LCoP results shown in section 4.4.1.4.



**Figure 4-28: Sensitivity of ethylene oxide-related LCoP to individual parameter variation.**  
**Source: Energieinstitut.**

## 5 OVERALL CONCLUSIONS AND RECOMMENDATIONS

### 5.1 General conclusions

Notably, water electrolysis is seeing increased deployment around the world because of a strong policy push, with governments in Japan, South Korea, European Union (EU), and Australia rolling out separate national roadmaps and strategies that advocate renewable hydrogen as key for effective decarbonization. [36,128] Furthermore, secondary CO<sub>2</sub> conversion technologies are also being demonstrated worldwide (e.g., synthetic methane production by Audi/Germany and synthetic methanol by Carbon Recycling International, Iceland).

The analyzed carbon utilization technology offers significant advantages compared to conventional ethylene oxide production routes. On one hand, it could be implemented in existing refineries, leading to reduced environmental impacts of the conventional system and reduced process cost due to utilization of pre-existing infrastructure (such as existing ethylene oxide or ethylene glycol process chains). Additionally, this would be an option to increase refinery outputs and mitigate climate change. On the other hand, being integrated into sites offering highly concentrated biogenic CO<sub>2</sub> (such as biomethane or bioethanol plants) and utilizing renewable power, a fully renewable and sustainable alternative to valuable fossil-based hydrocarbons, could be implemented. The sector coupling benefit of PtX is of significance, because at present, renewable energy utilization is improving the CO<sub>2</sub> footprint of only the electricity sector (accounting for a third of global CO<sub>2</sub> emissions), whereas the remaining industries are following a slower decarbonization route.

Despite this promising potentials, most renewable PtX products are still costlier when compared to their conventional fossil-based, production processes. [104,129] This price variation may arise because of the decentralized modes of PtX plants (most PtX plants are small-scale), whereas traditional chemical and energy industries take advantage of economies of scale and their ability to negotiate lower feedstock pricing. In addition, most PtX technologies suffer from relatively high capital costs (projected to decline as manufacturer's ramp up their production capacity) and have large electricity requirement. In fact, there is a growing consensus that the cost-competitiveness of PtX is dictated by the availability of cheap and excess renewable electricity.

The regulatory framework on European level must continue to develop with regard to CCU. In the case of the capture of fossil carbon dioxide and the further use of carbon dioxide in production processes in which the carbon dioxide is permanently chemically bound (production of, e.g., precipitated calcium carbonate), the European Emissions Trading Scheme provides incentives in that no allowances have to be surrendered for these quantities. An emission factor of zero is set for biogenic carbon dioxide. This means that no certificates have to be surrendered for biogenic carbon dioxide that is emitted. However, if this biogenic carbon dioxide is now put to further use, there are no incentives for this. Although different effects are achieved

for the climate depending on whether biogenic or fossil carbon dioxide is used, in the case of CCU they are currently treated in the same way. [130] This leads to a systemic disadvantage for biogenic CO<sub>2</sub> sources, especially in the context of European circular economy and climate goals.

Taking into consideration life-cycle costs and measures due to e.g. the circular economy plans of the European Union (e.g. the New Green Deal), we assume that the technology, if it reaches a higher TRL of 7-9, can experience significant production cost reductions within the next 15 years and potentially become competitive with fossil counterparts. The conducted TEA with extensive sensitivity analysis identified the predominant triggers towards this development.

## **5.2 Techno-economic conclusions**

For the base scenario, taking CO<sub>2</sub> cost of 0 €/kg into consideration in the base case (due to integration of the process in an existing biomethane upgrading process) and electricity cost of ca. 36 €/MWh, the average production cost are about 86 €-cent/kg, which would be within the range of the different considered product selling prices (see Table 4-13). Under the assumption that ethylene oxide is the only utilizable product, the LCoP rise to approx. 5.78 €/kg ethylene oxide. Consequently, the selling product prices would have to be significantly above current fossil-based products. In order to make the sustainable green ethylene oxide compatible with fossil alternatives, the sensitivity analyses (see 4.4.3) show that CO<sub>2</sub> compensation prices as well as energy efficiency (connected to cell voltage), electricity prices and CAPEX are the most relevant factors. Regarding the latter, increased plant life is a crucial factor as well.

In a summary, the product selling prices of ethylene oxide must be quite high, current market prices of ethylene oxide are not sufficient. For the 2040 scenario with optimized plant conditions and ETS remuneration, however, a positive NPV could already be reached with current market prices. Until such optimizations are reached, green premium prices could be an option for early market entry, if customers' willingness is given.

Despite the economic optimization that can be reached via close-to-zero CO<sub>2</sub> prices and ETS remuneration, it was clearly shown that the energy consumption of the ERU is of significant importance. Specifically, the cell potential must be significantly reduced while the current density should be kept at a reasonable high level, in order to guarantee high efficiencies and low CAPEX via smaller ERU units.

### **5.2.1 Limitations of the TEA**

As the analyzed core technology has a low Technology Readiness Level (TRL) of 3-4, only a simplified equipment list is available for the TEA. Furthermore, the energy efficiency of the process is assumed to be much higher when the technology reaches a TRL of 7-9 compared to the current state. This was partly taken into consideration via the scale up to the reference

year 2030 (see section 4) and even more for 2040. The first limitation was countered by adapting known technical and economic conditions of related technologies, for which cost and efficiency data as well as learning curves are available. Furthermore, sensitivity analyses were conducted to show a realistic range of energy demand and cost development. Finally, the focus in the TEA itself was laid on the main process rather than supply chains or product sales in order to rule out several variables that influence the overall result significantly. However, the case study was designed in a way that local resources with short transport routes are available. Also, product marketing was assumed being possible in an acceptable geographical range.

### 5.3 Recommendations

The combination of ethylene oxide and hydrogen peroxide production within one electrocatalytic process is highly complex in terms of chemical and energy engineering, i.e. balancing the production rates, product purity as well as energy efficiency. Considering these complex issues, the separation of the ethylene and hydrogen peroxide production in different electrocatalytic units might increase overall plant efficiency due to more efficiently and balanced operating half cells.

Furthermore, the subsequent epoxidation process (EOU) possibly operates in batch mode while the ERU is a continuous process. The consideration of intermediate storage systems and/or the combination of – for example – one large ERU with several EOUs (operating at different stages of the batch process) should be also in focus of future R&D activities.

Lastly, from an economic perspective – as mentioned before – the reduction of renewable electricity prices and the extensive roll-out of RES is of high importance to further drive economically feasible operation of a CO<sub>2</sub>EXIDE plant. At this point it has to be considered that such a RES roll-out would also affect conventionally produced chemicals in terms of their impact on climate change as well as their economic performance. Consequently, the fossil reference products for the CO<sub>2</sub>EXIDE and other CCU/PtX technologies would improve in terms of environmental and economic performance as well.

## REFERENCES

- [1] F.M. Baena-Moreno, M. Rodríguez-Galán, F. Vega, B. Alonso-Fariñas, L.F. Vilches Arenas, B. Navarrete, Carbon capture and utilization technologies: a literature review and recent advances, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 41 (2019) 1403–1433. <https://doi.org/10.1080/15567036.2018.1548518>.
- [2] A. Al-Mamoori, A. Krishnamurthy, A.A. Rownaghi, F. Rezaei, Carbon Capture and Utilization Update, *Energy Technol.* 5 (2017) 834–849. <https://doi.org/10.1002/ente.201600747>.
- [3] P. Gabrielli, M. Gazzani, M. Mazzotti, The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO<sub>2</sub> Emissions Chemical Industry, *Ind. Eng. Chem. Res.* 59 (2020) 7033–7045. <https://doi.org/10.1021/acs.iecr.9b06579>.
- [4] P. Zakkour, G. Cook, Carbon Counts Company (UK) Ltd, CCS Roadmap for Industry: High-purity CO<sub>2</sub> sources: Sectoral Assessment – Final Draft Report, 2010. <http://hub.globalccsinstitute.com/sites/default/files/publications/15686/ccs-roadmap-industry-high-purity-co2-sources-sectoral-assessment.pdf>.
- [5] J. Koornneef, P. van Breevoort, C. Hendriks, M. Hoogwijk, K. Koop, M. Koper, IEAGHG, Potential for Biomass and Carbon Dioxide Capture and Storage, IEAGHG, Cheltenham, UK, 2011. [https://ieaghg.org/docs/General\\_Docs/Reports/2013-11.pdf](https://ieaghg.org/docs/General_Docs/Reports/2013-11.pdf).
- [6] P.D. Mobley, J.E. Peters, N. Akunuri, J. Hlebak, V. Gupta, Q. Zheng, S.J. Zhou, M. Lail, Utilization of CO<sub>2</sub> for Ethylene Oxide, *Energy Procedia*. 114 (2017) 7154–7161. <https://doi.org/10.1016/j.egypro.2017.03.1878>.
- [7] Valerie Rodin, Johannes Lindorfer, Hans Böhm, Luciana Vieira, Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO<sub>2</sub>, *Journal of CO<sub>2</sub> Utilization*. 41 (2020) 101219.
- [8] D. Krekel, R.C. Samsun, R. Peters, D. Stolten, The separation of CO<sub>2</sub> from ambient air – A techno-economic assessment, *Applied Energy*. 218 (2018) 361–381. <https://doi.org/10.1016/j.apenergy.2018.02.144>.
- [9] H. Böhm, A. Zauner, D.C. Rosenfeld, R. Tichler, Projecting cost development for future large-scale power-to-gas implementations by scaling effects, *Applied Energy*. 264 (2020) 114780. <https://doi.org/10.1016/j.apenergy.2020.114780>.
- [10] Detailed Process – AssessCCUS, (n.d.). <https://assessccus.globalco2initiative.org/tea/detailed-process/> (accessed July 7, 2021).
- [11] A.W. Zimmermann, J. Wunderlich, L. Müller, G.A. Buchner, A. Marxen, S. Michailos, K. Armstrong, H. Naims, S. McCord, P. Styring, V. Sick, R. Schomäcker, Techno-Economic Assessment Guidelines for CO<sub>2</sub> Utilization, *Front. Energy Res.* 8 (2020) 5. <https://doi.org/10.3389/fenrg.2020.00005>.

- [12] G. Centi, S. Perathoner, A. Salladini, G. Iaquaniello, Economics of CO<sub>2</sub> Utilization: A Critical Analysis, *Front. Energy Res.* 8 (2020) 567986. <https://doi.org/10.3389/fenrg.2020.567986>.
- [13] J. Nyári, M. Magdeldin, M. Larmi, M. Järvinen, A. Santasalo-Aarnio, Techno-economic barriers of an industrial-scale methanol CCU-plant, *Journal of CO<sub>2</sub> Utilization.* 39 (2020) 101166. <https://doi.org/10.1016/j.jcou.2020.101166>.
- [14] International Energy Agency, *World Energy Outlook 2018*, OECD, 2018. <https://doi.org/10.1787/weo-2018-en>.
- [15] Ethylene Oxide, IHS Markit. (n.d.). <https://ihsmarkit.com/products/ethylene-oxide-chemical-economics-handbook.html> (accessed July 6, 2021).
- [16] Ethylene Oxide Market Share| COVID-19 Impact Report 2021 to 2026 - Mordor Intelligence, (n.d.). <https://www.mordorintelligence.com/industry-reports/ethylene-oxide-market> (accessed July 7, 2021).
- [17] Ethylene Oxide Market And Ethylene Glycol Market- Global Industry Analysis, Size and Forecast 2012-2018, (n.d.). <https://www.transparencymarketresearch.com/ethylene-oxide-and-ethylene-glycol-market.html> (accessed July 7, 2021).
- [18] Intratec | Market & Technology Intelligence About Process Industries, (n.d.). <https://www.intratec.us/> (accessed July 6, 2021).
- [19] Ethylene production capacity globally 2024, Statista. (n.d.). <https://www.statista.com/statistics/1067372/global-ethylene-production-capacity/> (accessed July 7, 2021).
- [20] Ethylene global demand distribution 2015, Statista. (n.d.). <https://www.statista.com/statistics/724520/distribution-of-global-ethylene-demand-by-end-product/> (accessed July 7, 2021).
- [21] Ethylene glycol production capacity globally 2024, Statista. (n.d.). <https://www.statista.com/statistics/1067418/global-ethylene-glycol-production-capacity/> (accessed July 7, 2021).
- [22] Shell, OMEGA Process, (n.d.). <https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/petrochemicals/ethylene-oxide-production/omega-process.html>.
- [23] Ethylene Glycol Production, *Chemical Engineering.* (2015). <https://www.chemengonline.com/ethylene-glycol-production/> (accessed July 6, 2021).
- [24] European Commission. Joint Research Centre., *Energy efficiency and GHG emissions :prospective scenarios for the chemical and petrochemical industry.*, Publications Office, LU, 2017. <https://data.europa.eu/doi/10.2760/630308> (accessed July 6, 2021).

- [25] European Commission. Joint Research Centre., Best Available Techniques (BAT) reference document for the production of large volume organic chemicals., Publications Office, LU, 2017. <https://data.europa.eu/doi/10.2760/77304> (accessed July 6, 2021).
- [26] A. Wang, A. Bonakdarpour, D.P. Wilkinson, E. Gyenge, Novel organic redox catalyst for the electroreduction of oxygen to hydrogen peroxide, *Electrochimica Acta*. 66 (2012) 222–229. <https://doi.org/10.1016/j.electacta.2012.01.086>.
- [27] R. Daiyan, I. MacGill, R. Amal, Opportunities and Challenges for Renewable Power-to-X, *ACS Energy Lett.* 5 (2020) 3843–3847. <https://doi.org/10.1021/acsenergylett.0c02249>.
- [28] S. Schwarz, U. Zuberbühler, M. Schmidt, J. Kretzschmar, A. Friedrich, R. Schröer, C. Hebling, S. Calnan, R. Peters, R. Dittmeyer, F. Harnisch, T. Nagel, Power-to-X: Technologien für Übermorgen?!, (n.d.). [https://www.fvee.de/fileadmin/publikationen/Themenhefte/th2017/th2017\\_05\\_01.pdf](https://www.fvee.de/fileadmin/publikationen/Themenhefte/th2017/th2017_05_01.pdf) (accessed June 30, 2021).
- [29] B. Rego de Vasconcelos, J.-M. Lavoie, Recent Advances in Power-to-X Technology for the Production of Fuels and Chemicals, *Front. Chem.* 7 (2019) 392. <https://doi.org/10.3389/fchem.2019.00392>.
- [30] V. Eveloy, L.M. Romeo, D. Parra, M. Qadrdan, Editorial: Advances in Power-to-X: Processes, Systems, and Deployment, *Front. Energy Res.* 9 (2021) 650510. <https://doi.org/10.3389/fenrg.2021.650510>.
- [31] C. Wulf, P. Zapp, A. Schreiber, Review of Power-to-X Demonstration Projects in Europe, *Front. Energy Res.* 8 (2020) 191. <https://doi.org/10.3389/fenrg.2020.00191>.
- [32] I.R. Skov, N. Schneider, G. Schweiger, J.-P. Schöggel, A. Posch, Power-to-X in Denmark: An Analysis of Strengths, Weaknesses, Opportunities and Threats, *Energies*. 14 (2021) 913. <https://doi.org/10.3390/en14040913>.
- [33] European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - Powering a climate-neutral economy: An EU Strategy for Energy System Integration COM/2020/299 final, (2020). <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:299:FIN>.
- [34] European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - A hydrogen strategy for a climate-neutral Europe COM(2020) 301 final, (2020). [https://ec.europa.eu/energy/sites/ener/files/hydrogen\\_strategy.pdf](https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf).
- [35] G. Kakoulaki, I. Kougias, N. Taylor, F. Dolci, J. Moya, A. Jäger-Waldau, Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables, *Energy Conversion and Management*. 228 (2021) 113649. <https://doi.org/10.1016/j.enconman.2020.113649>.

- [36] Fuel Cells and Hydrogen 2 Joint Undertaking, Hydrogen roadmap Europe: a sustainable pathway for the European energy transition., 2019. [http://publications.europa.eu/publication/manifestation\\_identifier/PUB\\_EG0618327ENN](http://publications.europa.eu/publication/manifestation_identifier/PUB_EG0618327ENN) (accessed July 6, 2021).
- [37] European Commission. Directorate-General for Energy, Energy : roadmap 2050, Publications Office, LU, 2012. <https://data.europa.eu/doi/10.2833/10759> (accessed July 6, 2021).
- [38] F. Sensfuß, B. Pfluger, Optimized pathways towards ambitious climate protection in the European electricity system, Fraunhofer ISI, Karlsruhe, 2014. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/2014/Optimized-pathways-final.pdf> (accessed June 30, 2021).
- [39] V. Duscha, J. Wachsmuth, J. Eckstein, B. Pfluger, GHG-neutral EU2050 – a scenario of an EU with net-zero greenhouse gas emissions and its implications, Umweltbundesamt Deutschland, Dessau-Roßlau, 2019. [https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-26\\_cc\\_40-2019\\_ghg\\_neutral\\_eu2050\\_0.pdf](https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-26_cc_40-2019_ghg_neutral_eu2050_0.pdf) (accessed June 30, 2021).
- [40] J. Perner, D. Bothe, International aspects of a Power-To-X Roadmap, World Energy Council - Weltenergieinstitut Deutschland, 2018. <https://www.frontier-economics.com/media/2642/frontier-int-ptx-roadmap-stc-12-10-18-final-report.pdf> (accessed June 29, 2021).
- [41] A. van Wijk, J. Chatzimarkakis, Green Hydrogen for a European Green Deal - A 2x40 GW Initiative, Hydrogen Europe, 2020. [https://static1.squarespace.com/static/5d3f0387728026000121b2a2/t/5e85aa53179bb450f86a4efb/1585818266517/2020-04-01\\_Dii\\_Hydrogen\\_Studie2020\\_v13\\_SP.pdf](https://static1.squarespace.com/static/5d3f0387728026000121b2a2/t/5e85aa53179bb450f86a4efb/1585818266517/2020-04-01_Dii_Hydrogen_Studie2020_v13_SP.pdf) (accessed June 30, 2021).
- [42] F. Pflugmann, N. De Blasio, The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets, *Geopol. Hist. Int. Relat.* 12 (2020) 7. <https://doi.org/10.22381/GHIR12120201>.
- [43] T. Van de Graaf, I. Overland, D. Scholten, K. Westphal, The new oil? The geopolitics and international governance of hydrogen, *Energy Research & Social Science.* 70 (2020) 101667. <https://doi.org/10.1016/j.erss.2020.101667>.
- [44] European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs., Study on the EU's list of critical raw materials (2020): final report., Publications Office, LU, 2020. <https://data.europa.eu/doi/10.2873/11619> (accessed July 6, 2021).
- [45] M. Szczepański, Critical raw materials for the EU - Enablers of the green and digital recovery, (2020). [https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659426/EPRS\\_BRI\(2020\)659426\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659426/EPRS_BRI(2020)659426_EN.pdf) (accessed June 28, 2021).
- [46] WGI 2020 Interactive > Home, (n.d.). <http://info.worldbank.org/governance/wgi/#home> (accessed July 6, 2021).

- [47] European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs., Critical raw materials for strategic technologies and sectors in the EU: a foresight study., Publications Office, LU, 2020. <https://data.europa.eu/doi/10.2873/58081> (accessed July 6, 2021).
- [48] R. Wüstenhagen, M. Wolsink, M.J. Bürer, Social acceptance of renewable energy innovation: An introduction to the concept, *Energy Policy*. 35 (2007) 2683–2691. <https://doi.org/10.1016/j.enpol.2006.12.001>.
- [49] C. Friedl, J. Reichl, Realizing energy infrastructure projects – A qualitative empirical analysis of local practices to address social acceptance, *Energy Policy*. 89 (2016) 184–193. <https://doi.org/10.1016/j.enpol.2015.11.027>.
- [50] F. Ausfelder, H.E. Dura, Optionen für ein Nachhaltiges Energiesystem mit Power-To-X Technologien, Kopernikus Projekt “Power-To-X,” 2018. <https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/2018-Power-to-X.pdf> (accessed June 30, 2021).
- [51] A. Partanen, M. Carus, S. Piotrowski, L. Dammer, M. Küppers, Bio-based products: Green premium prices and consumer perception of different biomass feedstocks, Nova Institute for Ecology and Innovation, Huerth, Germany, 2020. <http://bio-based.eu/downloads/bio-based-products-green-premium-prices-and-consumer-perception-of-different-biomass-feedstocks/> (accessed June 29, 2020).
- [52] R. Taylor, L. Natrass, G. Alberts, P. Robson, C. Chudziak, A. Bauen, I.M. Libelli, G. Lotti, M. Prussi, R. Nistri, D. Chiaramonti, A.M. López-Contreras, H.L. Bos, G. Eggink, J. Springer, R. Bakker, R. van Ree, From the Sugar Platform to biofuels and biochemicals : Final report for the European Commission Directorate-General Energy, E4tech/Re-CORD/Wageningen UR, 2015. <https://edepot.wur.nl/360244>.
- [53] A. Muscat, E.M. de Olde, I.J.M. de Boer, R. Ripoll-Bosch, The battle for biomass: A systematic review of food-feed-fuel competition, *Global Food Security*. 25 (2020) 100330. <https://doi.org/10.1016/j.gfs.2019.100330>.
- [54] A. Thorenz, L. Wietschel, D. Stindt, A. Tuma, Assessment of agroforestry residue potentials for the bioeconomy in the European Union, *Journal of Cleaner Production*. 176 (2018) 348–359. <https://doi.org/10.1016/j.jclepro.2017.12.143>.
- [55] L. Lutzke, J. Árvai, Consumer acceptance of products from carbon capture and utilization, *Climatic Change*. 166 (2021) 15. <https://doi.org/10.1007/s10584-021-03110-3>.
- [56] A European Green Deal, European Commission - European Commission. (n.d.). [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en) (accessed July 6, 2021).
- [57] European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - Chemicals Strategy for Sustainability

Towards a Toxic-Free Environment COM/2020/667 final, (2020). [https://eur-lex.europa.eu/resource.html?uri=cellar:f815479a-0f01-11eb-bc07-01aa75ed71a1.0003.02/DOC\\_1&format=PDF](https://eur-lex.europa.eu/resource.html?uri=cellar:f815479a-0f01-11eb-bc07-01aa75ed71a1.0003.02/DOC_1&format=PDF) (accessed June 30, 2021).

[58] A. Arnold, K. Steentjes, Perception of Climate Change and the Energy Transition: Results from a European Survey, *GAIA - Ecological Perspectives for Science and Society*. 26 (2017) 280–281. <https://doi.org/10.14512/gaia.26.3.13>.

[59] T.R. Peterson, J.C. Stephens, E.J. Wilson, Public perception of and engagement with emerging low-carbon energy technologies: A literature review, *MRS Energy & Sustainability*. 2 (2015) 11. <https://doi.org/10.1557/mre.2015.12>.

[60] O. Kaya, W. Florkowski, A. Us, A. Klepacka, Renewable Energy Perception by Rural Residents of a Peripheral EU Region, *Sustainability*. 11 (2019) 2075. <https://doi.org/10.3390/su11072075>.

[61] P. Emmerich, A.-G. Hülemeier, D. Jendryczko, M.J. Baumann, M. Weil, D. Baur, Public acceptance of emerging energy technologies in context of the German energy transition, *Energy Policy*. 142 (2020) 111516. <https://doi.org/10.1016/j.enpol.2020.111516>.

[62] H.S. Boudet, Public perceptions of and responses to new energy technologies, *Nat Energy*. 4 (2019) 446–455. <https://doi.org/10.1038/s41560-019-0399-x>.

[63] N.M.A. Huijts, E.J.E. Molin, L. Steg, Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework, *Renewable and Sustainable Energy Reviews*. 16 (2012) 525–531. <https://doi.org/10.1016/j.rser.2011.08.018>.

[64] A. Taubitz, J. Hildebrand, Akzeptanz neuer Energiewende-Technologien – Beispiel Power-to-X, 69 (2019) 39–42.

[65] G. Reiter, J. Lindorfer, Evaluating CO<sub>2</sub> sources for power-to-gas applications – A case study for Austria, *Journal of CO<sub>2</sub> Utilization*. 10 (2015) 40–49. <https://doi.org/10.1016/j.jcou.2015.03.003>.

[66] European Biogas Association (EBA), Gas Infrastructure Europe (gie), European Biomethane Map 2018: Infrastructure for Biomethane Production, (2018). [http://european-biogas.eu/wp-content/uploads/2018/01/2018.01.09.GIE\\_BIO\\_2018\\_A0\\_1189x841\\_FULL\\_415\\_clean\\_final.pdf](http://european-biogas.eu/wp-content/uploads/2018/01/2018.01.09.GIE_BIO_2018_A0_1189x841_FULL_415_clean_final.pdf).

[67] European Biogas Association (EBA), Gas Infrastructure Europe (GIE), European Biomethane Map 2020: Infrastructure for Biomethane Production, (2020). <https://www.european-biogas.eu/eba-gie-biomethane-map/>.

[68] ePURE, eURE Activity Report 2016-2017, Brussels, 2017. <https://epure.org/media/1559/170531-epure-activity-report-2016-2017.pdf>.

[69] Enerdata intelligence + consulting, Power Plant Tracker, Enerdata intelligence + consulting, 2021. <https://www.enerdata.net/research/power-plant-database.html>.

- [70] The Wind Power, Wind energy database, (2021). [https://www.thewindpower.net/wind-farm\\_de\\_105\\_bruck-an-der-leitha.php](https://www.thewindpower.net/wind-farm_de_105_bruck-an-der-leitha.php) (accessed February 18, 2021).
- [71] P. (Ineos) Skelley, The Trans European Olefins Pipelines Network Project – Benefits to the European Industry, (2008). <https://ec.europa.eu/DocsRoom/documents/11993/attachments/1/translations/en/renditions/native>.
- [72] European ethylene pipeline network, ARG | English. (n.d.). <https://argkg.com/european-ethylene-pipeline-network/> (accessed July 6, 2021).
- [73] UKOPA, UK Ethylene System, (2009). <https://www.ukopa.co.uk/pdfs/UKOPA-09-0016.pdf>.
- [74] Interactive-Simulator, GB Simulation Technology (GBST), n.d. [www.gbsimtech.com/Solutions/Interactive-Simulator](http://www.gbsimtech.com/Solutions/Interactive-Simulator) (accessed July 1, 2019).
- [75] SABIC - SABIC UK Cross Country Pipelines, (n.d.). <https://www.sabic.com/en/about/ehss/sabic-uk-pipelines> (accessed July 6, 2021).
- [76] M. Lichtarowicz, The Chemical Industry, (n.d.). <https://www.essentialchemicalindustry.org/index.php/the-chemical-industry/the-chemical-industry> (accessed July 6, 2021).
- [77] Maps , Refineries and Crackers, Petrochemicals Europe. (n.d.). <https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/maps-refineries-and-crackers/> (accessed July 6, 2021).
- [78] M. Ghanta, T. Ruddy, D. Fahey, D. Busch, B. Subramaniam, Is the Liquid-Phase H<sub>2</sub>O<sub>2</sub>-Based Ethylene Oxide Process More Economical and Greener Than the Gas-Phase O<sub>2</sub>-Based Silver-Catalyzed Process?, *Ind. Eng. Chem. Res.* 52 (2013) 18–29. <https://doi.org/10.1021/ie301601y>.
- [79] F. Ausfelder, A.M. Bazzanella, A. Möller, R. Geres, A. Kohn, S. Lenz, Roadmap Chemie 2050 Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland, 2019. [https://www.researchgate.net/publication/336496114\\_Roadmap\\_Chemie\\_2050\\_Auf\\_dem\\_Weg\\_zu\\_einer\\_treibhausgasneutralen\\_chemischen\\_Industrie\\_in\\_Deutschland](https://www.researchgate.net/publication/336496114_Roadmap_Chemie_2050_Auf_dem_Weg_zu_einer_treibhausgasneutralen_chemischen_Industrie_in_Deutschland).
- [80] PlasticsEurope AISBL, Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers: Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), Ethylene Glycols (MEG, DEG, TEG), PlasticsEurope AISBL, Brussels, Belgium, 2012. <https://www.plasticseurope.org/en/resources/eco-profiles>.
- [81] M. Ghanta, Development of an Economically Viable H<sub>2</sub>O<sub>2</sub>-based, Liquid-Phase Ethylene Oxide Technology: Reactor Engineering and Catalyst Development Studies, 2012. Chemical and Petroleum Engineering.
- [82] ECHA European Chemicals Agency, Hydrogen peroxide - Registration Dossier - ECHA, (2020). <https://echa.europa.eu/it/registration-dossier/-/registered-dossier/15701>.

- [83] Ecofys, Fraunhofer Institute for Systems and Innovation Research, Öko-Institut e.V, Methodology for the free allocation of emission allowances in the EU ETS post 2012 Sector report for the chemical industry, 2009. [https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/bm\\_study-lime\\_en.pdf](https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/bm_study-lime_en.pdf).
- [84] P.P. van Uytvanck, B. Hallmark, G. Haire, P.J. Marshall, J.S. Dennis, Impact of Biomass on Industry: Using Ethylene Derived from Bioethanol within the Polyester Value Chain, ACS Sustainable Chem. Eng. 2 (2014) 1098–1105. <https://doi.org/10.1021/sc5000804>.
- [85] S. Pfenninger, I. Staffell, Renewables.ninja: Online RES simulation tool, (2016). <https://www.renewables.ninja/> (accessed February 18, 2021).
- [86] VERBUND AG, Windpark Bruck-Göttlesbrunn, (2021). <https://www.verbund.com/de-at/ueber-verbund/kraftwerke/unsere-kraftwerke/windpark-bruck-goettlesbrunn>.
- [87] VERBUND AG, Windpark Bruck an der Leitha, (2021). <https://www.verbund.com/de-at/ueber-verbund/kraftwerke/unsere-kraftwerke/windpark-bruck-an-der-leitha>.
- [88] Biogas Bruck/Leitha GmbH & Co KG, ed., Folder Biogas Bruck/Leitha, (2015). [http://www.energiepark.at/fileadmin/user\\_upload/Dokumente/Biogas/FOLDER\\_ENGLISCH\\_RZ.pdf](http://www.energiepark.at/fileadmin/user_upload/Dokumente/Biogas/FOLDER_ENGLISCH_RZ.pdf).
- [89] A. Makaruk, WP2 - CO2 feedstock preparation, (2019).
- [90] European Commission, Joint Research Centre Energy Efficiency and Renewables Unit, JRC Photovoltaic Geographical Information System (PVGIS), (2016). [https://re.jrc.ec.europa.eu/pvg\\_tools/en/tools.html](https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html).
- [91] GETEC green energy GmbH, Mitteldeutscher Energieverbund ZUKUNFT, (2021). <https://www.getec-greenenergy.de/mitteldeutscher-energieverbund-zukunft> (accessed June 23, 2021).
- [92] A. Rüsche, Energiepark Zerbst: Windkraftanlagen feierlich eingeweiht, Batteriespeicher folgt, Mittelstand Nachrichten. (2015). <https://www.mittelstand-nachrichten.de/unternehmen/energiepark-zerbst-windkraftanlagen-feierlich-ingeweiht-batteriespeicher-folgt/>.
- [93] B. Schwingenheuer, Besucher erkunden Biogasanlage und Windräder in Zerbst, Volksstimme. (2015). [https://www.volksstimme.de/nachrichten/lokal/zerbst/1491392\\_Besucher-erkunden-Biogasanlage-und-Windraeder-in-Zerbst.html](https://www.volksstimme.de/nachrichten/lokal/zerbst/1491392_Besucher-erkunden-Biogasanlage-und-Windraeder-in-Zerbst.html).
- [94] S. Siebert, Riesenkran zieht Windräder hoch, Volksstimme. (2015). <https://www.volksstimme.de/lokal/zerbst/20151008/energiepark-zerbst-riesenkran-zieht-windraeder-hoch>.
- [95] Pentair Food & Beverage, HAFFMANS Biogas Upgrading - Wight Farm Energy LLP: Case Study, (2016). [https://foodandbeverage.pentair.com/~media/websites/food-and-beverage/downloads/case-studies/biogas-upgrading/biogas\\_upgrading\\_haffmans\\_case-study\\_wight-farm-energy.pdf](https://foodandbeverage.pentair.com/~media/websites/food-and-beverage/downloads/case-studies/biogas-upgrading/biogas_upgrading_haffmans_case-study_wight-farm-energy.pdf).

- [96] J. Cartwright, UK Electricity Production (beta) - Ventnor Road Solar Park, (2020). <https://electricityproduction.uk/plant/GBR0001096/>.
- [97] Renewables Map UK, Grange Farm Solar Farm, (2018). <http://www.renewables-map.co.uk/project.asp?pageid=3592>.
- [98] Renewables Map UK, Fieldscale, (2016). <http://www.renewables-map.co.uk/dec-cpop.asp?deccrefid=4833>.
- [99] Exxonmobil, Fawley refinery, (2019). <https://www.exxonmobil.co.uk/Company/Overview/UK-operations/Fawley-refinery>.
- [100] Nuclear Energy Agency (NEA), International Energy Agency (IEA), Projected Costs of Generating Electricity 2020, 2020. <https://doi.org/10.1787/a6002f3b-en>.
- [101] Verein Deutscher Ingenieure e.V., VDI 2067 Blatt 1 - Wirtschaftlichkeit gebäudetechnischer Anlagen: Grundlagen und Kostenberechnung, 2012.
- [102] M.S. Peters, K.D. Timmerhaus, Plant design and economics for chemical engineers, 4. ed, McGraw-Hill, New York, 1991.
- [103] H. Böhm, S. Goers, A. Zauner, Estimating future costs of power-to-gas – a component-based approach for technological learning, International Journal of Hydrogen Energy. 44 (2019) 30789–30805. <https://doi.org/10.1016/j.ijhydene.2019.09.230>.
- [104] M. Jouny, W. Luc, F. Jiao, General Techno-Economic Analysis of CO<sub>2</sub> Electrolysis Systems, Ind. Eng. Chem. Res. 57 (2018) 2165–2177. <https://doi.org/10.1021/acs.iecr.7b03514>.
- [105] S. Anantharaj, S. Pitchaimuthu, S. Noda, A review on recent developments in electrochemical hydrogen peroxide synthesis with a critical assessment of perspectives and strategies, Advances in Colloid and Interface Science. 287 (2021) 102331. <https://doi.org/10.1016/j.cis.2020.102331>.
- [106] J. Na, B. Seo, J. Kim, C.W. Lee, H. Lee, Y.J. Hwang, B.K. Min, D.K. Lee, H.-S. Oh, U. Lee, General technoeconomic analysis for electrochemical coproduction coupling carbon dioxide reduction with organic oxidation, Nat Commun. 10 (2019) 5193. <https://doi.org/10.1038/s41467-019-12744-y>.
- [107] S.R. Kelly, X. Shi, S. Back, L. Vallez, S.Y. Park, S. Siahrostami, X. Zheng, J.K. Nørskov, ZnO As an Active and Selective Catalyst for Electrochemical Water Oxidation to Hydrogen Peroxide, ACS Catal. 9 (2019) 4593–4599. <https://doi.org/10.1021/acscatal.8b04873>.
- [108] S. Ma, M. Sadakiyo, R. Luo, M. Heima, M. Yamauchi, P.J.A. Kenis, One-step electro-synthesis of ethylene and ethanol from CO<sub>2</sub> in an alkaline electrolyzer, Journal of Power Sources. 301 (2016) 219–228. <https://doi.org/10.1016/j.jpowsour.2015.09.124>.
- [109] C.-T. Dinh, T. Burdyny, M.G. Kibria, A. Seifitokaldani, C.M. Gabardo, F.P. García de Arquer, A. Kiani, J.P. Edwards, P. De Luna, O.S. Bushuyev, C. Zou, R. Quintero-Bermudez,

- Y. Pang, D. Sinton, E.H. Sargent, CO<sub>2</sub> electroreduction to ethylene via hydroxide-mediated copper catalysis at an abrupt interface, *Science*. 360 (2018) 783–787. <https://doi.org/10.1126/science.aas9100>.
- [110] J.-B. Vennekoetter, R. Sengpiel, M. Wessling, Beyond the catalyst: How electrode and reactor design determine the product spectrum during electrochemical CO<sub>2</sub> reduction, *Chemical Engineering Journal*. 364 (2019) 89–101. <https://doi.org/10.1016/j.cej.2019.01.045>.
- [111] D.S. Ripatti, T.R. Veltman, M.W. Kanan, Carbon Monoxide Gas Diffusion Electrolysis that Produces Concentrated C<sub>2</sub> Products with High Single-Pass Conversion, *Joule*. 3 (2019) 240–256. <https://doi.org/10.1016/j.joule.2018.10.007>.
- [112] C.-T. Dinh, Y.C. Li, E.H. Sargent, Boosting the Single-Pass Conversion for Renewable Chemical Electrosynthesis, *Joule*. 3 (2019) 13–15. <https://doi.org/10.1016/j.joule.2018.10.021>.
- [113] F.P. García de Arquer, C.-T. Dinh, A. Ozden, J. Wicks, C. McCallum, A.R. Kirmani, D.-H. Nam, C. Gabardo, A. Seifitokaldani, X. Wang, Y.C. Li, F. Li, J. Edwards, L.J. Richter, S.J. Thorpe, D. Sinton, E.H. Sargent, CO<sub>2</sub> electrolysis to multicarbon products at activities greater than 1 A cm<sup>-2</sup>, *Science*. 367 (2020) 661–666. <https://doi.org/10.1126/science.aay4217>.
- [114] F. Li, A. Thevenon, A. Rosas-Hernández, Z. Wang, Y. Li, C.M. Gabardo, A. Ozden, C.T. Dinh, J. Li, Y. Wang, J.P. Edwards, Y. Xu, C. McCallum, L. Tao, Z.-Q. Liang, M. Luo, X. Wang, H. Li, C.P. O'Brien, C.-S. Tan, D.-H. Nam, R. Quintero-Bermudez, T.-T. Zhuang, Y.C. Li, Z. Han, R.D. Britt, D. Sinton, T. Agapie, J.C. Peters, E.H. Sargent, Molecular tuning of CO<sub>2</sub>-to-ethylene conversion, *Nature*. 577 (2020) 509–513. <https://doi.org/10.1038/s41586-019-1782-2>.
- [115] M. Zhong, K. Tran, Y. Min, C. Wang, Z. Wang, C.-T. Dinh, P. De Luna, Z. Yu, A.S. Rasouli, P. Brodersen, S. Sun, O. Voznyy, C.-S. Tan, M. Askerka, F. Che, M. Liu, A. Seifitokaldani, Y. Pang, S.-C. Lo, A. Ip, Z. Ulissi, E.H. Sargent, Accelerated discovery of CO<sub>2</sub> electrocatalysts using active machine learning, *Nature*. 581 (2020) 178–183. <https://doi.org/10.1038/s41586-020-2242-8>.
- [116] S. Mavrikis, M. Göltz, S. Rosiwal, L. Wang, C. Ponce de León, Boron-Doped Diamond Electrocatalyst for Enhanced Anodic H<sub>2</sub>O<sub>2</sub> Production, *ACS Appl. Energy Mater.* 3 (2020) 3169–3173. <https://doi.org/10.1021/acsaem.0c00093>.
- [117] X. Shi, Y. Zhang, S. Siahrostami, X. Zheng, Light-Driven BiVO<sub>4</sub>-C Fuel Cell with Simultaneous Production of H<sub>2</sub>O<sub>2</sub>, *Adv. Energy Mater.* 8 (2018) 1801158. <https://doi.org/10.1002/aenm.201801158>.
- [118] I. Salmerón, K.V. Plakas, I. Sirés, I. Oller, M.I. Maldonado, A.J. Karabelas, S. Malato, Optimization of electrocatalytic H<sub>2</sub>O<sub>2</sub> production at pilot plant scale for solar-assisted water treatment, *Applied Catalysis B: Environmental*. 242 (2019) 327–336. <https://doi.org/10.1016/j.apcatb.2018.09.045>.

- [119] E. Peralta, R. Natividad, G. Roa, R. Marin, R. Romero, T. Pavon, A comparative study on the electrochemical production of H<sub>2</sub>O<sub>2</sub> between BDD and graphite cathodes, *Sustain. Environ. Res.* 23 (2013) 259–266.
- [120] K. Wenderich, B.A.M. Nieuweweme, G. Mul, B.T. Mei, Selective Electrochemical Oxidation of H<sub>2</sub>O to H<sub>2</sub>O<sub>2</sub> Using Boron-Doped Diamond: An Experimental and Techno-Economic Evaluation, *ACS Sustainable Chem. Eng.* (2021) acssuschemeng.1c01244. <https://doi.org/10.1021/acssuschemeng.1c01244>.
- [121] M.S. Peters, K.D. Timmerhaus, R.E. West, *Plant design and economics for chemical engineers*, 5th ed, McGraw-Hill, New York, 2003.
- [122] Energy Exchange Austria (EXAA), Historical Data EXAA Energy Exchange Austria, (2019). <https://www.exaa.at/en/marketdata/historical-data>.
- [123] International Energy Agency (IEA), Techno-economic inputs – World Energy Model – Analysis, IEA. (2021). <https://www.iea.org/reports/world-energy-model/techno-economic-inputs> (accessed June 29, 2021).
- [124] Statista, Ethylene prices globally 2022, Statista. (2020). <https://www.statista.com/statistics/1170573/price-ethylene-forecast-globally/> (accessed June 29, 2021).
- [125] Eurostat, Gas prices for non-household consumers - bi-annual data (from 2007 onwards): nrg\_pc\_203, (2020). [http://ec.europa.eu/eurostat/product?code=nrg\\_pc\\_203](http://ec.europa.eu/eurostat/product?code=nrg_pc_203).
- [126] Carbon Price Viewer, Ember. (n.d.). <https://ember-climate.org/data/carbon-price-viewer/> (accessed July 7, 2021).
- [127] M. Ellerstorfer, M. Harasek, „Greening the gas“; Task 3.2: Standardisierte Aufbereitung CH<sub>4</sub>-basierter biogener Gase, Montanuniversität Leoben (VTiU), 2020. <https://www.gruenes-gas.at/assets/Uploads/2-Montanuniversitat-Leoben-2019-Entwicklung-eines-Standard-Konzept-Aufbereitung-Rohbiogas.pdf>.
- [128] A. Chaube, A. Chapman, Y. Shigetomi, K. Huff, J. Stubbins, The Role of Hydrogen in Achieving Long Term Japanese Energy System Goals, *Energies.* 13 (2020) 4539. <https://doi.org/10.3390/en13174539>.
- [129] T. Kober, C. Bauer, C. Bach, M. Beuse, G. Georges, M. Held, S. Heselhaus, P. Korba, L. Küng, A. Malhotra, S. Moebus, D. Parra, J. Roth, M. Rüdüsüli, T.J. Schildhauer, T.J. Schmidt, T. Schmidt, M. Schreiber, F.R. Segundo Sevilla, B. Steffen, S.L. Teske, *Power-to-X: Perspektiven in der Schweiz: Ein Weissbuch*, ETH Zurich, 2019. <https://doi.org/10.3929/ETHZ-B-000341153>.
- [130] European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012, Commission implementing regulation (EU) 2018/2066 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012, 2018.

## ABBREVIATIONS

Abbreviation	Explanation
$C_2H_4$	Ethylene (Ethene)
$C_2H_4O$	Ethylene Oxide
CAPEX	CAPital EXpenditure
CAS	Chemical Abstract Service
$CH_4$	Methane
CO	Carbon monoxide
$CO_2$	Carbon Dioxide
CoLLeCT	Component Level Learning Curve Tool
DAC	Direct Air Capture
EEU	Ethylene Enrichment Unit
EO	Ethylene Oxide
EOU	Ethylene Oxide Reaction Unit
ERU	Electrocatalytic Reaction Unit
FE	Faraday Efficiency (= Selectivity)
RU	Reference Unit
GIS	Geographical Information System
$H_2$	Hydrogen
$H_2O$	Water
HVC	High Value Chemical
IUPAC	International Union of Pure and Applied Chemistry
kg	kilogram
kWh	kilo Watt hour
LCA	Life Cycle Assessment
LHV	Lower Heating Value
MJ	Megajoule
MW	Mega Watt
NUTS	Nomenclature des unités territoriales statistiques
OPEX	OPerational EXpenditure
PtX	Power-to-X
PV	Photovoltaics
RES	Renewable Energy Source
SAMBA	Socio- And Multicriteria Model for reducing Barriers Analysis
SEA	Socio-Economic Assessment
SOTA	State Of The Art
TEA	Techno-Economic Assessment
TRL	Technology Readiness Level
UHV	Upper Heating Value

## LIST OF FIGURES

Figure 0-1:	Typical electricity production characteristic of a 30 MW wind farm. The power is divided in the share of grid feed-in and power for the CO2EXIDE plant (in this example the maximum grid feed-in is set to 11 MW, the surpluses are utilized by the electrocatalysis with a nominal power of 75 MW). Source: Energieinstitut... 9
Figure 1-1:	Prognosis of future installed power of fluctuating renewable power sources. Source: Energieinstitut, data based on IEA (2018) World Energy Outlook 2018. [14]..... 11
Figure 1-2	Overview of Ethylene Oxide Market Segments: Source: Energieinstitut based on IHS Markit Chemical Economics Handbook, Ethylene Oxide, 2020 [15]..... 12
Figure 1-3:	Production capacity of ethylene oxide worldwide in 2018 and 2023 (in million metric tons): Source: Energieinstitut based on globaldata.com (2020) ..... 13
Figure 1-4.	Distribution of worldwide consumption of ethylene oxide (2020) Source: Energieinstitut based on [15] and [16]. ..... 13
Figure 1-5:	World end-user industry of ethylene oxide (2020). Source: Energieinstitut based on [15] and [16]..... 14
Figure 1-6:	Market prices for ethylene, ethylene oxide & ethylene glycol (4-year-average). Source: Energieinstitut based on data from [18] - chemicals pricing data & production cost reports. .... 15
Figure 1-7:	Production capacity of ethylene worldwide from 2014 to 2024 (in million metric tons). Source: Energieinstitut based on [19]. ..... 16
Figure 1-8:	Ethylene global demand distribution by end product 2015. Source: Energieinstitut based on [20]. ..... 16
Figure 1-9:	Production capacity of ethylene glycol worldwide from 2014 to 2024 (in million metric tons). Source: Energieinstitut based on [21]. ..... 17
Figure 1-10:	Monoethylene glycol (MEG) production, according to a process similar to the Shell OMEGA process. Source: [23]..... 18
Figure 2-1:	Historical development of PtX projects Europe and outlook on projected projects. Source: Wulf et al. [31]..... 21
Figure 2-2:	Raw materials identified to be critical. Source: European Commission (2020) [44] ..... 24
Figure 2-3:	The concept of the „green premium price“. Source: Energieinstitut based on Partanen et al (2020) [51] ..... 27
Figure 2-4:	Technology Acceptance Framework according to Huijts et al. [63] ..... 29
Figure 2-5:	Classification of potential biogenic CO <sub>2</sub> sources including the available typical CO <sub>2</sub> concentration. Source: Energieinstitut based on [65]..... 36
Figure 2-6:	Biogenic CO <sub>2</sub> potential in Europe. Source: Energieinstitut based on data from [7] ..... 36

Figure 3-1: Procedure of GIS-based potential analysis for Europe.....	39
Figure 3-2: Exemplary result of the GIS processing of existing bioethanol plants. Color indicates the theoretical CO <sub>2</sub> potential. No claim to completeness.....	40
Figure 3-3: Exemplary result of the GIS processing of existing onshore wind farms 5 to 600 MW. Color indicates the rated power. No claim to completeness.....	41
Figure 3-4: Exemplary result of the GIS processing of existing PV plants 1 to 230 MW. Color indicates the rated power. No claim to completeness.....	42
Figure 3-5: Exemplary result of the GIS processing of ethylene pipelines across Europe as well as their crossing points and large chemical industry being related to ethylene (yellow triangles). No claim to completeness. Source: Energieinstitut based on [71–77]......	43
Figure 3-6: Biomethane upgrading (162) and bioethanol (13) plants with PV/wind farms within a 5 km range available. Also, ethylene pipelines are displayed. ....	44
Figure 4-1: Schematic overview of analyzed CO <sub>2</sub> EXIDE process with on-site waste-product recycling, cascade synthesis to Ethylene Oxide and optional side product valorisation. Source: Energieinstitut.....	49
Figure 4-2: Individual and total power generation of the RES considered in the Austrian case study. Data source: simulated with Renewables.Ninja [85] based on wind farm data from VERBUND [86,87] .....	53
Figure 4-3: Location of the biomethane plant Bruck/Leitha and wind farms in close proximity. Additionally, an Ethylene pipeline crossing Austria is located in 27 km distance in Schwechat/Vienna. Sources: Energieinstitut based on Google Maps & input data: compare Table 4-2.....	54
Figure 4-4: Individual and total power generation of the RES considered in the German case study. Data source: wind power simulated with Renewables.Ninja [85], PV power simulated with PVGIS [90] based on wind and solar farm data from [91–94]...	56
Figure 4-5: Location of the biomethane plant Zerbst within Energy Park Zerbst and the close by wind farm and solar farm, which are also part of Energy Park Zerbst. Energieinstitut based on Google Maps & input data: compare Table 4-3. Illustration: Energieinstitut.....	57
Figure 4-6: Individual and total power generation of the RES considered in the UK case study. Data source: PV power simulated with PVGIS [90] based on solar farm data from [96–98].....	59
Figure 4-7: Location of the biomethane plant Gore Cross close to Arreton and the close by solar farms. The port of the Isle of Wight is approx. 10 km away. Approx. 20 km away on the mainland in Fawley, near Southampton, the United Kingdom's largest conventional refinery is located. Sources: Google Maps, input data: compare Table 4-4 and ExxonMobil [99], illustration: Energieinstitut. ....	60
Figure 4-8: Load duration curves for the RES at the three case studies. Source: Energieinstitut based on simulation with renewables.ninja.....	61

Figure 4-9: Exemplary grid-supportive power generation and supply profile for one month at the location in Bruck an der Leitha. Source: Energieinstitut based on simulation with renewables.ninja. ....	62
Figure 4-10: Illustration of the learning curve assessment process using CoLLeCT .....	66
Figure 4-11: EU ETS carbon price development. Source: Energieinstitut based on [126]....	74
Figure 4-12: Hourly EXAA <i>grey</i> electricity spot prices in the year 2019, unsorted. Energieinstitut based on [122] .....	78
Figure 4-13: Hourly EXAA <i>grey</i> electricity spot prices in the year 2019, sorted. Energieinstitut based on [122] .....	79
Figure 4-14: Hourly EXAA <i>green</i> electricity spot prices in the year 2019, unsorted. Energieinstitut based on [122] .....	79
Figure 4-15: Hourly EXAA <i>green</i> electricity spot prices in the year 2019, sorted. Energieinstitut based on [122] .....	80
Figure 4-16: Individual cost shares of CAPEX in the 2030 scenario. Source: Energieinstitut. ....	82
Figure 4-17: Individual cost shares of CAPEX in the 2040 scenario. Source: Energieinstitut. ....	83
Figure 4-18: Individual cost shares of OPEX in the 2030 scenario. Source: Energieinstitut.	84
Figure 4-19: Individual cost shares of OPEX in the 2040 scenario. Source: Energieinstitut.	84
Figure 4-20: Shares of the proceeds generated from product sales based on the 2030 scenario. Source: Energieinstitut. ....	85
Figure 4-21: Development of the net present value (NPV) in the generic scenario for 2030. Source: Energieinstitut.....	86
Figure 4-22: Development of the net present value (NPV) in the generic scenario for 2040. Source: Energieinstitut.....	86
Figure 4-23: LCoP composition for the generic scenario in 2030 related to total products (left) and ethylene oxide only (right) without by-product sales. Source: Energieinstitut. ....	87
Figure 4-24: LCoP composition for the generic scenario in 2040 related to total products (left) and ethylene oxide only (right) without by-product sales. Energieinstitut. ....	88
Figure 4-25: LCoP composition under consideration of by-product sales (without H <sub>2</sub> O <sub>2</sub> ) for 2030 (left) and 2040 (right). Source: Energieinstitut. ....	89
Figure 4-26: Sensitivity of net present value (NPV) to individual parameter variation. Source: Energieinstitut. ....	92
Figure 4-27: Sensitivity of payback time (PBT) to individual parameter variation. Source: Energieinstitut. ....	93
Figure 4-28: Sensitivity of ethylene oxide-related LCoP to individual parameter variation. Source: Energieinstitut.....	94



## LIST OF TABLES

Table 1-1:	Literature values on energy and material flows of fossil based ethylene oxide and MEG production in Europe.....	19
Table 2-1:	Overview on aspects influencing social acceptance of renewable energy and infrastructure projects. Source: own table based on Christina Friedl and Johannes Reichl (2016). Realizing energy infrastructure projects – A qualitative empirical analysis of local practices to address social acceptance. Source: [49] .....	26
Table 4-1:	Characteristics of polymer precursors (Ethylene, Ethylene oxide) under consideration and potential subsequent ethylene glycols as well as Hydrogen Peroxide. Source: adapted from [80,82] .....	48
Table 4-2:	Overview of CO <sub>2</sub> and power sources in Bruck an der Leitha, Austria.....	52
Table 4-3:	Overview of CO <sub>2</sub> and power sources in Zerbst, Germany. ....	55
Table 4-4:	Overview of CO <sub>2</sub> and power sources on the Isle of Wight, United Kingdom. Sources: [66,69,90,95–98].....	58
Table 4-5:	Overview of the simulated energy production for the combined RES considered in the three case studies .....	61
Table 4-6:	Calculation factors used for cost conversion between sources of different currencies and publication dates .....	67
Table 4-7:	Overview of electrocatalytic processes of CO / CO <sub>2</sub> to ethylene conversion according to literature. (1/2) .....	70
Table 4-8:	Overview of electrocatalytic processes of CO / CO <sub>2</sub> to Ethylene conversion according to literature. (2/2) .....	71
Table 4-9:	Overview of electrocatalytic processes O <sub>2</sub> /H <sub>2</sub> O to H <sub>2</sub> O <sub>2</sub> according to literature.....	70
Table 4-10:	Characteristics of the electrochemical reactor unit .....	71
Table 4-11:	Characteristics of the ethylene enrichment unit.....	71
Table 4-12:	Characteristics of the epoxidation reactor.....	72
Table 4-13:	Economic calculation parameters .....	73
Table 4-14:	Overview of fossil reference products and der GWP. ....	74
Table 4-15:	Modularized PEM water electrolysis costs and electrical characteristics in relevant system sizes. Based on [9] .....	75
Table 4-16:	Specific CAPEX for the ERU considering learning curve and scaling effects using the CoLLeCT model.....	76
Table 4-17:	Equipment costs for EEU and EOU .....	77
Table 4-18:	Costs for expected replacements of equipment during the observation period .....	77
Table 4-19:	Addition factors for indirect costs .....	78
Table 4-20:	Comparative TEA results for the considered case studies dependent on the available electricity production .....	90



## ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 768789. The authors would like to express their gratitude to the European Commission for this financial support.