Life cycle assessment and impact-related studies

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 768789.

SPIRE Sustainable Process Industry through Resource and Energy Efficiency

Life cycle assessment and impact-related studies

Outline

Topics related to **environmental impacts** are quantified

- **Biogenic CO_2** as single carbon source for ethylene/ethylene oxide via **electrocatalytic conversion**
- **Life Cycle Assessment** & benchmarking to relevant reference systems

Topics of **techno-economic impact** and exploitation scenarios are elaborated

- **Availability** & **matching** of **biogenic CO_2** and **renewable electricity sources** for CO_2EXIDE exploitation scenarios
- Data acquisition to **estimate production cost** and identify the **relevant variables** for further **development** & **future deployment**

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Building blocks for a vast range of chemicals

Reactive molecules produced on a vast scale as a plastics precursor

Ethylene

Oxygen

Ethylene Oxide

EO

Direct use of purified Ethylene Oxide

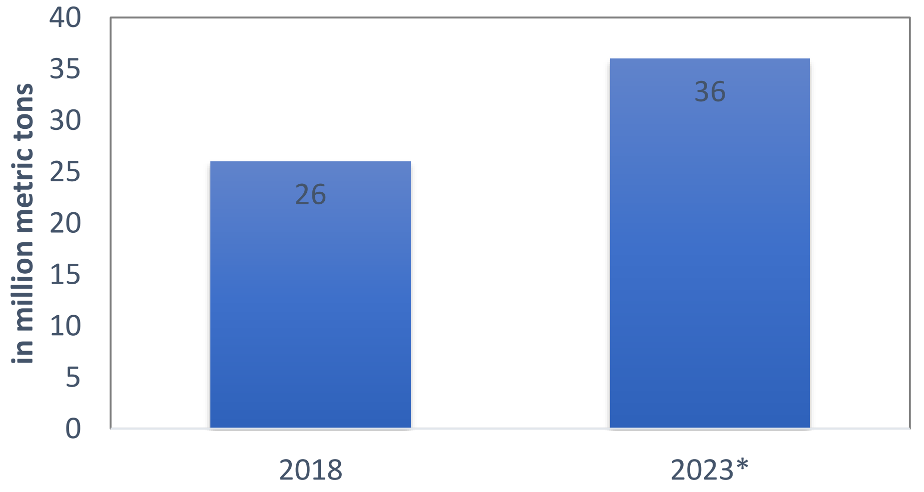
C_2H_4

+ 73 % 2014-2024*

C_2H_4O

+ 38 % 2018-2023*

Global production capacity of ethylene oxide 2018 & 2023



Source: EI-JKU based on globaldata.com

* Forecast.

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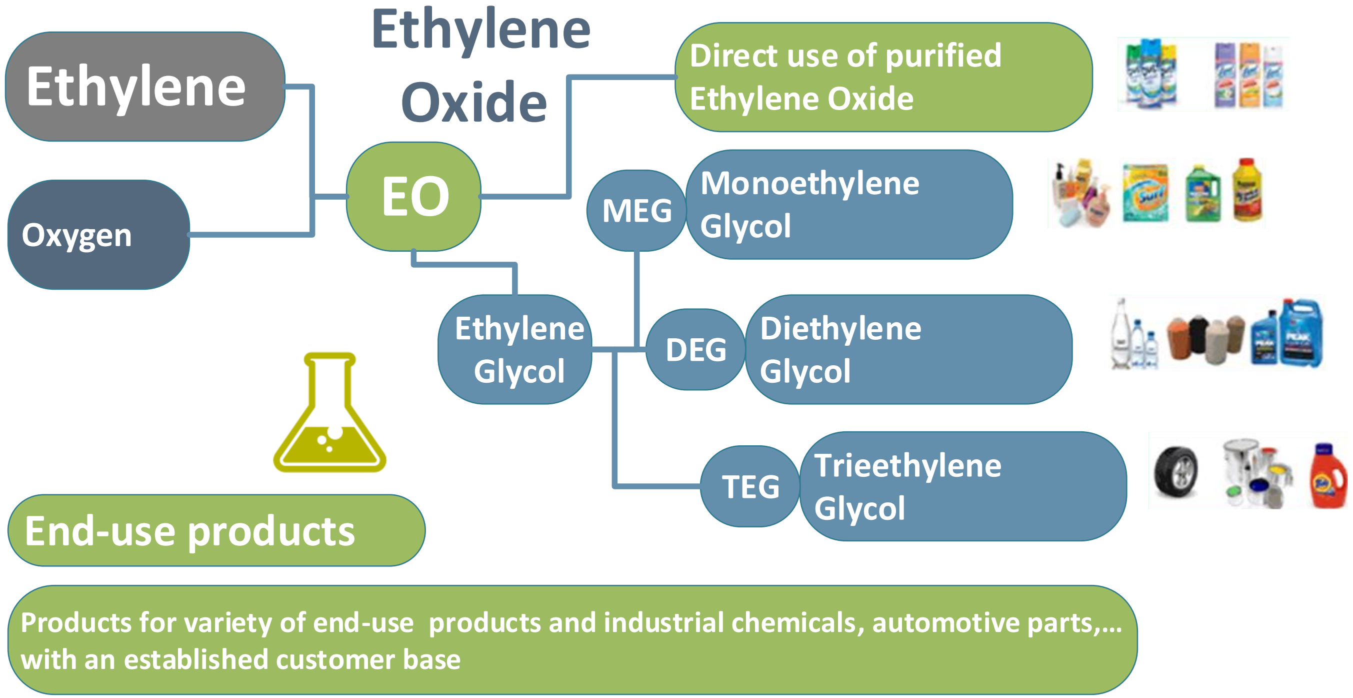
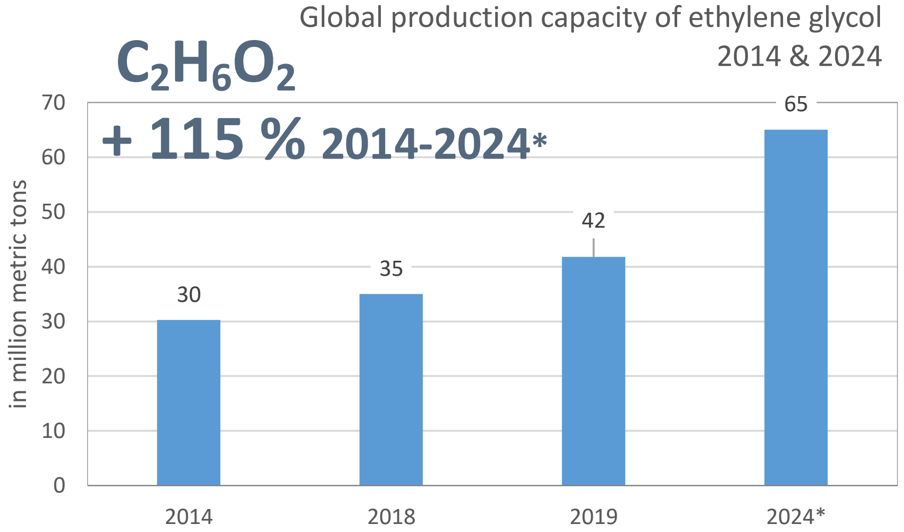
Building blocks for a vast range of chemicals

Intermediates in production of terephthalate polyester resins for fibers, films, and bottles





Source: EI-JKU based on globaldata.com

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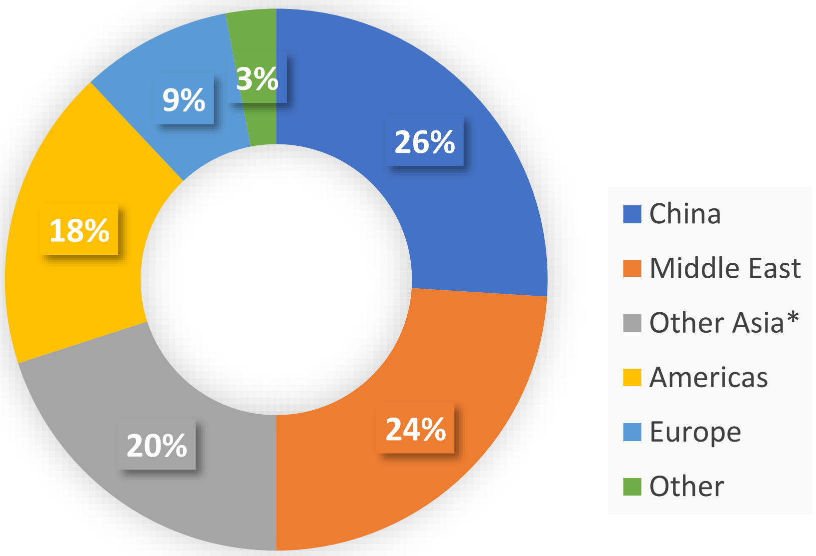
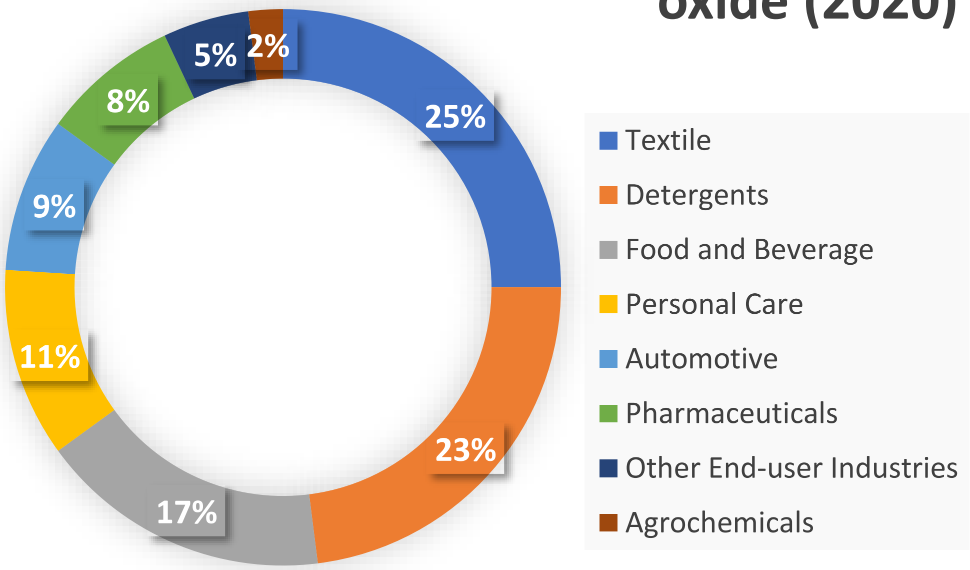
A growing market with growing dependencies

Asia is leading production & consumption of EO in the world

World consumption of ethylene oxide (2020)



World end-user industry of ethylene oxide (2020)



Source: EI-JKU based on IHS Market 2020 and Mordor Intelligence 2020

* other Asia includes the Indian Subcontinent, Japan, Taiwan, South Korea and Southeast Asia

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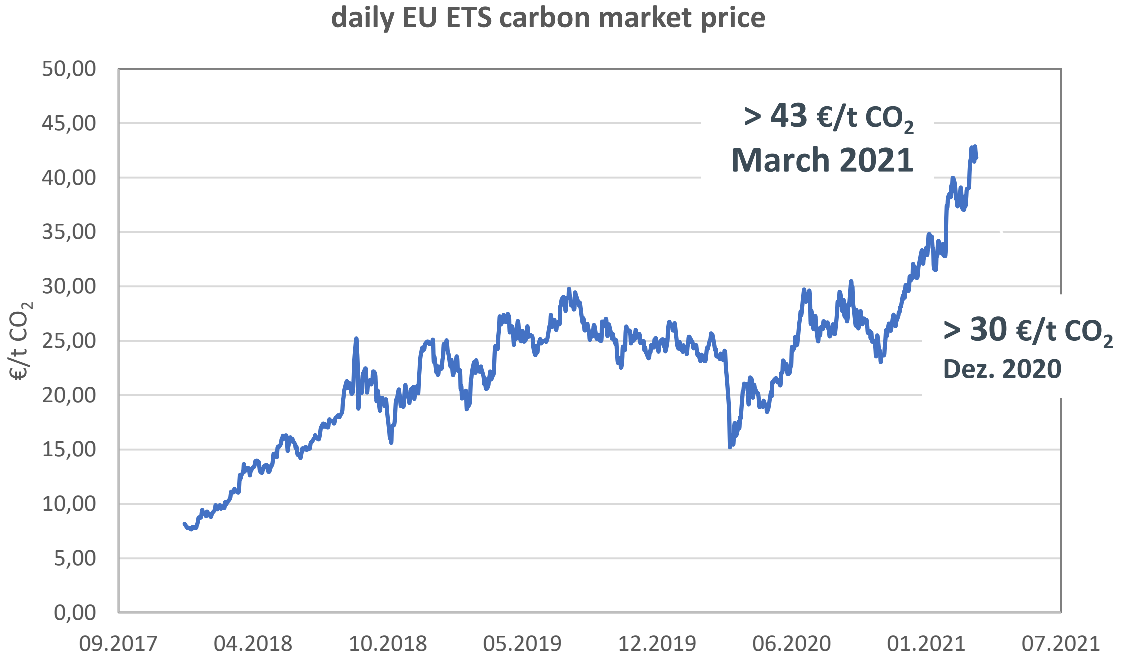
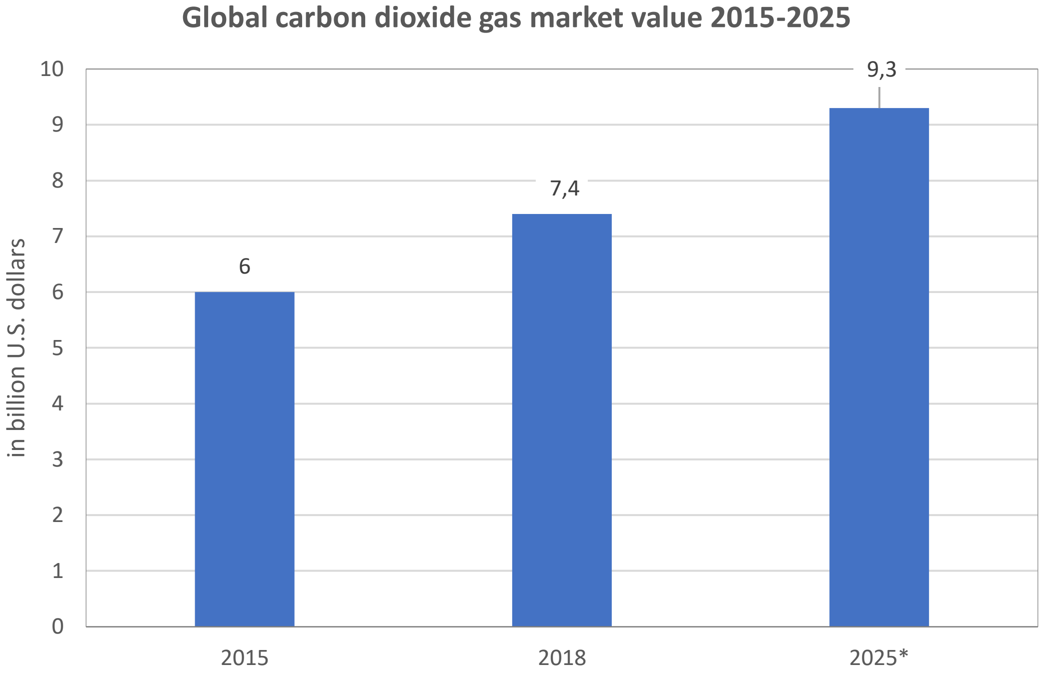
CO_2 – from emission to feedstock

Simple classification of pathways for CO_2 reuse





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The CO_2EXIDE project approach

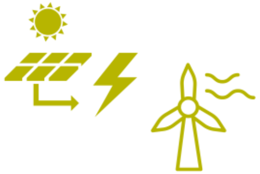
Renewable inputs for sustainable process design

The project aims for sustainable environmentally friendly products, thus the focus is on biogenic CO_2 and renewable electricity as main resources. As cost are a determining factor, further focus is on existing, high-purity CO_2-sources such as:

- ➔ Biogas upgrading
- ➔ Bioethanol production

P2X/CCU technologies can balance future energy systems with high shares of fluctuating renewable energy sources such as:

- ➔ Photovoltaics (PV)
- ➔ Wind power



Thus, the focus is on existing large PV and wind farms.

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Potential sources of biogenic CO_2

existing, high-purity point sources in the focus

CO_2 from combustion processes	CO_2 as by-product from industrial processes			CO_2 from the atmosphere
Coal 12 – 15 vol.-%	**Biogas upgrading** 30-100 vol.-%	Ethylene 12 vol.-%	Cement 20 vol.-%	Ambient air 0.039 vol.-%
Natural gas 3 – 10 vol.-%	**Bioethanol** up to 100 vol.-%	Ammonia up to 100 vol.-%	Steel & Iron 15 vol.-%	
Fuel oil 3 – 8 vol.-%	**Fermentations** up to 100 vol.-%	Refineries 3 – 13% vol.-%		
Biomass 3 – 8 vol.-%	Biotechnological processes	Chemical industry	Industrial production processes	

CO_2-sources
with ratio of CO_2
in the off-gas

Most important biogenic sources are highlighted in green

Source: Rodin, V. et al. (2020) Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO_2, Journal of CO2 Utilization, Vol. 41, 101219

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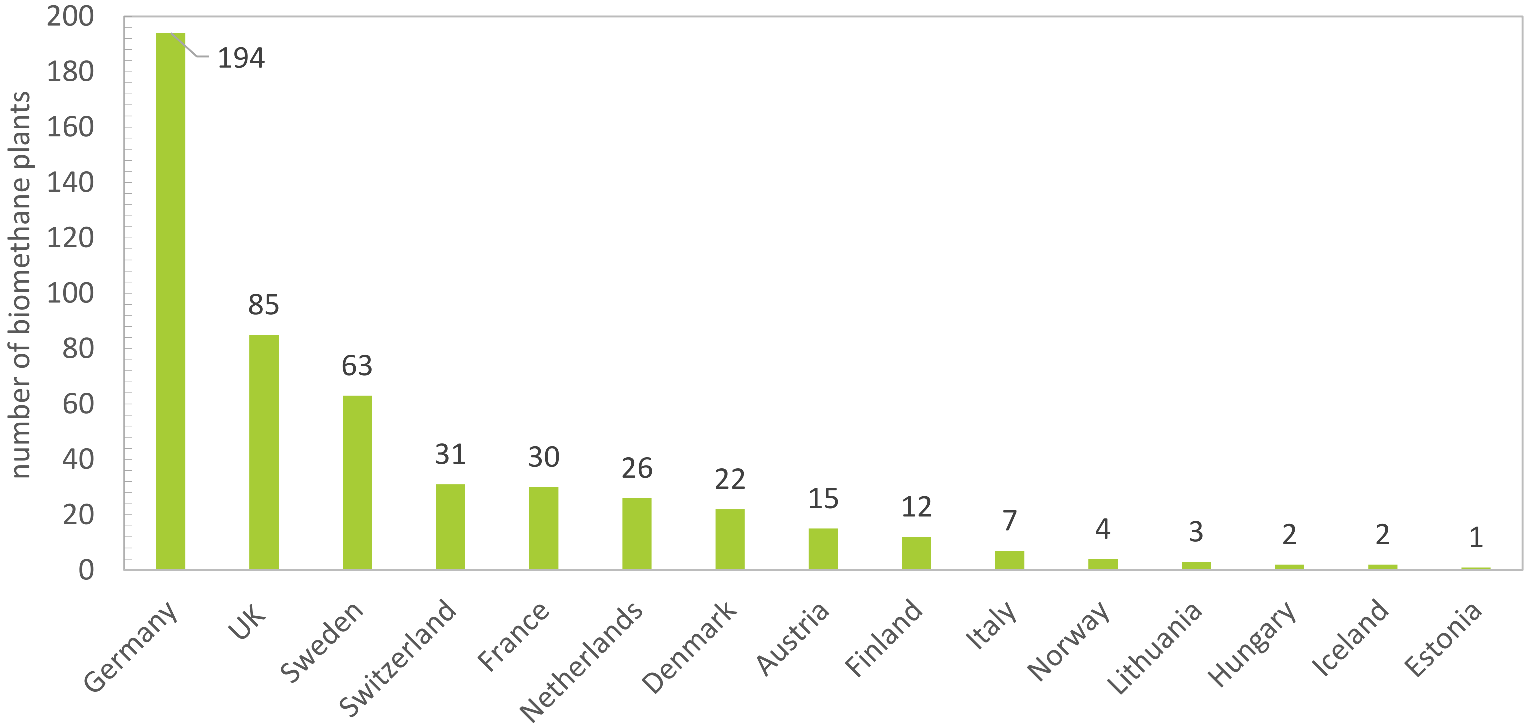
Biogas plant distribution in Europe

existing, high-purity point sources in the focus



- **Biogas plant distribution** in Europe at the end of 2017
- European country ranking according to the number of **biogas upgrading plants** in early 2017

Source: Rodin, V. et al. (2020) Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO_2, Journal of CO2 Utilization, Vol. 41, 101219

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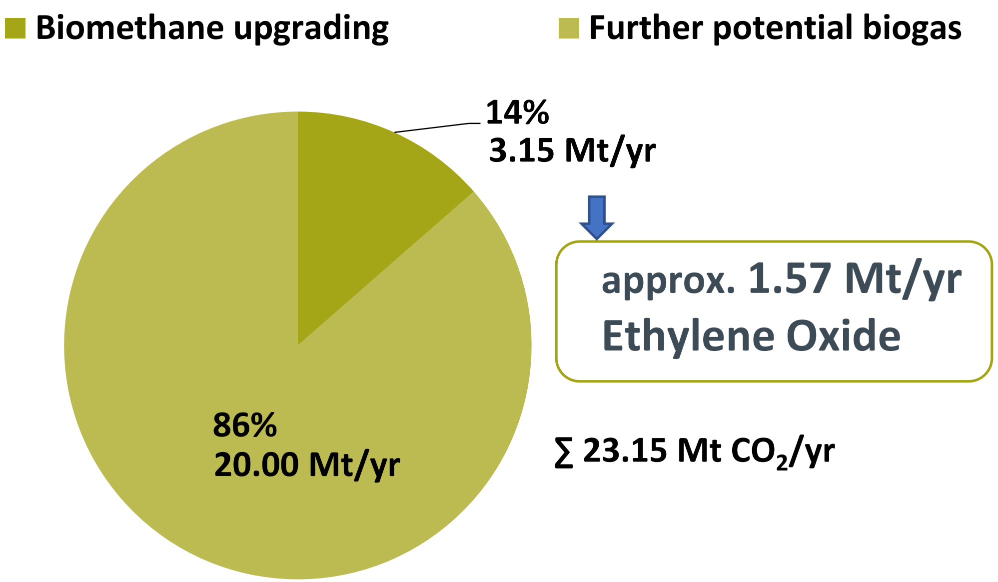
Biogenic CO_2 from biomethane production

existing, high-purity point sources in the focus

- **approx. 500 biogas upgrading plants to biomethane in operation in Europe**
- 14 % of biogenic CO_2 from biogas is already separated, but hardly utilized
- **Significant potential of highly concentrated biogenic CO_2 for valorization**



CO_2 potential in Mt/year from biomethane upgrading as part of total CO_2 potential from biogas production for the EU-28 (data for 2016)

Source: Rodin, V. et al. (2020) Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO_2, Journal of CO2 Utilization, Vol. 41, 101219

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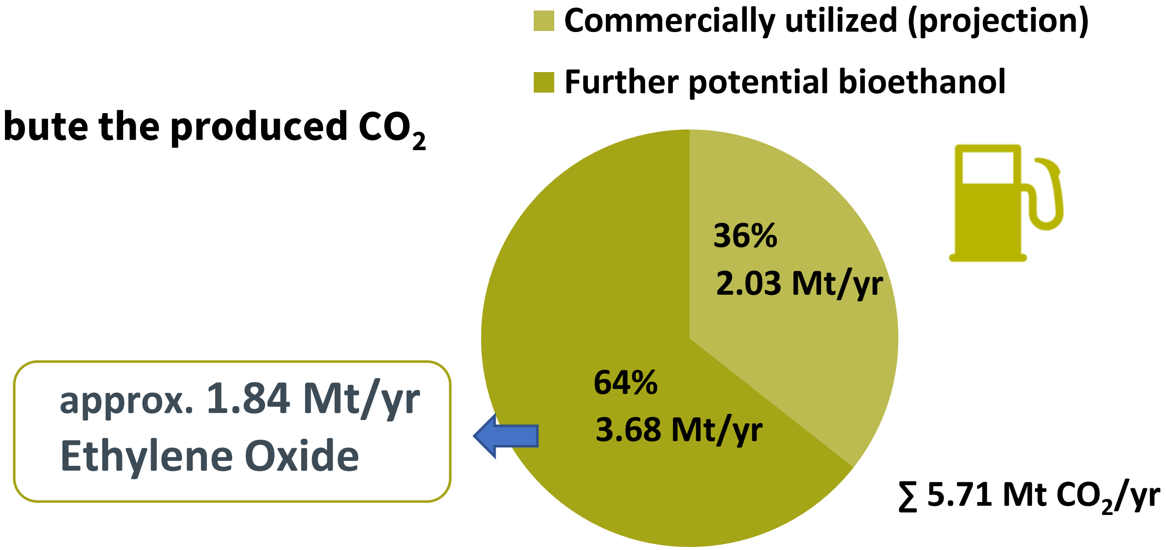
Biogenic CO_2 from bioethanol fermentation

existing, high-purity point sources in the focus

- **CCU technically feasible without extensive effort**
- **Some production site capture the CO_2 already distribute the produced CO_2 commercially**
  - Dry ice
  - Carbonic acid for beverages
  - Fertilizer for greenhouses



Amount of CO_2 in Mt/year produced in the EU bioethanol industry in 2016 including amount of possibly commercialized CO_2

Source: Rodin, V. et al. (2020) Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO_2, Journal of CO2 Utilization, Vol. 41, 101219

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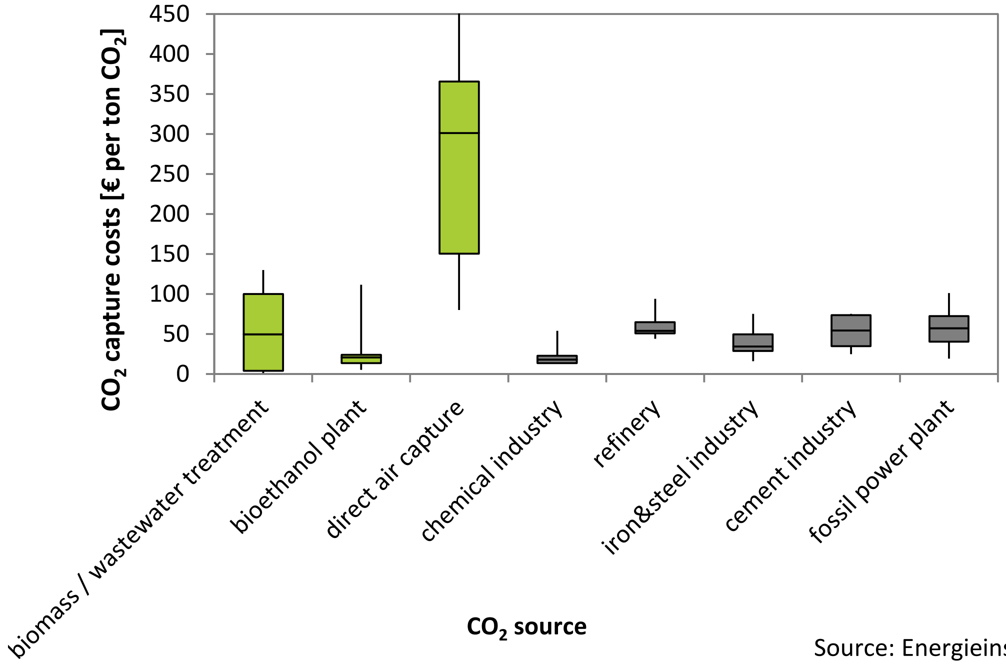
CO_2 capture

Capture costs

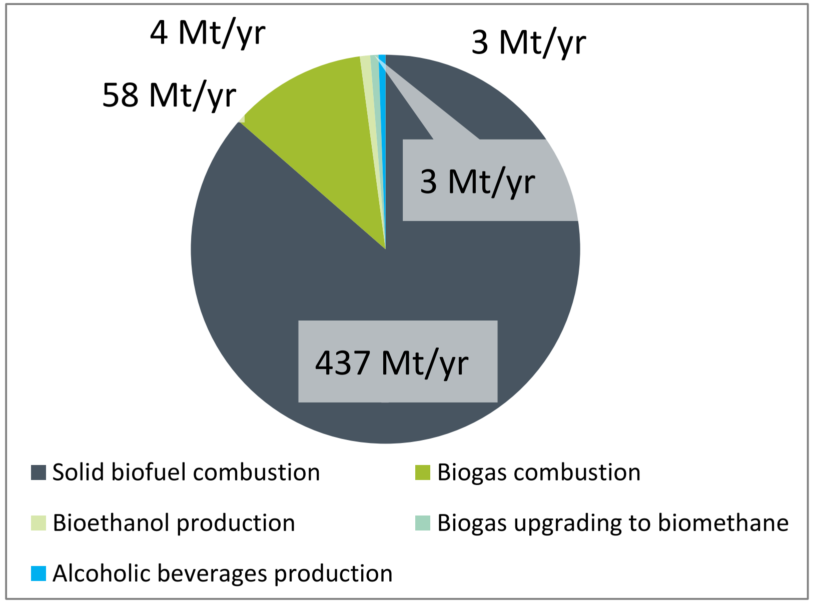
CO_2 from **biogenic sources** can provide **lowest capture costs**

Direct Air Capture (DAC) is expected to rapidly **reduce its costs**



Biogenic CO_2 in Europe

In total approximately **506 Mt/yr of biogenic CO_2** are produced annually in Europe



→ Of which 86% imply cost intensive flue gas purification

Source: Energieinstitut an der JKU

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Matching of biogenic CO_2 and RES sources

GIS-based analysis of potential CO_2EXIDE production sites

Based on GIS analysis tools, **existing** CO_2 and renewable power sources were **matched** to **identify possible CO_2EXIDE production sites within Europe** to …

… **provide 100 % renewable based products**

… avoid transport of (hazardous) reagents

… support grid operation by balancing out fluctuating, locally generated renewable energy

For the **specific case studies**, additionally favorable infrastructure was considered…

…ethylene producers/consumers

…pipeline infrastructure

- **Mapping of biogenic CO_2 sources**
  - existing biomethane upgrading plants (>16 kt CO_2/yr)
  - existing bioethanol production sites (> 160 kt CO_2/yr)
- **Mapping of RES sources**
  - Existing onshore wind farms > 1 MW
  - Existing solar power plants > 1 MW
- **Focus on 4 categories of plant sizes from 1 to 500 MW**

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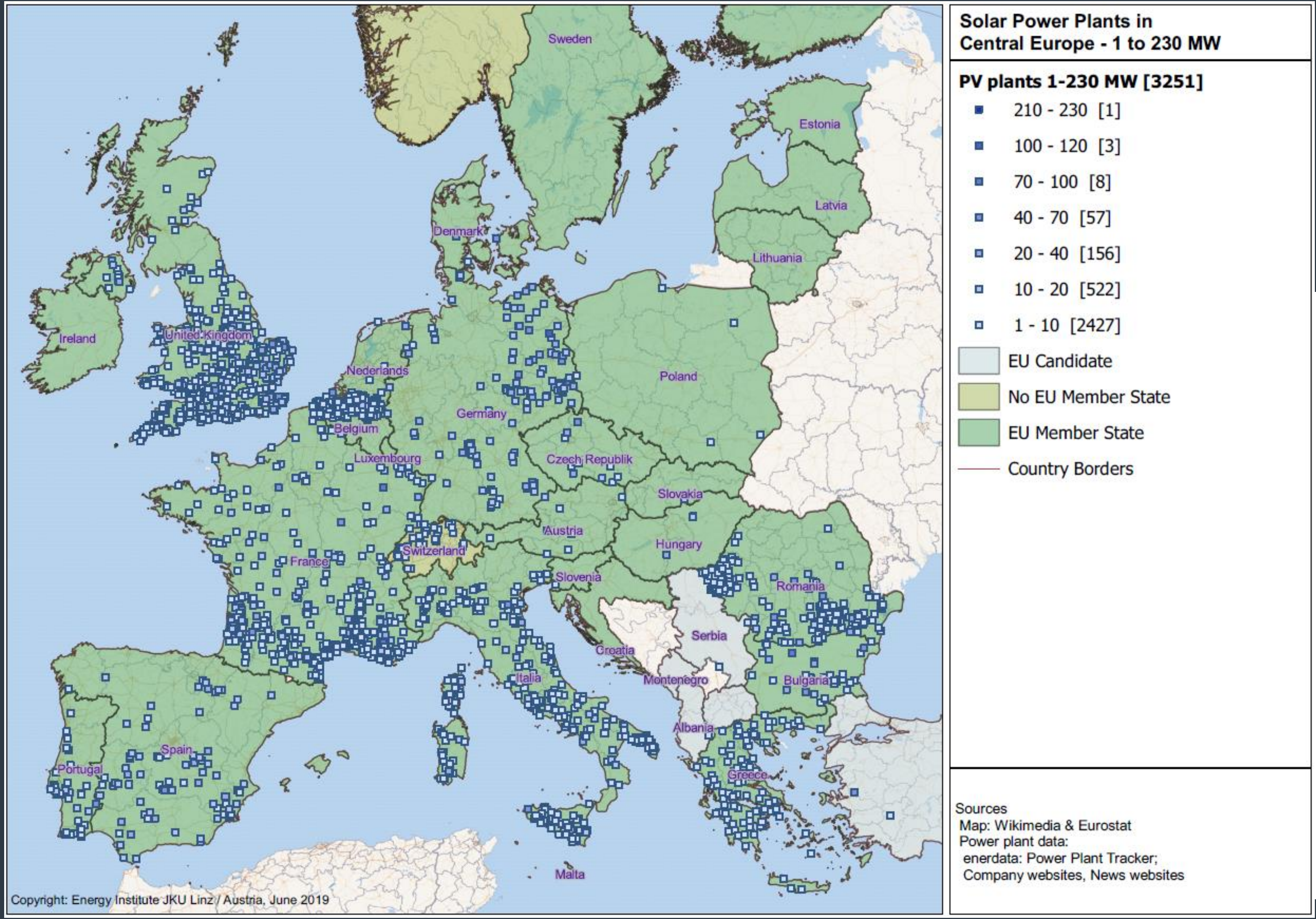

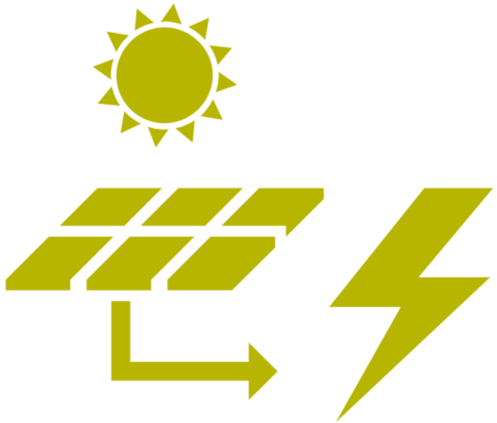

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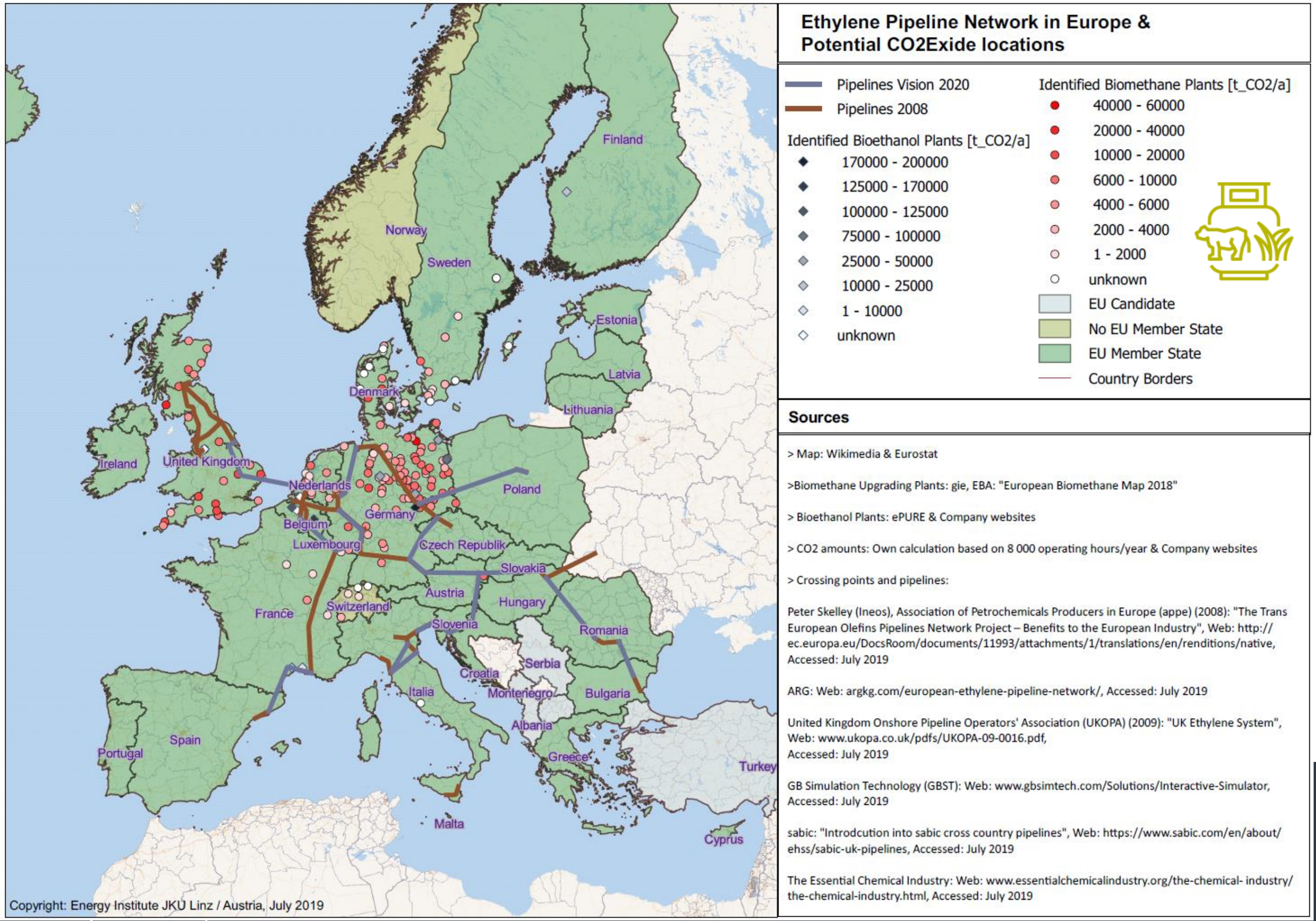
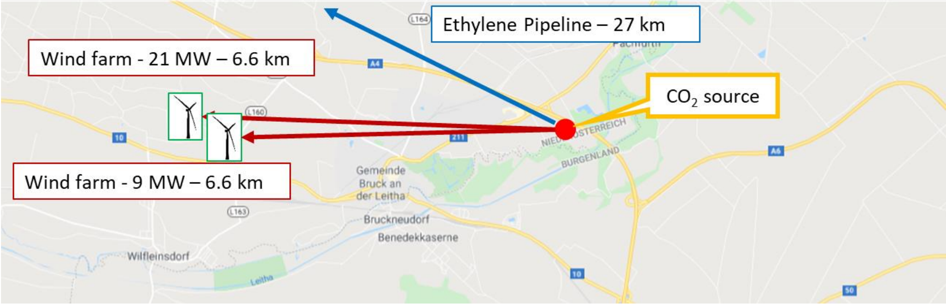
GIS based approach for roll-out scenarios

Visualisation & intersection of CO_2-point sources and renewable power plants



➔ **3 case studies in 3 countries**

considering local conditions, existing infrastructures

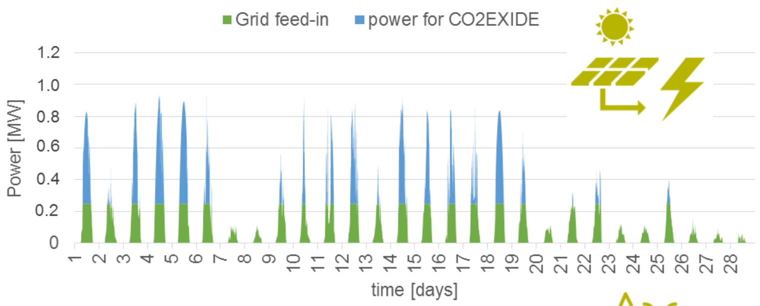


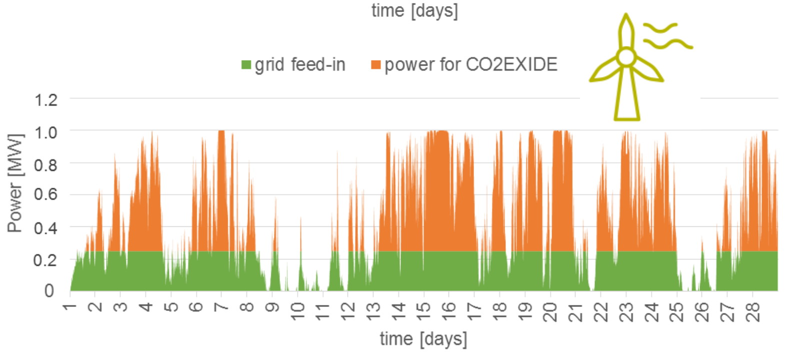
Source: Energieinstitut an der JKU

Development of specific case studies for potential technology roll-out

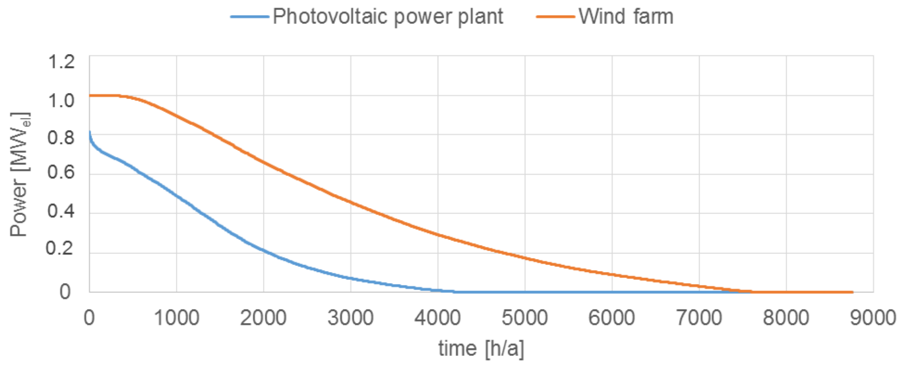
Modelling of fluctuating renewable power generation

Typical electricity production characteristic of a 1 MW photovoltaic power plant (top) & wind farm (bottom)





Source: Energieinstitut an der JKU



- avoidance of usage competition & system inefficiencies
- minimum levelized cost of CCU product

The power is divided in the share of grid feed-in and power for the potential CO2EXIDE-plant for scenario development; central European conditions applied

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Impact related studies

On the way from TRL 3-4 to TRL 7-9

- **Virtual upscale** based on **experimental data** and **modelling**
- **Scenario based comparative LCA**
  - cradle to gate
  - fossil & biobased benchmarking
- **Technoeconomic Assessment**
- CAPEX, OPEX, ROI, NPV, for implementation oriented case studies

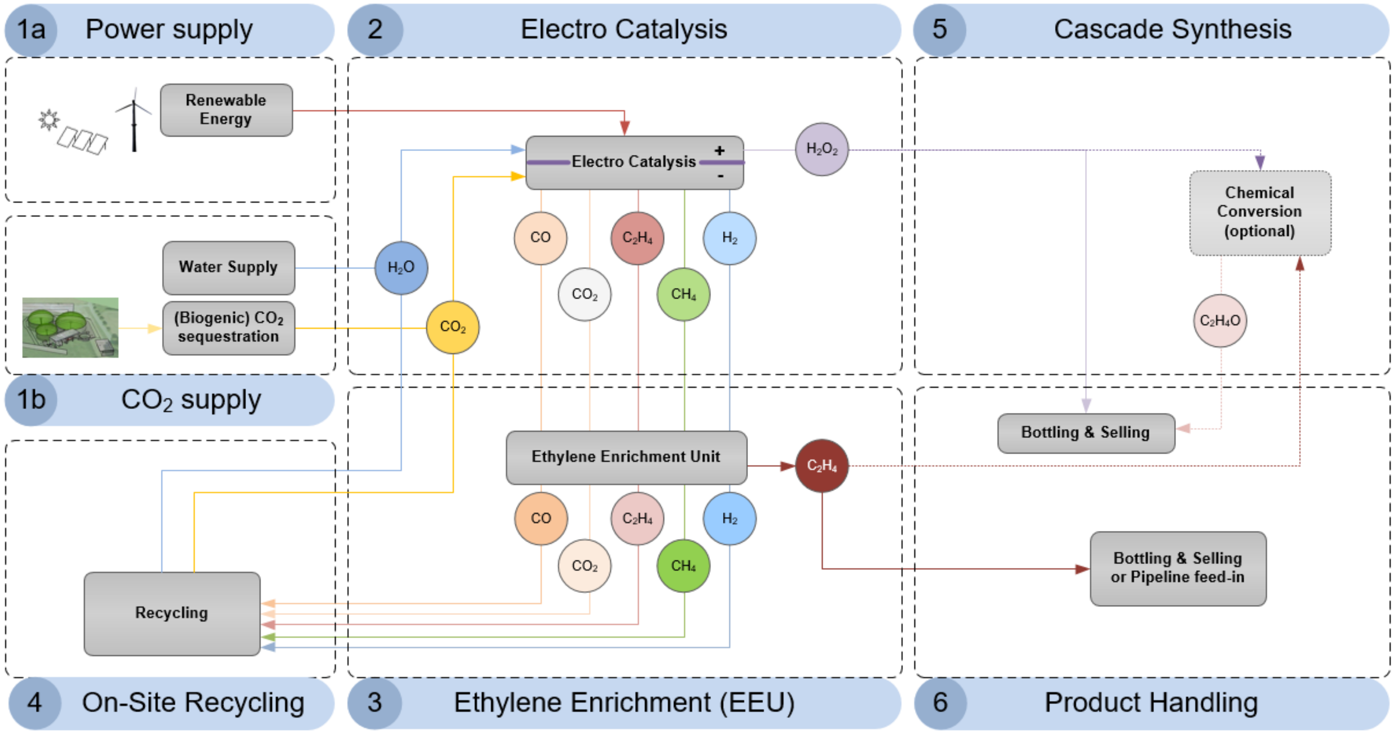

Figure: **Schematic overview of analyzed CO_2EXIDE process** with on-site by-product recycling and cascade synthesis to ethylene oxide and potentially to ethylene glycols

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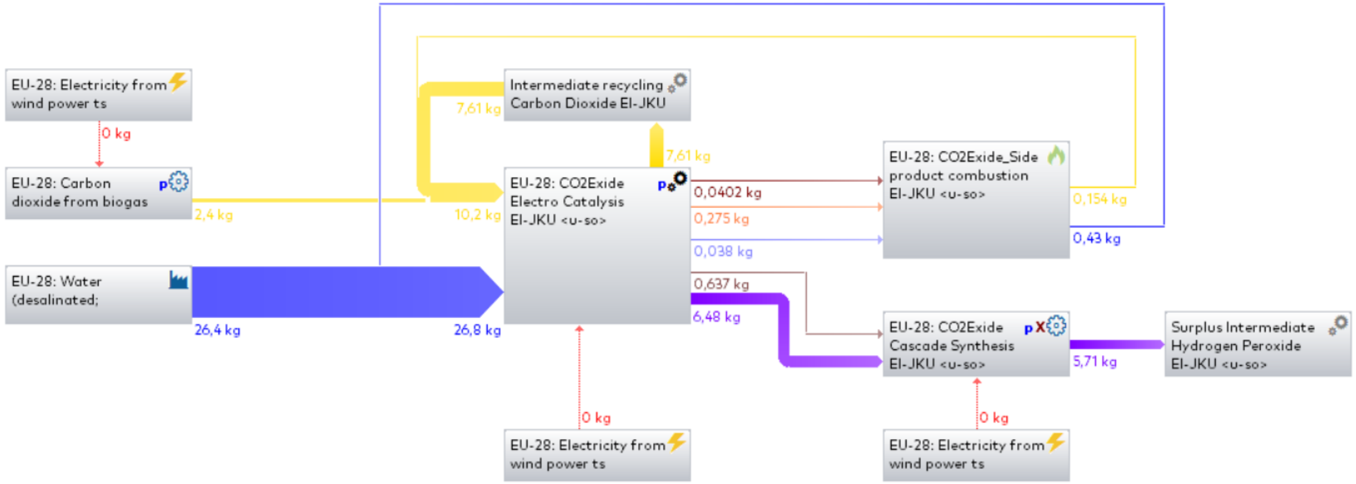
Source: Energieinstitut an der JKU

Life Cycle Assessment Modeling

CO_2EXIDE process, cradle-to-gate, scenario with internal recycling



Process energy supply fully dominates the environmental impacts ➡ **renewable supply is** an **essential** prerequisite
Side products, especially with significant LHV as H_2,.. require full valorisation ➡ **on site recycling**

Functional unit:
1 kg ethylene oxide

process energy electricity
1) EU28-mix
2) Local supply from PV
3) Local supply from Wind

Feedstock:
i) CO_2 from biogas upgrading
ii) fossil CO_2 from EO production

Side product treatment/utilization
a) on-site recycling
b) up-grading / feed-in

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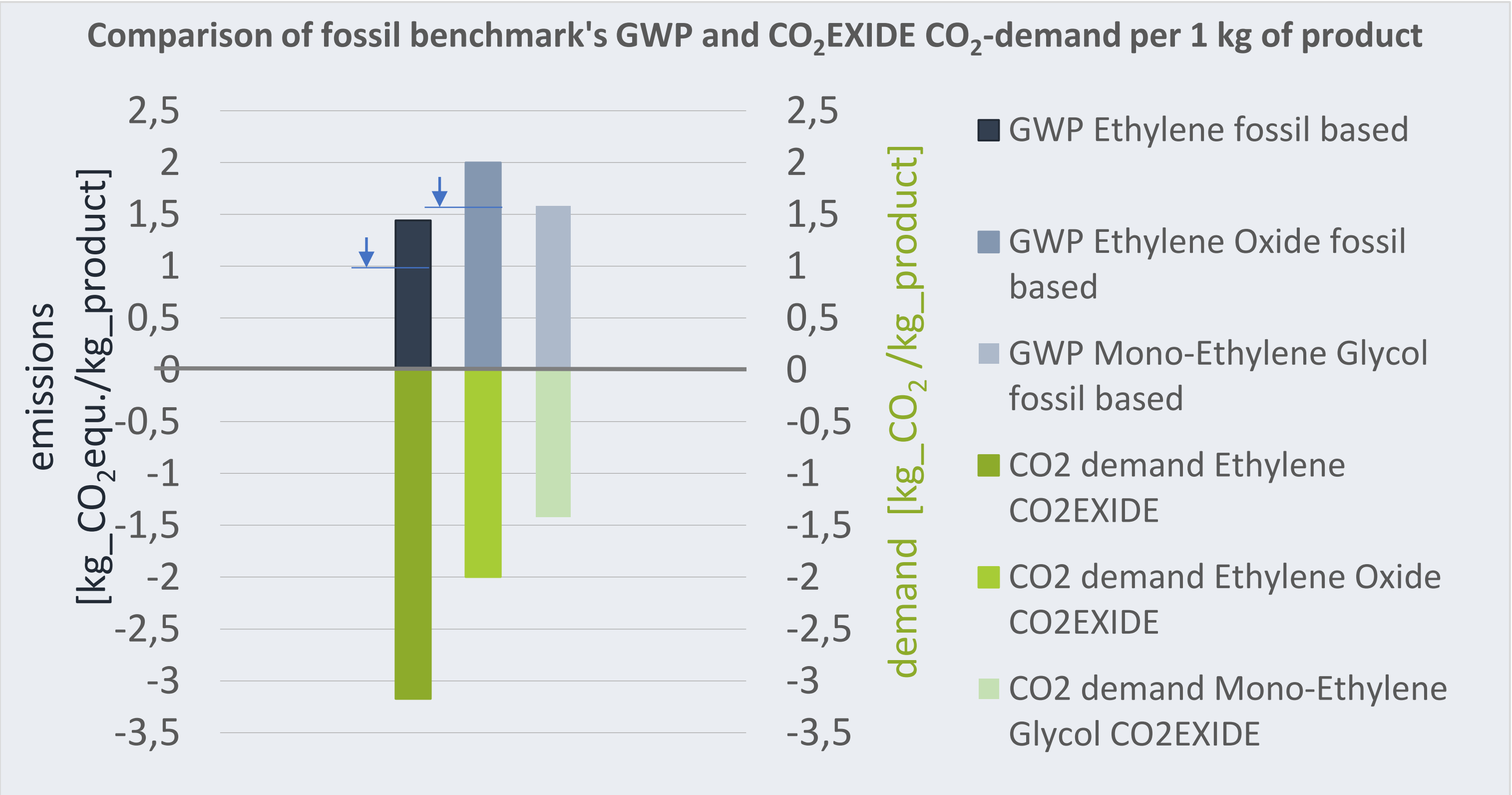
Source: Energieinstitut an der JKU

Life Cycle Assessment Modeling

CO_2 reduction potential of the CO_2EXIDE approach

CO_2 demand per 1 kg ethylene: 3.14 kg (stoichiometric)
> -300 % compared to fossil ethylene
Ethylene demand per 1 kg ethylene oxide: 0.637 kg (stoichiometric)
2 kg CO_2 per 1 kg ethylene oxide
-200 % compared to fossil ethylene oxide

GHG footprint of utilized CO_2 is crucial
Biogenic CO_2 source has significant impact
net CO_2 reduction could be achieved, depending on source



Source: Energieinstitut an der JKU

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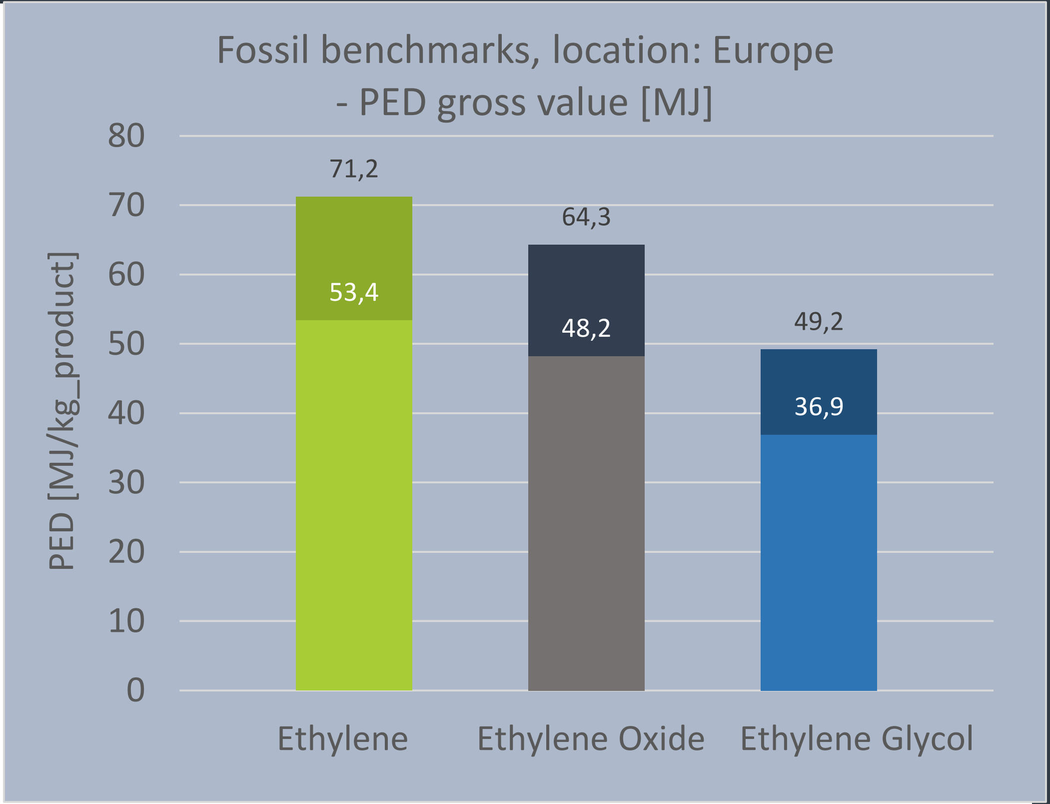
Life Cycle Assessment Modeling

Primary Energy Demand (PED) of the CO_2EXIDE approach

- The PED consists of renewable and **fossil energy sources** – the latter can be **reduced basically to 0** for the CO2EXIDE approach.
- Due to **electrochemical conversion of stable, low-energy molecules** (rather than fossil resources with high calorific value), the CO_2EXIDE process **can hardly be competitive to fossil production from primary energy perspectives**
- The **targeted efficiency is comparable to other renewable PtX technologies**, using renewable power and concentrated CO_2 streams



Source: Energieinstitut an der JKU

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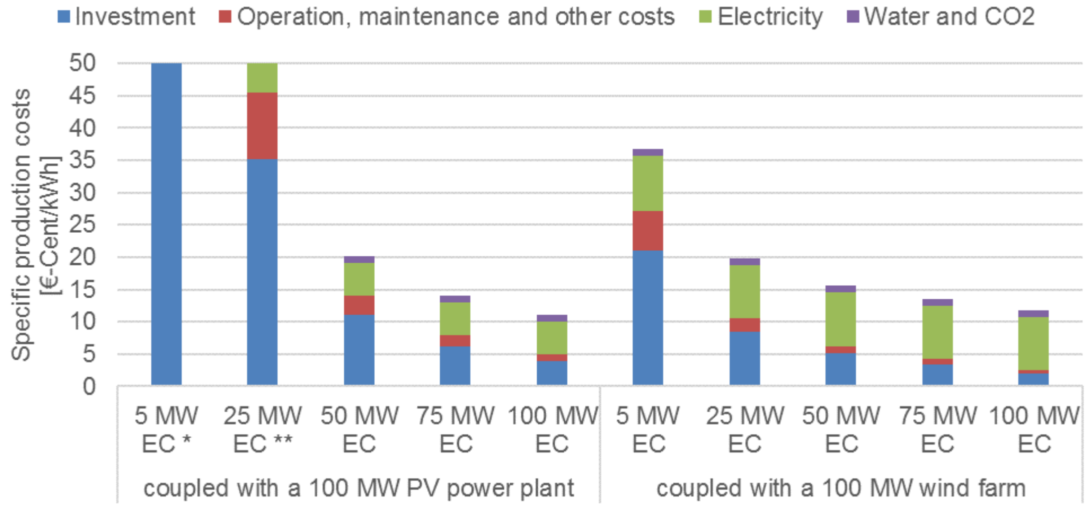
Techno-economic scenario development

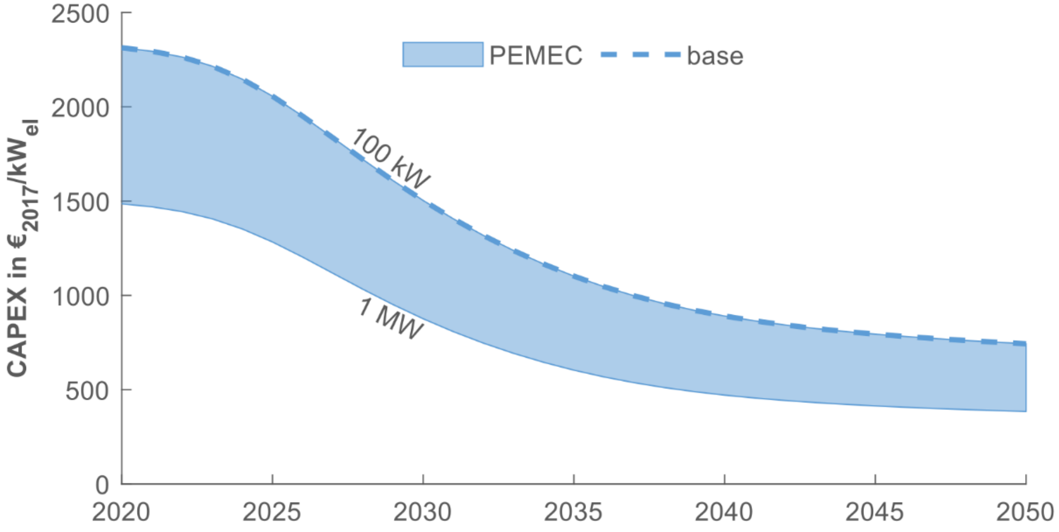
CAPEX & OPEX estimates – for now and future conditions

Estimating specific product costs now and 2030 based on a total cost estimate for representative plant capacities



Source: Energieinstitut

Component Level Learning Curve Tool to estimate CAPEX reduction potential



Source: Energieinstitut

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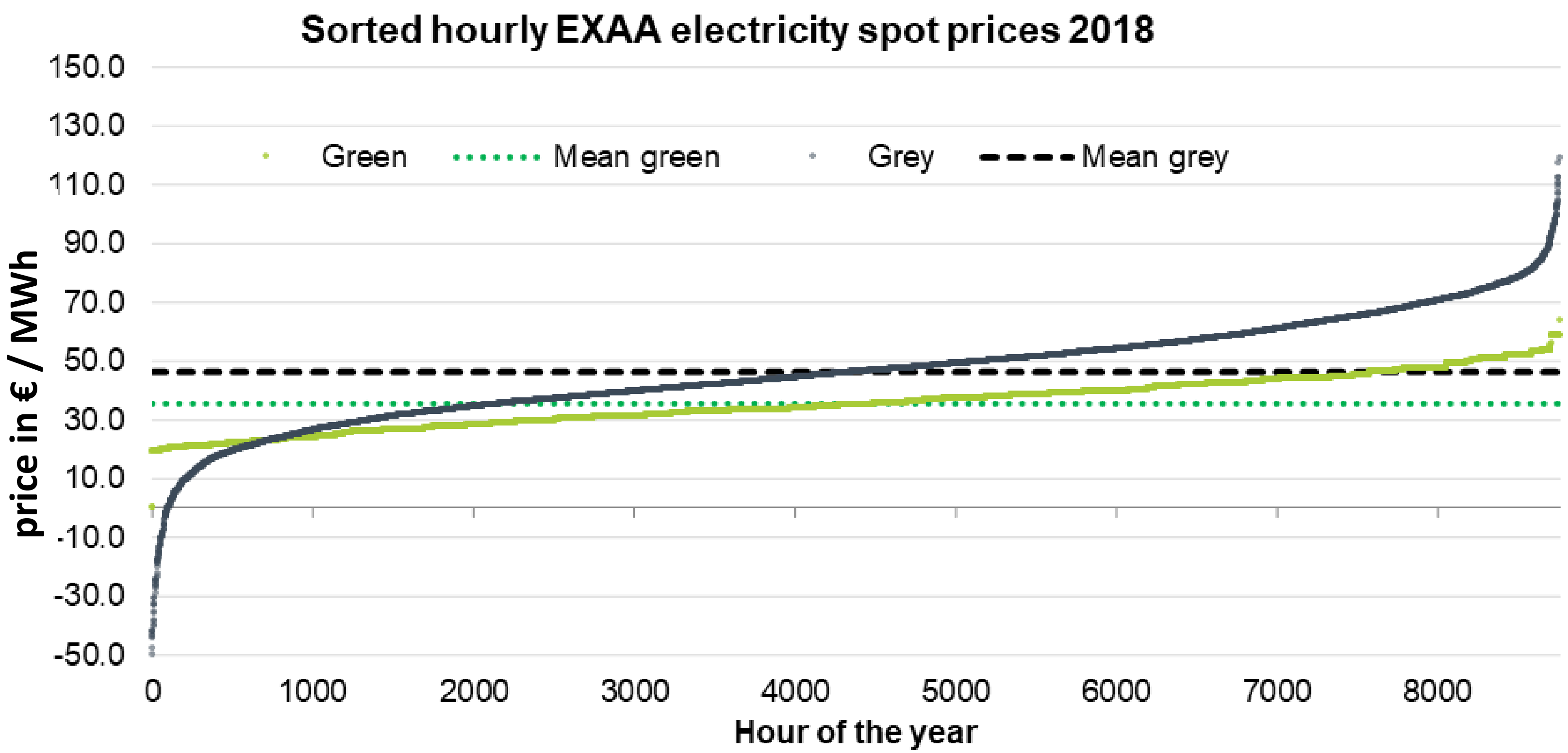
Source: Energieinstitut an der JKU

Techno-economic scenarios

Electricity spot market prices for green (and grey) electricity



→ **Lowest marginal cost**

< 50 €/MWh for

fluctuating renewables

→ **Challenge of dynamics!**

Renewable electricity is a new „production commodity" with the price curve pointing downwards

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Implementation case study at biomethane facility

Biogas plant & wind farms & ethylene pipeline in vicinity

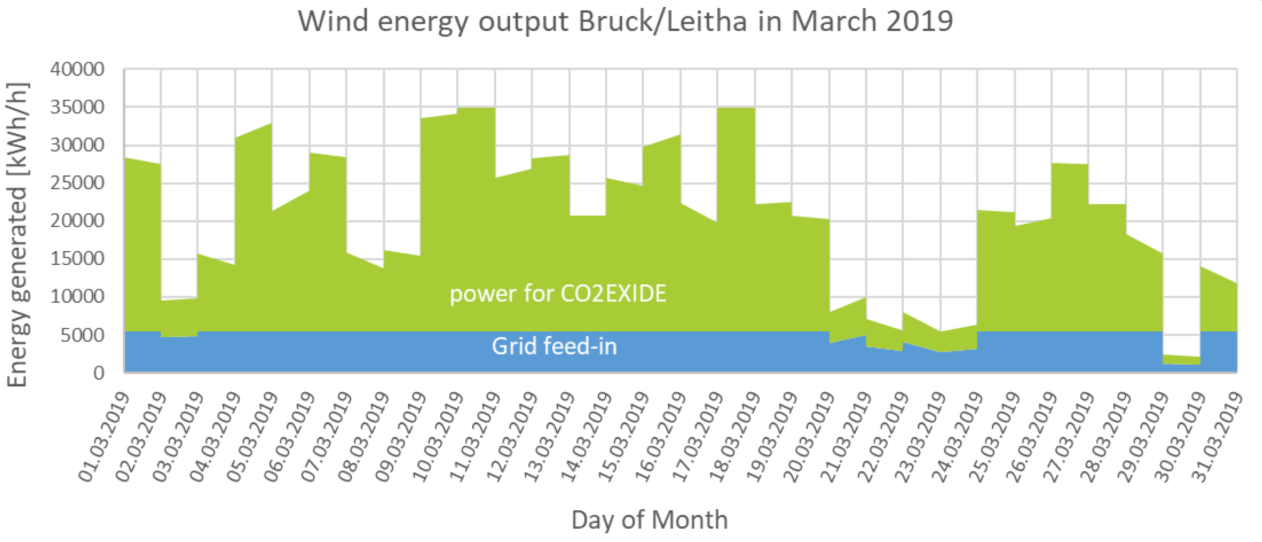
- **Input material:** **Bio- and municipal waste as feedstock for the anaerobic digestion**
- **Biogas upgrading** → CO_2 with high technical quality & concentration
- **Membrane separation of CH_4 / CO_2 with feed in of CH_4 to the natural gas grid**
- **Simulation** of hourly energy production **of the local wind power**

CO_2 output: approx. 3,370 t/a

Power Input: approx. 3.2 MW
350 days/yr, 15 years lifetime

Ethylene Output: approx. 1,050 t/a

Ethylene Oxide Output (w/o losses): approx. 1,649 t/a



Source: Energieinstitut an der JKU

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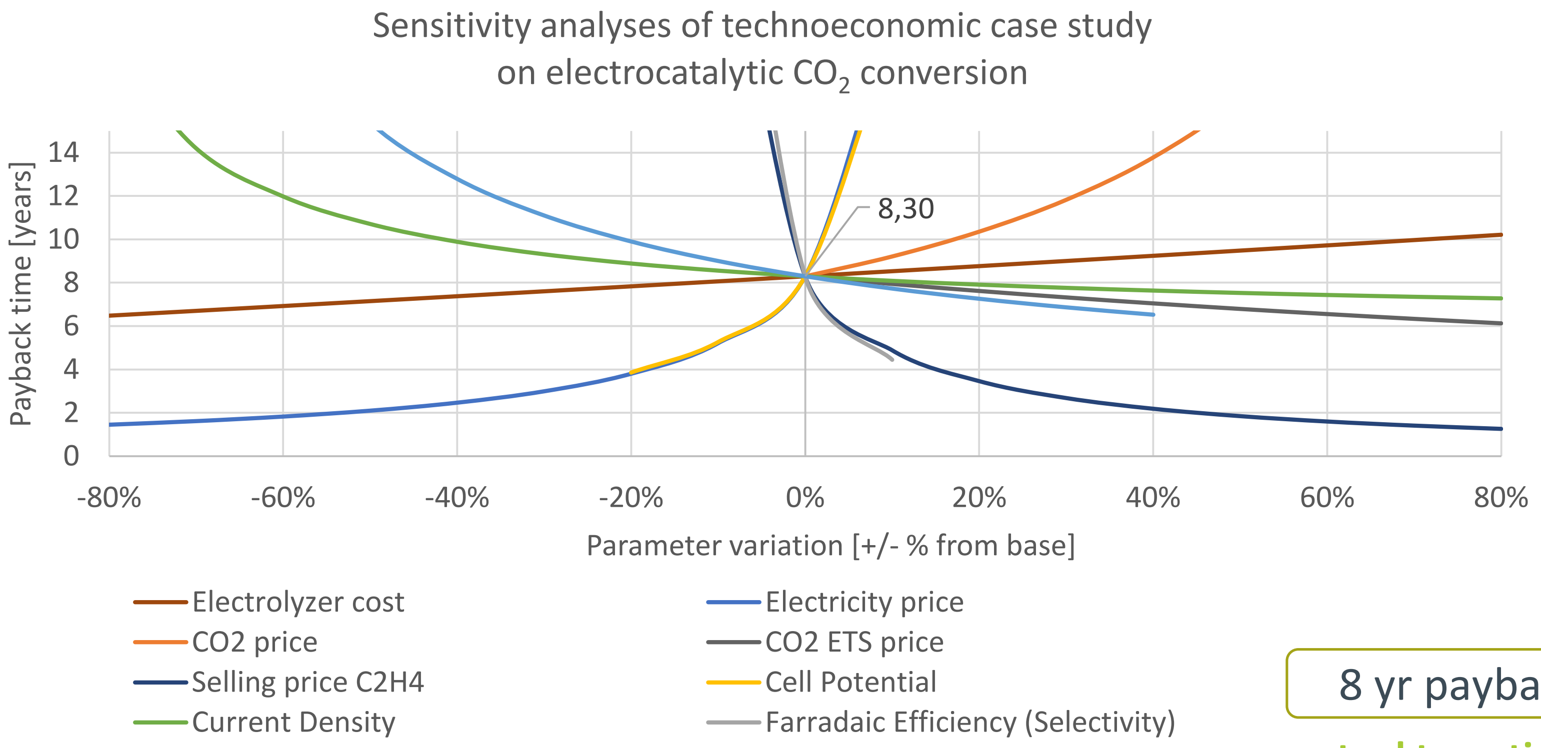
Implementation case study at biomethane facility

Estimate for payback time – sensitivity analysis results



Source: Energieinstitut an der JKU

VARIABLES	Min	Base	Max	Unit
electrolyzer cost	139	**695**	1,250	€/m²active area
electricity price	28.5	**35.6**	64.1	€/MWh
CO_2 price (raw material)	n/a	**0**	40	€/ton
CO_2 ETS price (avoided emissions)	n/a	**0**	40	€/ton
market price C_2H_4	220	**1,100**	1,980	€/ton
cell potential	1.6	**2**	3.6	V
current density	100	**500**	900	mA/cm²
selectivity to C_2H_4	n/a	**90**	99	%
conversion rate of CO_2	21	**70**	98	%

8 yr payback time in base case

actual targeting scenarios to increase economic performance

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For takeway…

Ecological implications

- **Main focus** to showcase the proof of concept is on **already available biogenic carbon dioxide** like CO_2 from biogas upgrading to **minimize feedstock cost & maximize carbon off take.**
- Achieving a **net zero emissions EU energy system by 2050** based on predominantly renewables **is a prerequisite.**
- In **absence of binding international climate agreements, a sufficient high price on CO_2** emissions, CCU is actually hardly economic.
- Nevertheless the **need to bring the CO_2 electrolysis as future-proof CCU technology to the next TRLs now** due to the expected long periods to market.
- As with all renewables scale up and market division needs to be linked to **stringent sustainability criteria** to take full advantage. A framework for analysis is currently evolving.

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For takeway…

Economic implications

- A high performance especially in the **reductive activation, catalytic technologies for CO_2 conversion** (especially faradaic efficiency) is **most crucial.**
- The **cost of electricity** is of most significant relevance, **fluctuating production sources** can provide already now promising levels.
- The **cost of CO_2 as raw material** cannot be neglected, especially if **complex upgrading and purification** is required.
- **CO_2 electrolyzer investment costs** are less critical in comparison, with the outlook of **learning curves** and **economies of numbers.**
- Renewable ethylene / ethylene oxide **production cost** can **correspond to current market prices but hardly to production costs**. Emission trading compensation, Green premium incentives can be medium-term tools to face international competition.

What are the right benchmarks for a transformed production system?

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Many thanks for your attention!

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Further Information

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