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State of the art and future perspectives of electrochemical CO_2 conversion

Webinar: Thursday November 30th, 2023

Speakers

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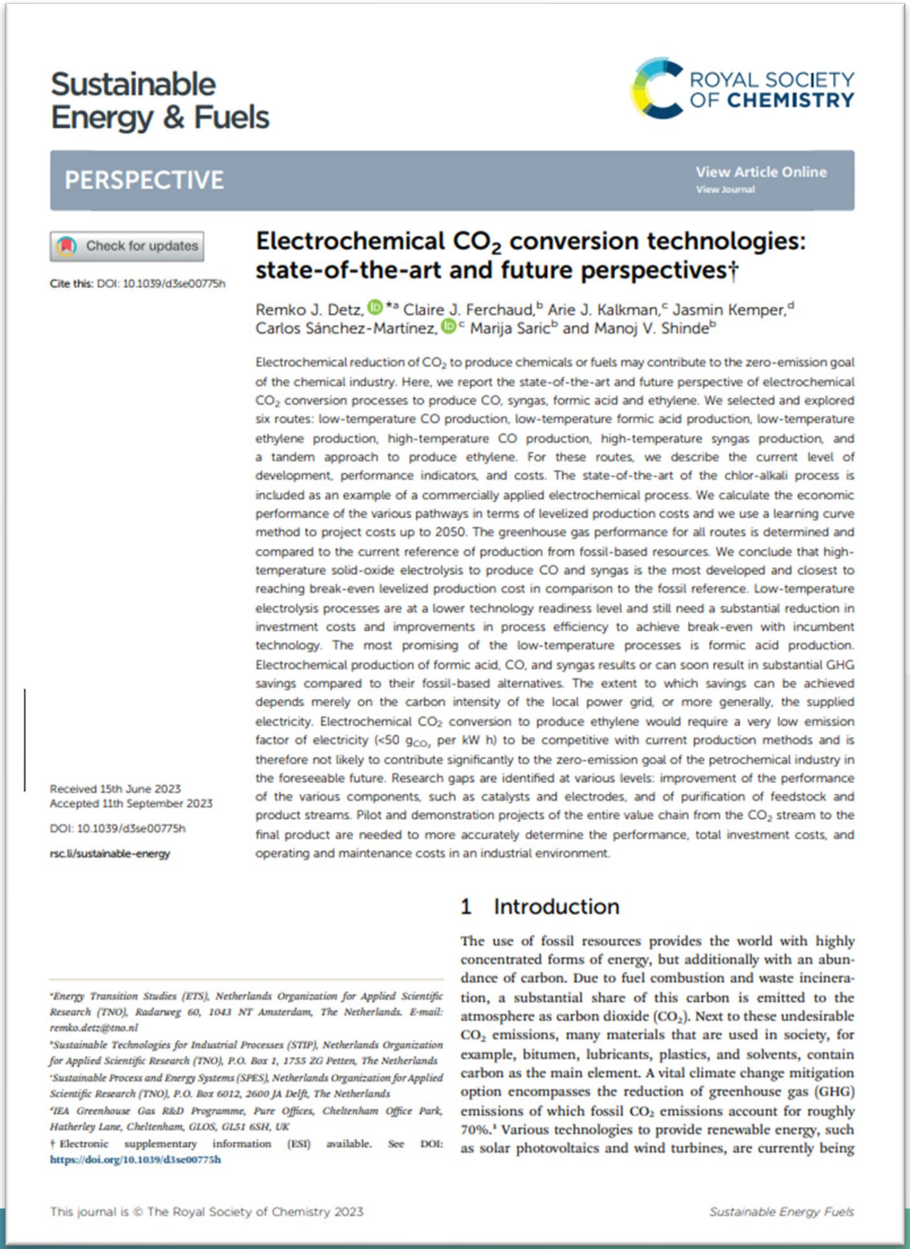
Agenda for today

- **Introduction** (Yvette Veninga)
- **Presentation** (Remko Detz)
- **Q/A** (chat)



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Electrochemical CO_2 conversion technologies: state-of-the-art and future perspectives†

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Carlos Sánchez-Martínez,[c] Marija Saric[b] and Manoj V. Shinde[b]

Electrochemical reduction of CO_2 to produce chemicals or fuels may contribute to the zero-emission goal of the chemical industry. Here, we report the state-of-the-art and future perspective of electrochemical CO_2 conversion processes to produce CO, syngas, formic acid and ethylene. We selected and explored six routes: low-temperature CO production, low-temperature formic acid production, low-temperature ethylene production, high-temperature CO production, high-temperature syngas production, and a tandem approach to produce ethylene. For these routes, we describe the current level of development, performance indicators, and costs. The state-of-the-art of the chlor-alkali process is included as an example of a commercially applied electrochemical process. We calculate the economic performance of the various pathways in terms of levelized production costs and we use a learning curve method to project costs up to 2050. The greenhouse gas performance for all routes is determined and compared to the current reference of production from fossil-based resources. We conclude that high-temperature solid-oxide electrolysis to produce CO and syngas is the most developed and closest to reaching break-even levelized production cost in comparison to the fossil reference. Low-temperature electrolysis processes are at a lower technology readiness level and still need a substantial reduction in investment costs and improvements in process efficiency to achieve break-even with incumbent technology. The most promising of the low-temperature processes is formic acid production. Electrochemical production of formic acid, CO, and syngas results or can soon result in substantial GHG savings compared to their fossil-based alternatives. The extent to which savings can be achieved depends merely on the carbon intensity of the local power grid, or more generally, the supplied electricity. Electrochemical CO_2 conversion to produce ethylene would require a very low emission factor of electricity (<50 g_{CO_2} per kW h) to be competitive with current production methods and is therefore not likely to contribute significantly to the zero-emission goal of the petrochemical industry in the foreseeable future. Research gaps are identified at various levels: improvement of the performance of the various components, such as catalysts and electrodes, and of purification of feedstock and product streams. Pilot and demonstration projects of the entire value chain from the CO_2 stream to the final product are needed to more accurately determine the performance, total investment costs, and operating and maintenance costs in an industrial environment.

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1 Introduction

The use of fossil resources provides the world with highly concentrated forms of energy, but additionally with an abundance of carbon. Due to fuel combustion and waste incineration, a substantial share of this carbon is emitted to the atmosphere as carbon dioxide (CO_2). Next to these undesirable CO_2 emissions, many materials that are used in society, for example, bitumen, lubricants, plastics, and solvents, contain carbon as the main element. A vital climate change mitigation option encompasses the reduction of greenhouse gas (GHG) emissions of which fossil CO_2 emissions account for roughly 70%.[1] Various technologies to provide renewable energy, such as solar photovoltaics and wind turbines, are currently being

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† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d3se00775h

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Sustainable Energy Fuels

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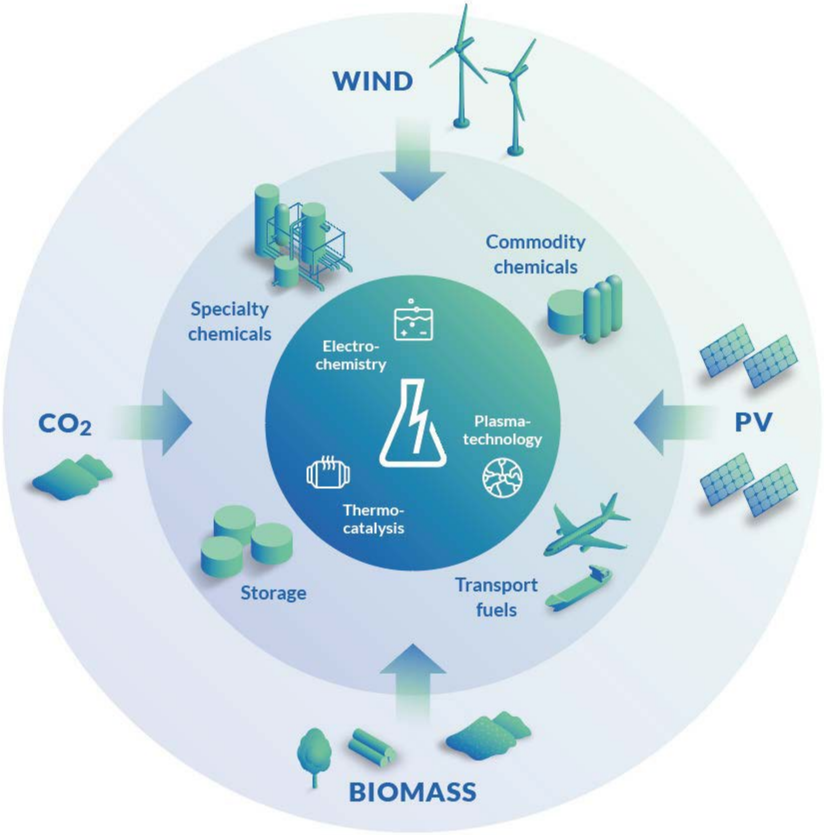
- Please mute your microphone in case unmuted
- Feel free to ask questions in the chat during the webinar
- Be informed that this webinar is being recorded and will be shared afterwards

VoltaChem at a glance

We accelerate development and scale-up of Power-2-X technology for a net zero and circular world



- Public-Private internationally oriented **Shared Innovation Program of 12 M/year** initiated in 2014 by TNO, government and industry.
- **Executed by TNO** with >50 research scientists, technical consultants and system integrators, 4 research labs, 3 industrial fieldlabs, >50 customers.
- For customers and partners from the international **chemical, equipment supply and EPC** industries and **renewable energy and materials** sectors.
- Working collaboratively on **assessment, development and integration** of Power-2-X technologies and associated value chains for conversion of feedstocks to **chemical building blocks for materials, fuels and food**.
- With focus on **Power-2-Hydrogen** and **Power-2-Chemicals** processes, developing and integrating **electrochemical, plasma and integrated thermocatalytical** technologies.

VoltaChem Business community

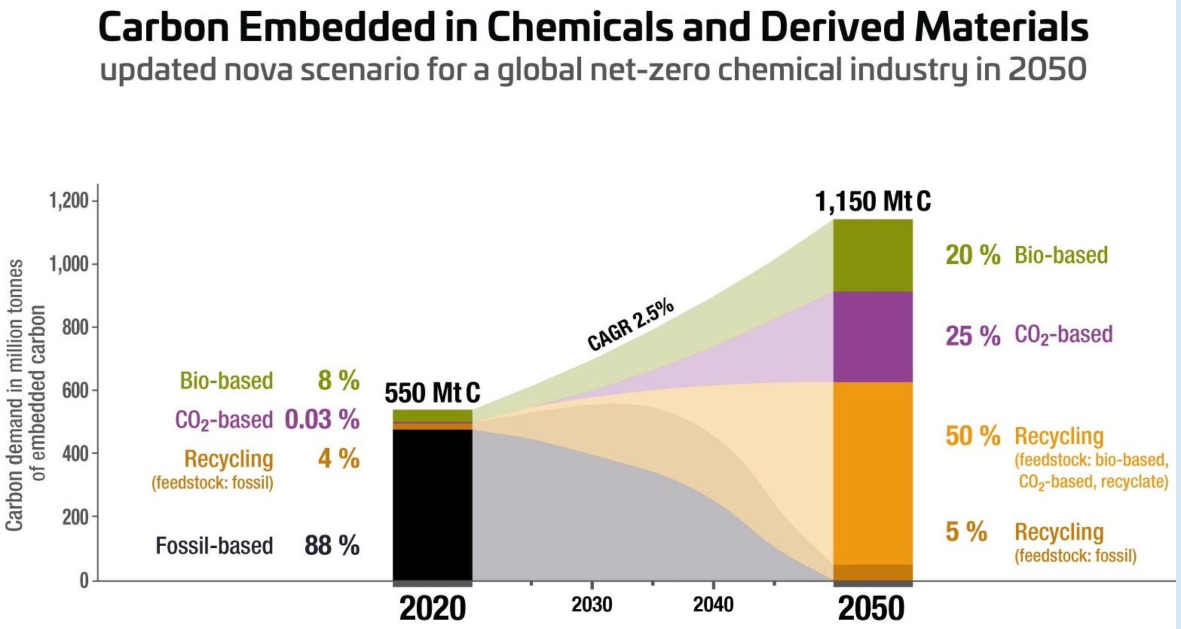
accelerate development and scale-up of Power-2-X technologies

- **Bring together stakeholders of new value chains**, cross-fertilization of the energy, chemical & equipment sector and service providers **in an exclusive forum**.
- **Dissemination of insights and knowledge** gained from TNO’s "Knowledge investment projects“.
- **Work together on specific high-level projects** that are needed for implementation of the roadmap.

Interested? Send a mail to **yvette.veninga@tno.nl**

Systemic overview identifying barriers, opportunities and collaboration partners

Why CO2 conversion?



Carbon Embedded in Chemicals and Derived Materials

updated nova scenario for a global net-zero chemical industry in 2050

Only bio-based and recyled carbon will not be enough to cover C-demand

Carbon as building block in a net zero world comes from:

- ✓ No fossil carbon
- ✓ Sustainable carbon sources:
  - ✓ Bio-based
  - ✓ Recycling
  - ✓ CO2 from green emissions or atmosphere

CO2 as carbon source will become important in the future

Source: Renewable Carbon Publications (renewable-carbon.eu)

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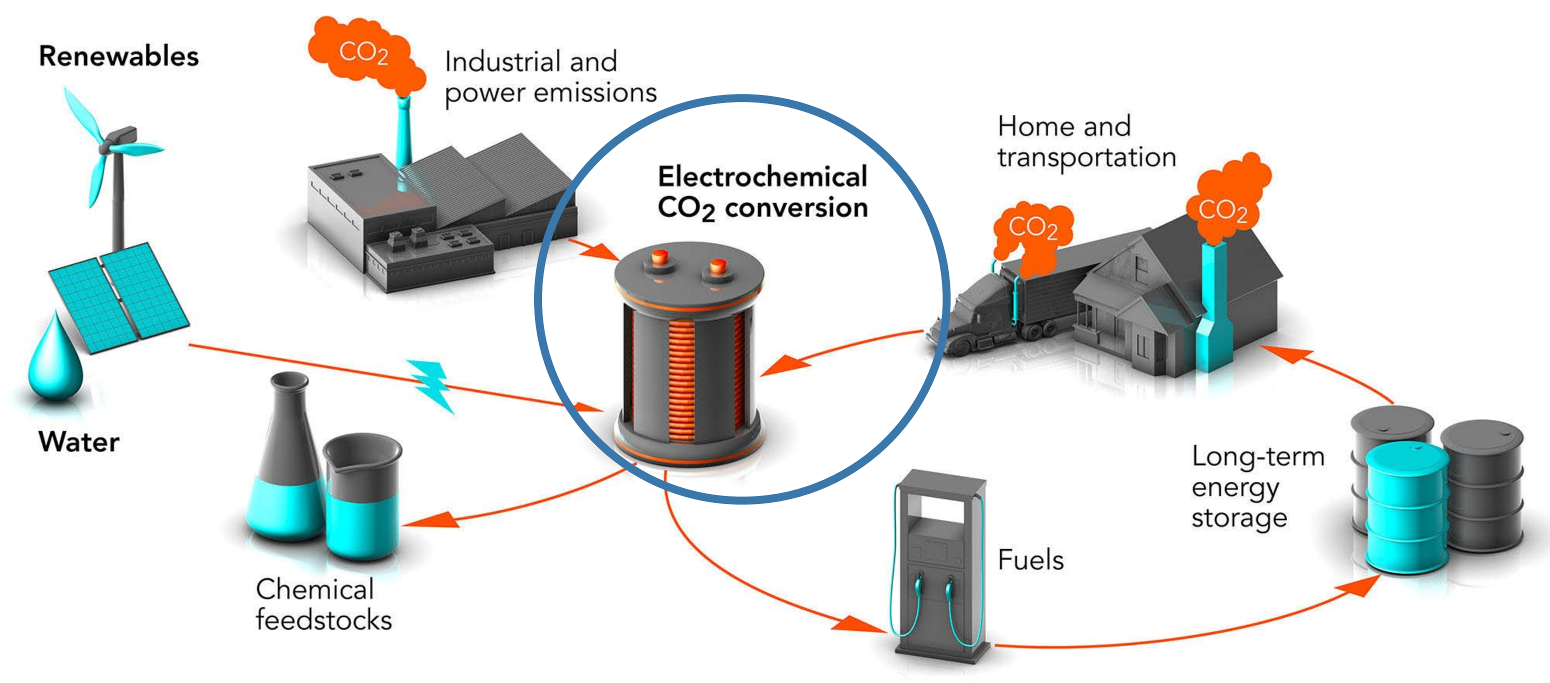
State of the art and future perspectives of electrochemical CO_2 conversion

Remko Detz,

C.J. Ferchaud, A.J. Kalkman, C. Sánchez Martínez, M. Saric, M.V. Shinde, J. Kemper

Background of the study

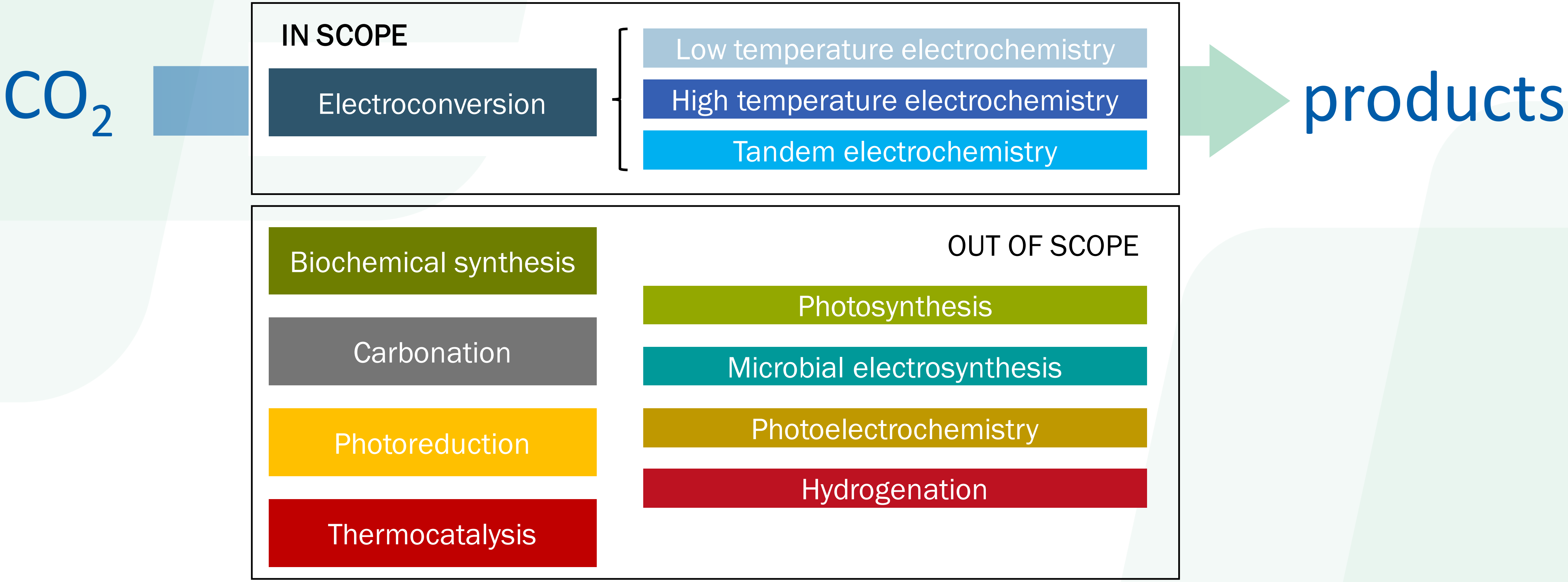
- The IEA Greenhouse Gas R&D Programme (IEAGHG) requested TNO to provide an independent scientific advice regarding state-of-the-art, economics, life-cycle greenhouse gas performance and the associated trade-offs between several electrochemical CO_2 conversion technologies



Courtesy: Stanford University

CO_2 conversion approaches

- Multiple approaches exist to convert CO_2 into products, such as chemicals and fuels. Our study focuses specifically on different electrochemical CO_2 conversion routes.



CO_2

IN SCOPE

Electroconversion

Low temperature electrochemistry

High temperature electrochemistry

Tandem electrochemistry

products

OUT OF SCOPE

Biochemical synthesis

Carbonation

Photoreduction

Thermocatalysis

Photosynthesis

Microbial electrosynthesis

Photoelectrochemistry

Hydrogenation

Selected electrochemical CO_2 conversion routes

- Several electrochemical CO_2 conversion processes are studied and reported in literature
- From these, we identified four routes that are developed at a technology readiness level (TRL) of more than 4 and next to these we as well included two routes (TRL < 4) to produce ethylene to our analysis

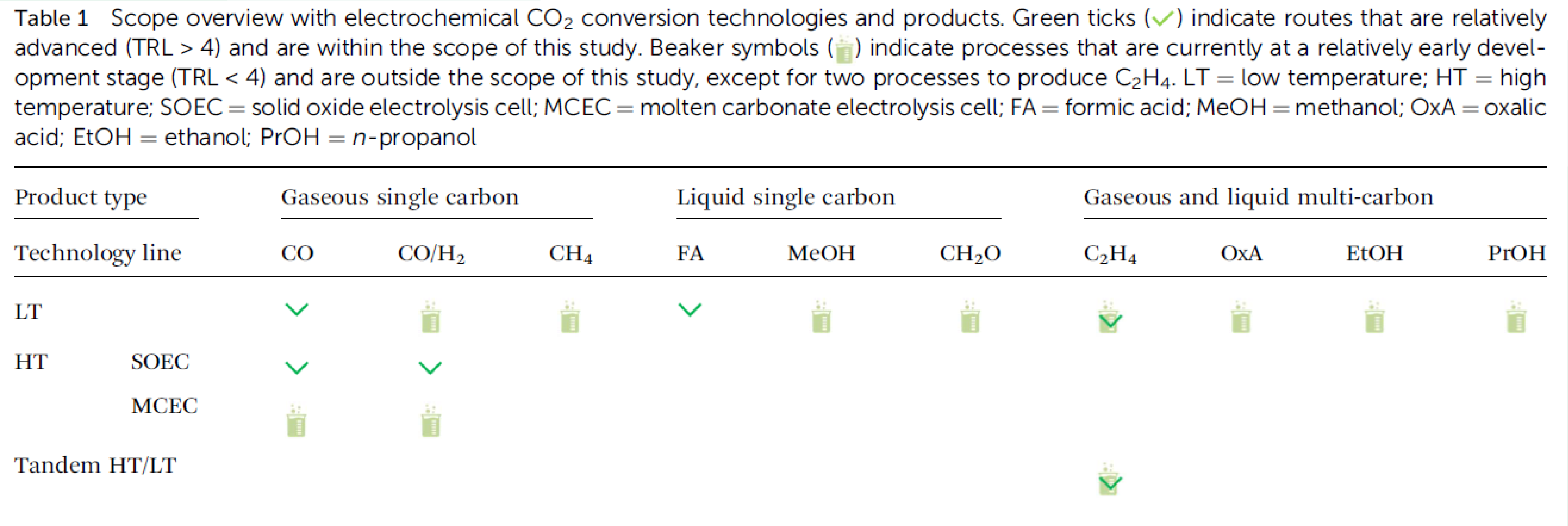
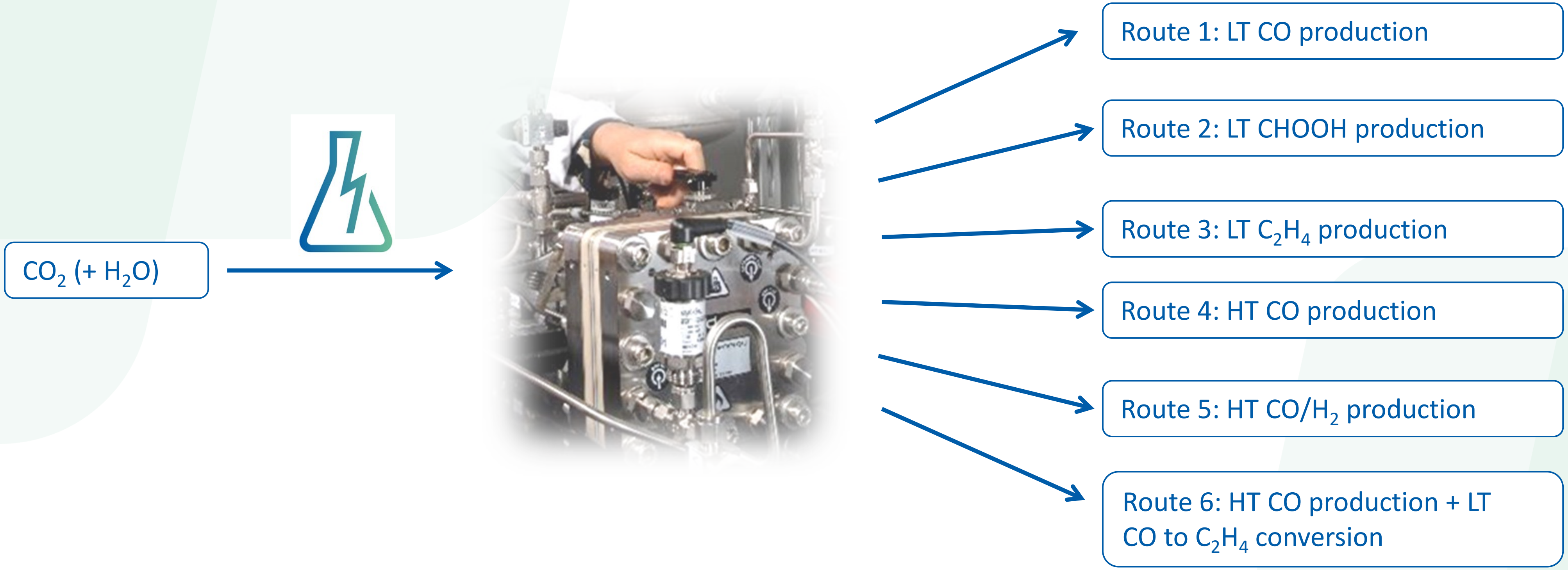


Table 1 Scope overview with electrochemical CO_2 conversion technologies and products. Green ticks (✓) indicate routes that are relatively advanced (TRL > 4) and are within the scope of this study. Beaker symbols (🧪) indicate processes that are currently at a relatively early development stage (TRL < 4) and are outside the scope of this study, except for two processes to produce C_2H_4. LT = low temperature; HT = high temperature; SOEC = solid oxide electrolysis cell; MCEC = molten carbonate electrolysis cell; FA = formic acid; MeOH = methanol; OxA = oxalic acid; EtOH = ethanol; PrOH = *n*-propanol

Product type		Gaseous single carbon			Liquid single carbon			Gaseous and liquid multi-carbon			
Technology line		CO	CO/H_2	CH_4	FA	MeOH	CH_2O	C_2H_4	OxA	EtOH	PrOH
LT		✓	🧪	🧪	✓	🧪	🧪	🧪✓	🧪	🧪	🧪
HT	SOEC	✓	✓								
	MCEC	🧪	🧪								
Tandem HT/LT								🧪✓			

Six routes

- We assess six routes in which low temperature (LT) and high temperature (HT) electrochemical conversion processes convert CO_2 into several products: CO, syngas (CO/H_2), formic acid (CHOOH), and ethylene (C_2H_4)



CO_2 (+ H_2O)

Route 1: LT CO production

Route 2: LT CHOOH production

Route 3: LT C_2H_4 production

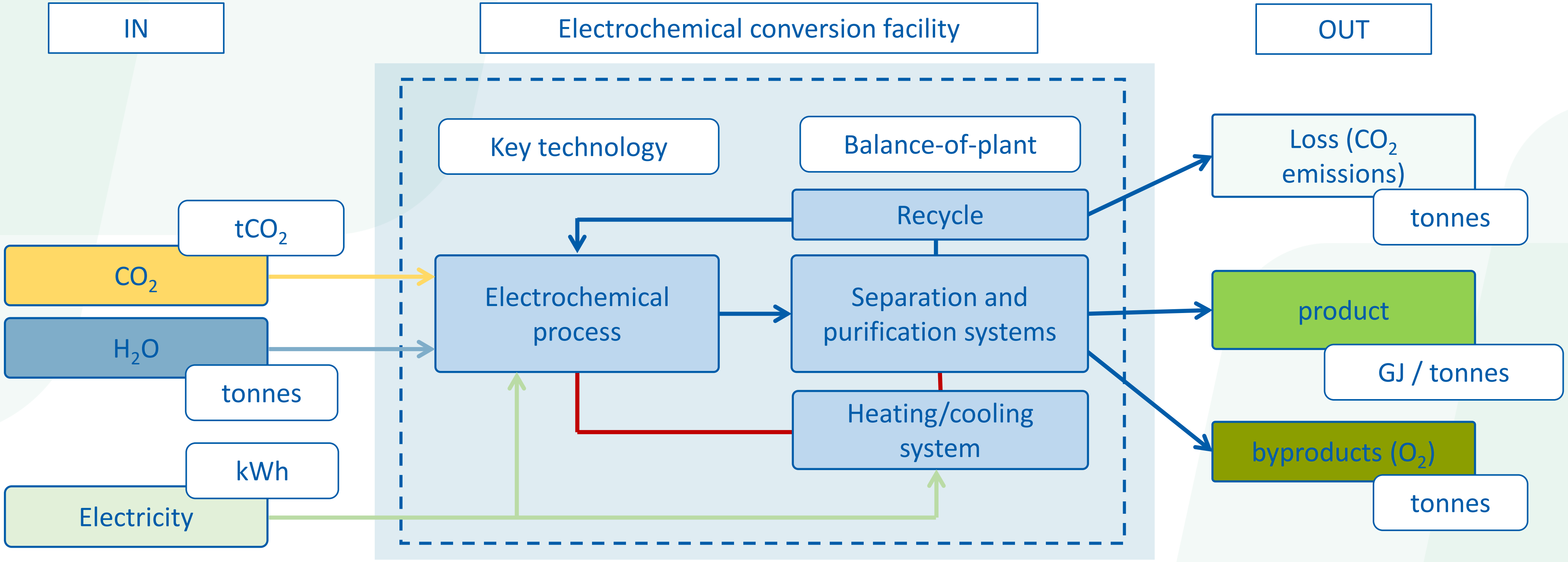
Route 4: HT CO production

Route 5: HT CO/H_2 production

Route 6: HT CO production + LT CO to C_2H_4 conversion

System scope

- To assess all routes in a similar fashion, we fixed the system scope and determined the mass & energy balances for each of the routes



State-of-the-art

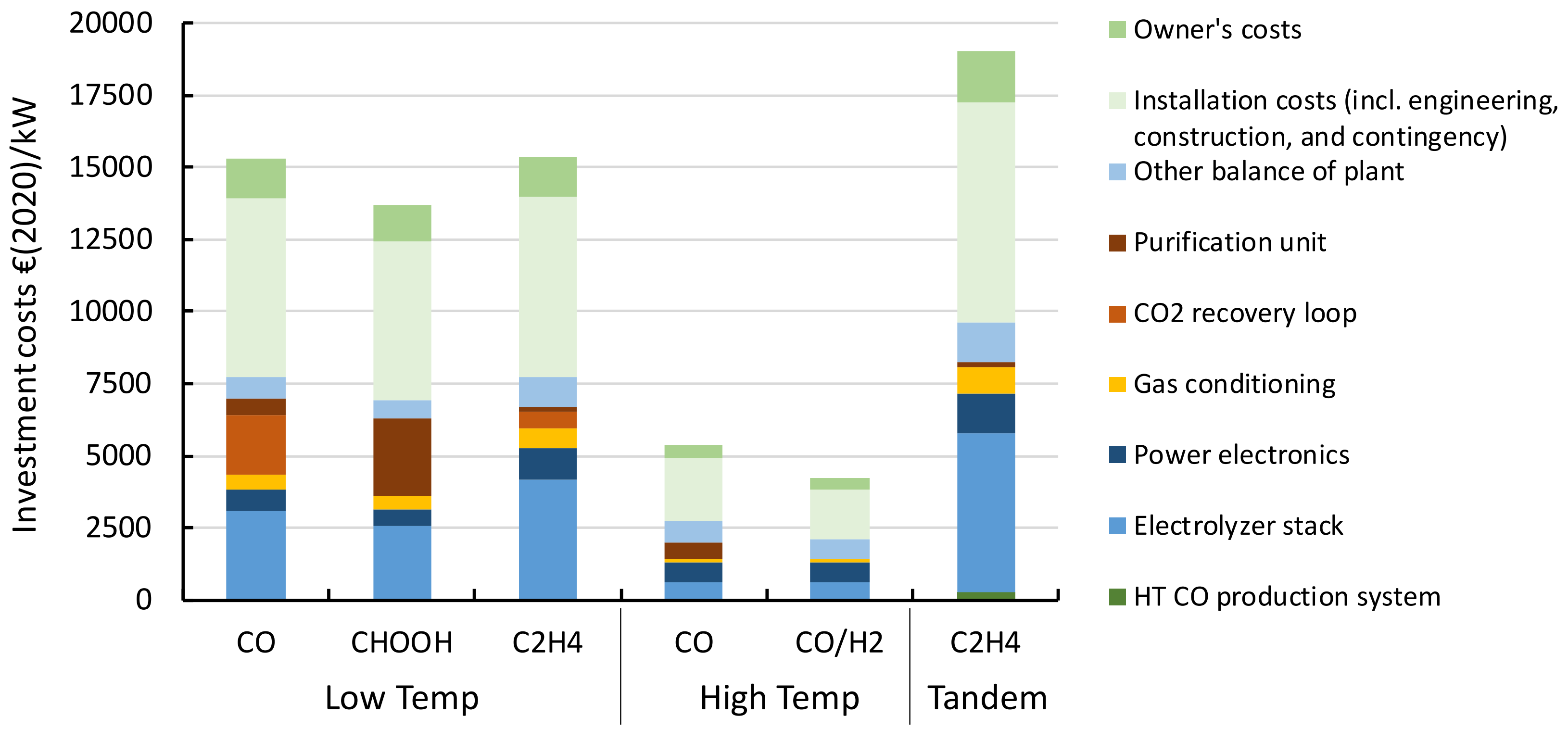
- The technologies differ in their technology development level and performance

Route	Technology	Voltage (V)	Current density (A/cm ^{2})	FE$_{prod}$ (%)	Products (at cathode)	TRL
1	LT CO	3.0	0.20	98	CO, H_2	5-6
2	LT CHOOH	3.8	0.20	82	CHOOH, H_2	4-5
3	LT C_2H_4	3.7	0.12	64	C_2H_4, CO, H_2	3-4
4	HT CO	1.5	0.75	100	CO	8
5	HT CO/H_2	1.3	0.75	100	CO/H_2	5-6
6	Tandem C_2H_4	2.3	0.14	35	C_2H_4, CO, H_2, EtOH	3
	Chlor-alkali	*2 - 4*	*0.10 - 0.65*	*>95*	*H_2, NaOH*	*9*
	PEMEC	*1.7*	*2-3*	*>99*	*H_2*	*8-9*

- Chlor-alkali production is a comparable electrochemical conversion technology, which is already deployed at GW scale

Investment costs

- We assessed the key equipment costs for each of the routes for a single MW_e capacity plant.
- Installation costs are fixed at 80% of the total equipment costs. Owner's costs add another 10% to arrive at the total investment costs



Production costs

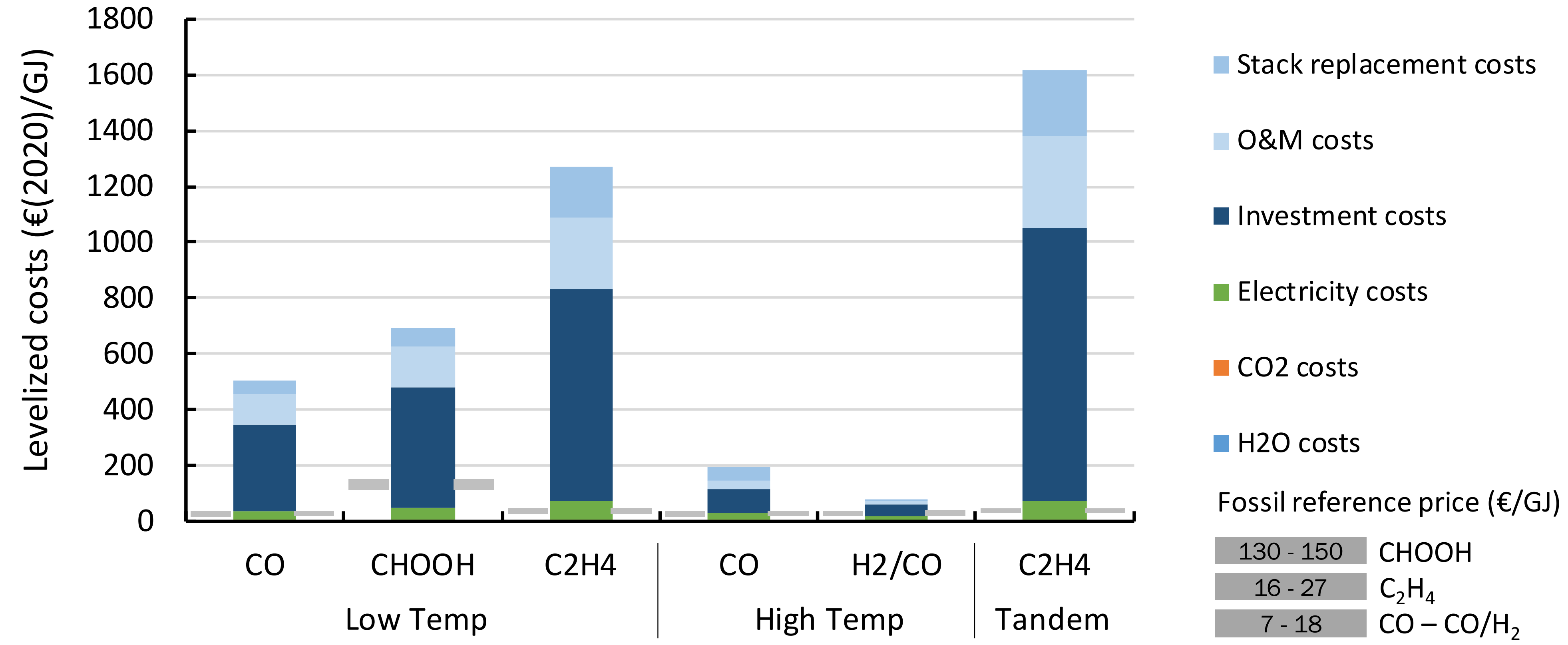
- We assessed the production costs for our six routes based on the state-of-the-art
- We made several assumptions, which clearly influence the uncertainty range and results of the analysis. Here we only present the base case scenarios to indicate the main dependencies
- $$C_x = \frac{\alpha \times \mathrm{CAPEX} + \mathrm{O\&M} + \mathrm{F}}{P_x}$$

C_x = levelized cost for product
α = capital recovery factor
$CAPEX$ = investment costs
$O\&M$ = operating and maintenance costs
F = costs for the required feedstocks
P_x = amount of product produced

Parameter	Base value	Unit
Plant lifetime	20	Years
Operational hours	4000	h/yr
Discount rate	10	%
O&M costs factor	4	% of initial CAPEX
H_2O costs	1	€/tH_2O
CO_2 costs	50	€/tCO_2
Electricity costs	40	€/MWh_e

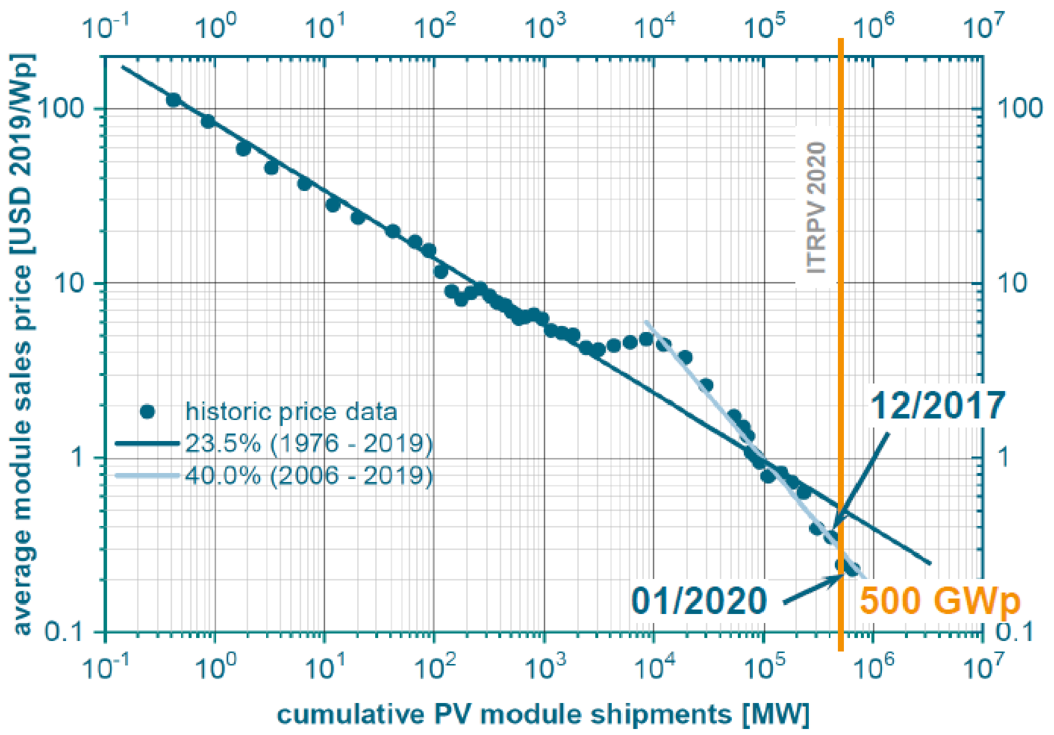
Production costs

- We assessed the production costs for our six routes based on the state-of-the-art



Projected costs

- Learning curve analysis – example of PV modules



Shipments /avg. module price at year end:

ITRPV

2018: 109 GWp / 0.24 US$/Wp
2019: 130 GWp / 0.23 US$/Wp

o/a shipment: ≈ 654 GWp
o/a installation: ≈ 628 GWp

LR ≈ 23.5 % (1976 …. 2019)
LR ≈ 40.0 % (2006 …. 2019)

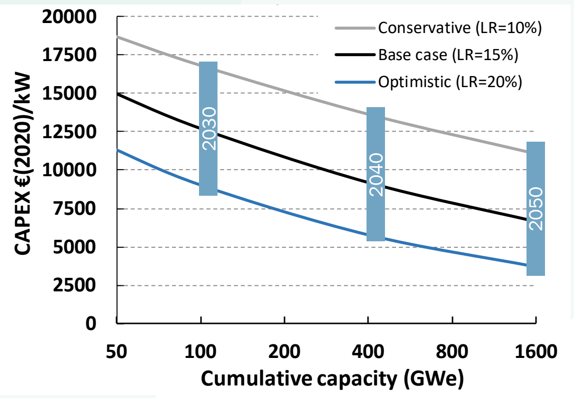
→ high volume shipped w/ increased product diversity
→ Significant change in module concepts

→ **Price learning continued**

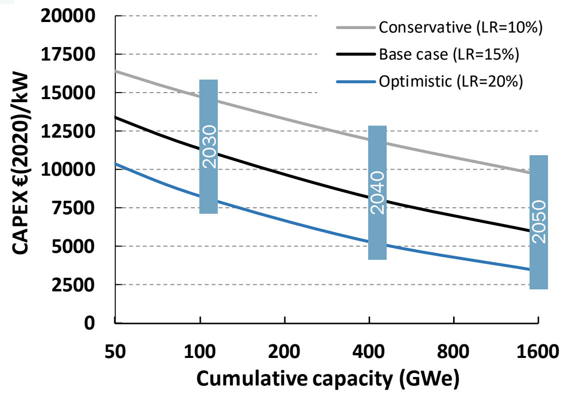
CAPEX projections

- Learning curves CAPEX

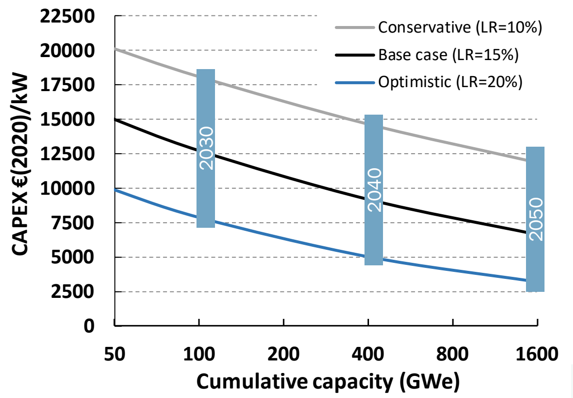
ROUTE 1 – LT CO production



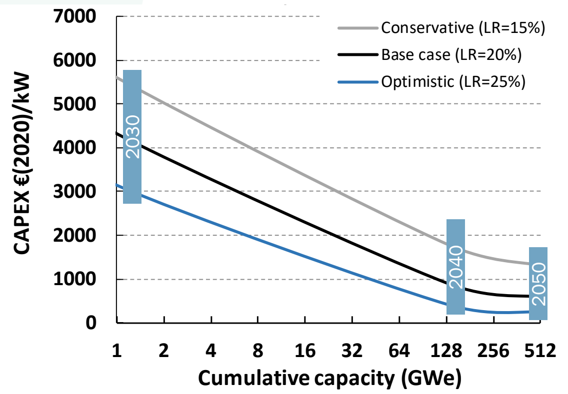
ROUTE 2 – LT CHOOH production



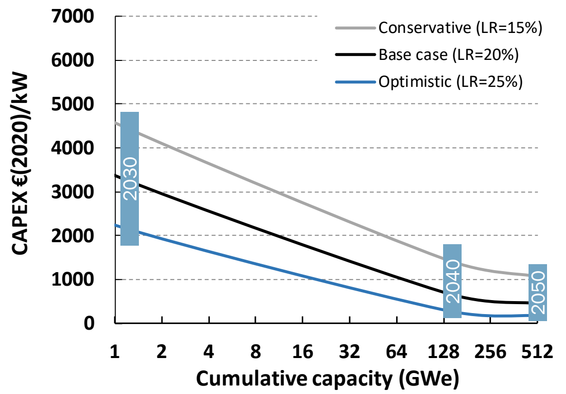
ROUTE 3 – LT C_2H_4 production



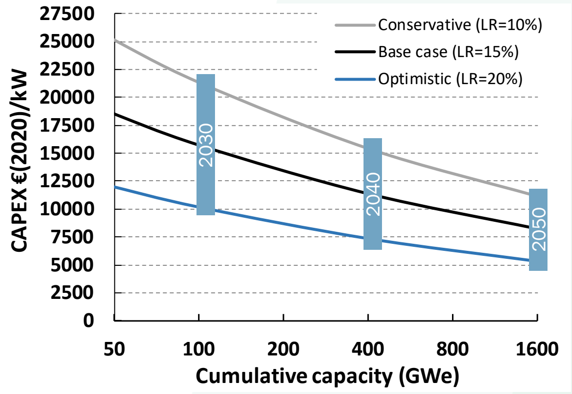
ROUTE 4 – HT CO production



ROUTE 5 – HT CO/H_2 production



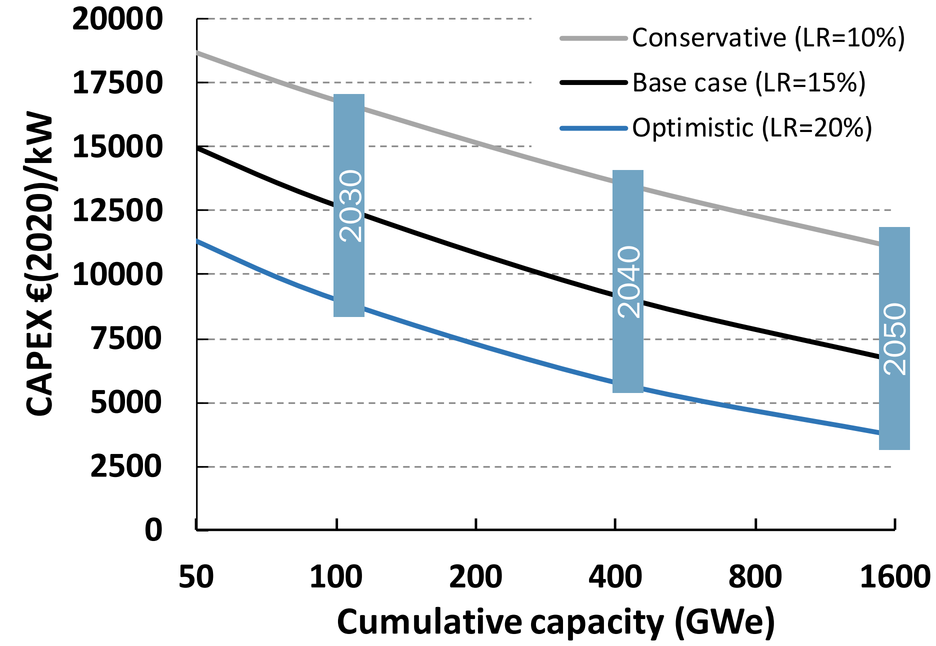
ROUTE 6 – Tandem C_2H_4 production



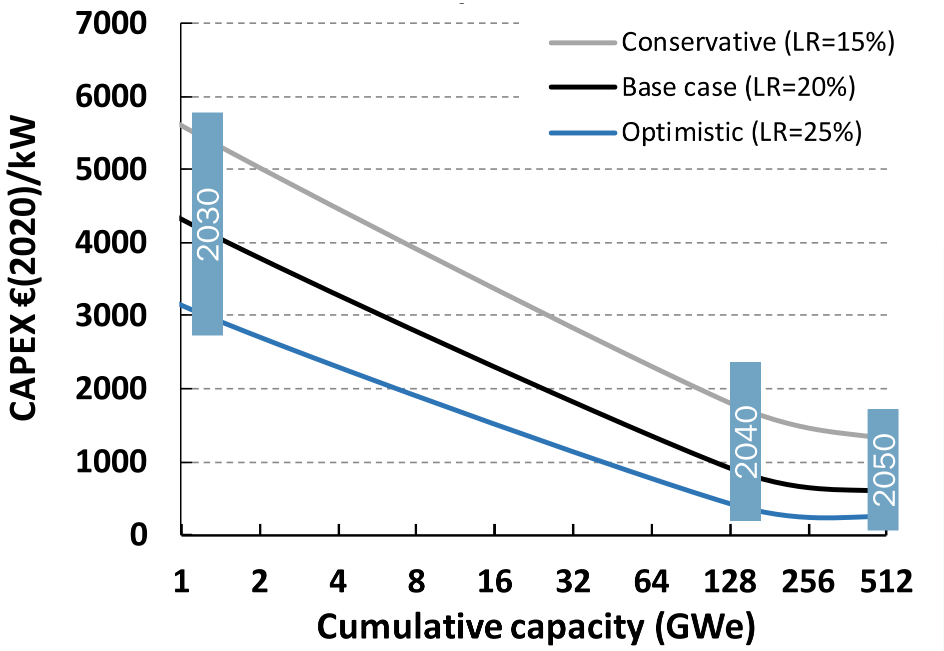
Cost projections

- Learning curves CAPEX – LT and HT electrochemical CO_2 conversion to CO

ROUTE 1 – LT CO production



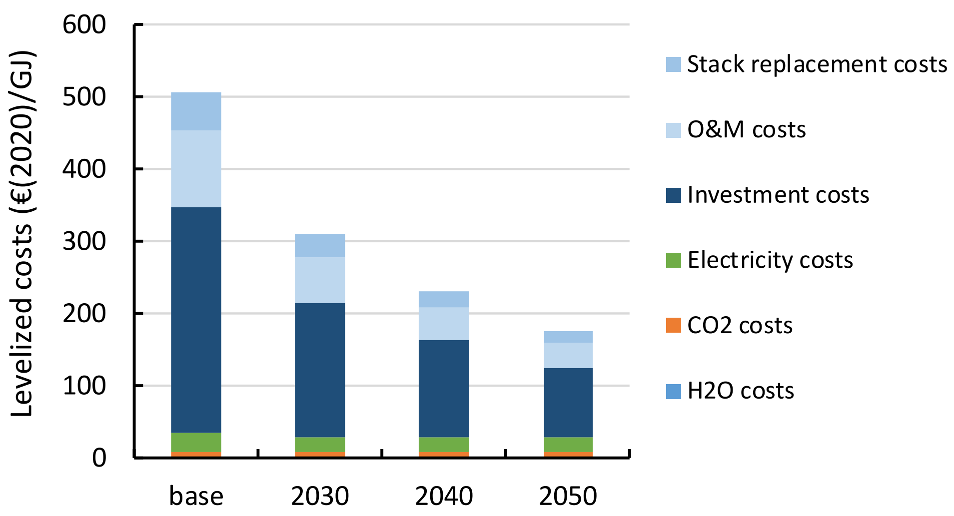
ROUTE 4 – HT CO production



Cost projections

- Production costs projections (base case)– LT and HT electrochemical CO_2 conversion to CO

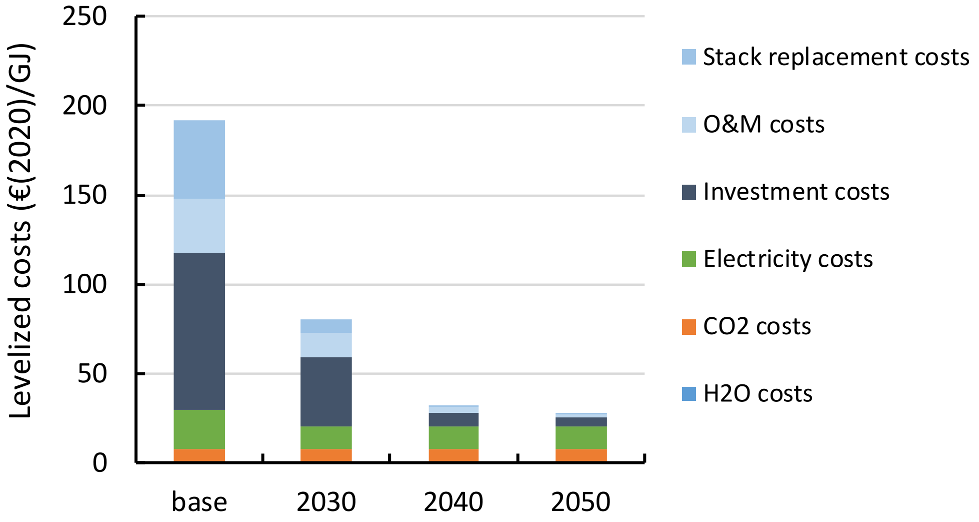
ROUTE 1 - LT CO production



Fossil reference price: 7 -18 €/GJ

Required CO_2 taxation for 2050 breakeven: 636 €/tCO_2

ROUTE 4 - HT CO production

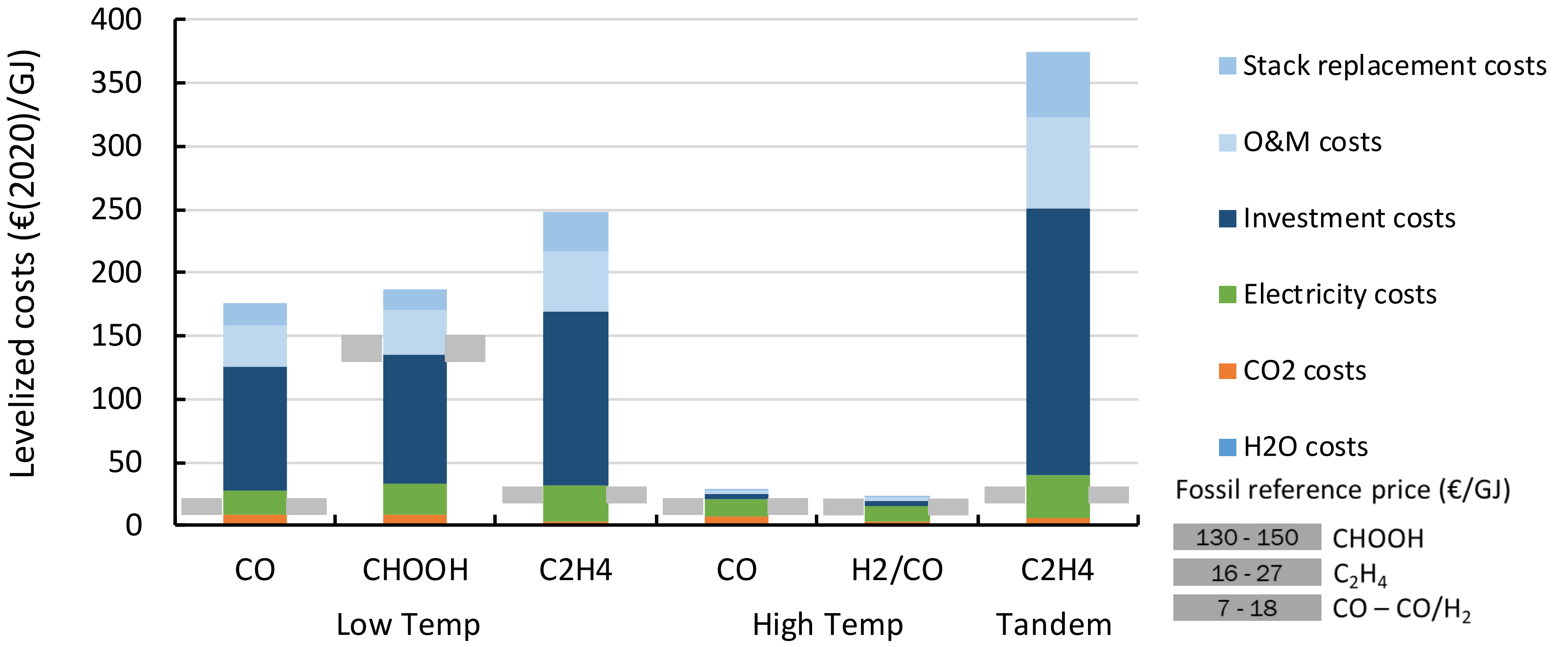


Fossil reference price: 7 - 18 €/GJ

Required CO_2 taxation for 2050 breakeven: 60 €/tCO_2

Production costs projections 2050

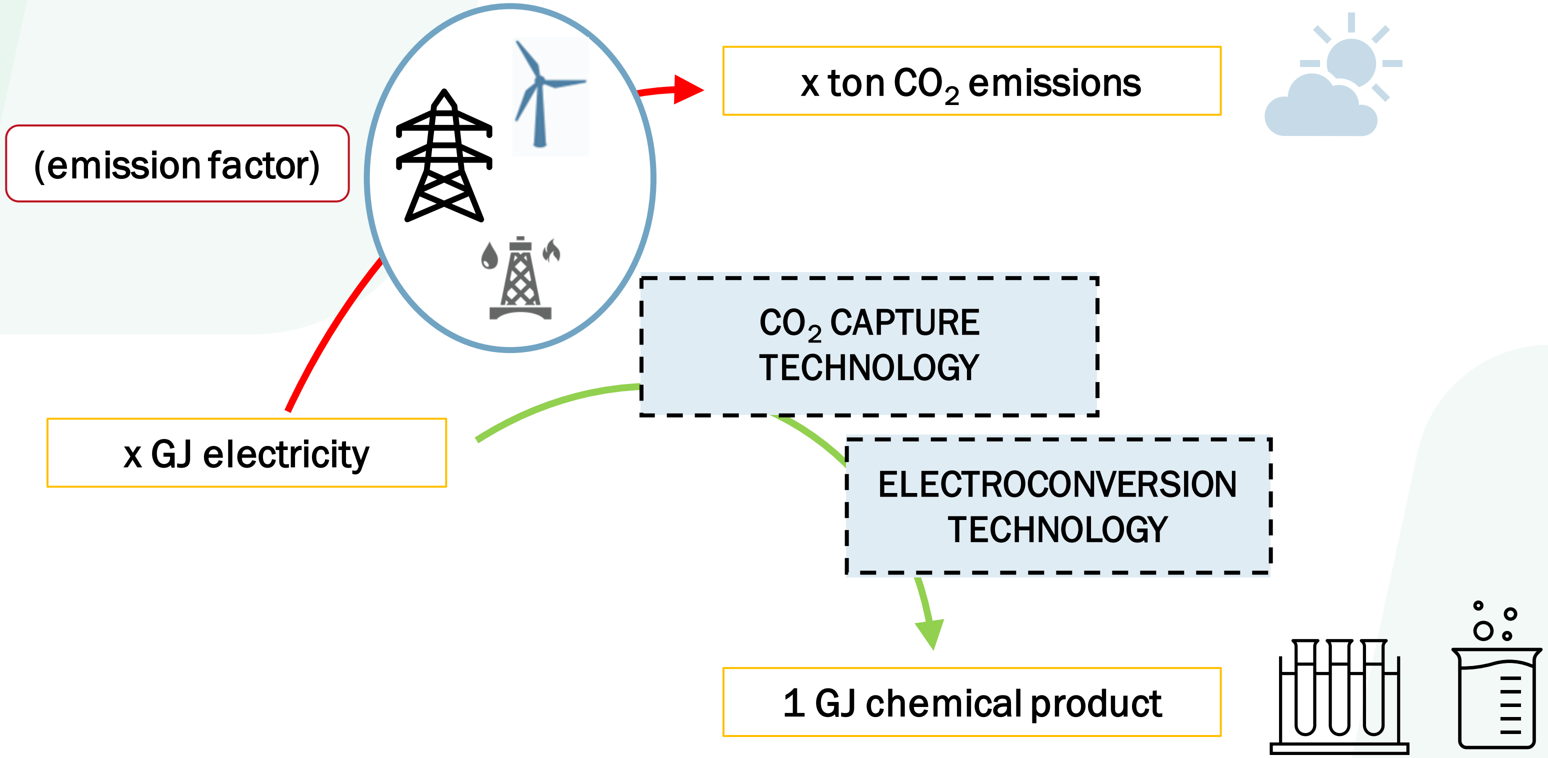
- Projected base case production costs of the six CO_2 electrochemical conversion routes in 2050



Product costs per kg	*1.8*	*1.0*	*12*	*0.3*	*0.5*	*18*	*€/kg product*
Required CO_2 tax:	*636*	*72*	*2330*	*60*	*102*	*3610*	*€/tCO_2*

Emission reductions

- The emissions related to electricity use of the routes are compared with emissions from fossil-based production



(emission factor)

x ton CO_2 emissions

CO_2 CAPTURE TECHNOLOGY

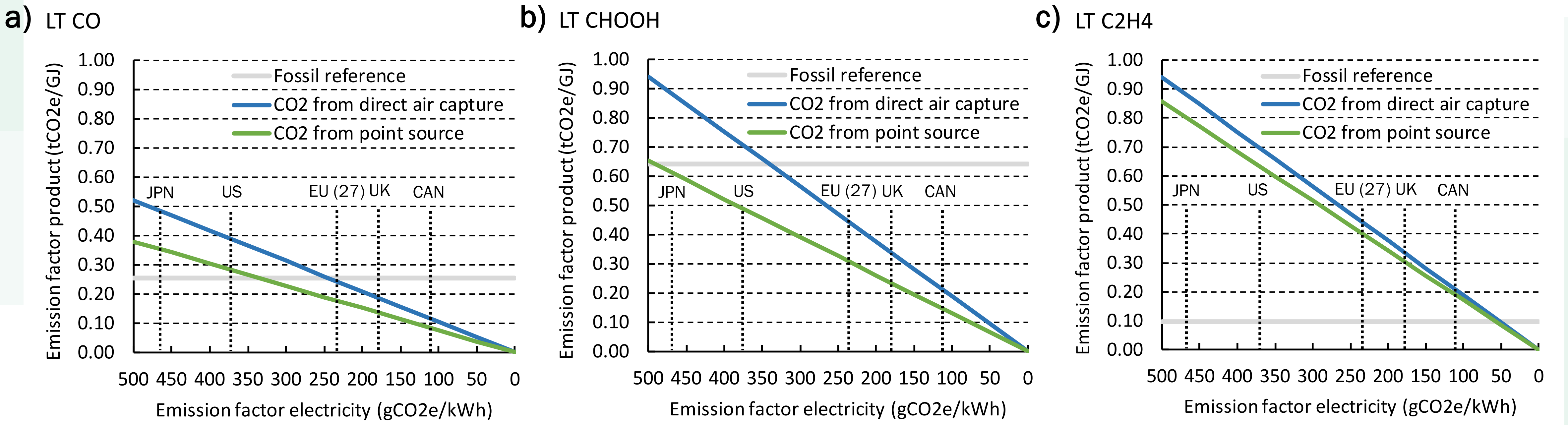
x GJ electricity

ELECTROCONVERSION TECHNOLOGY

1 GJ chemical product

Emission reductions

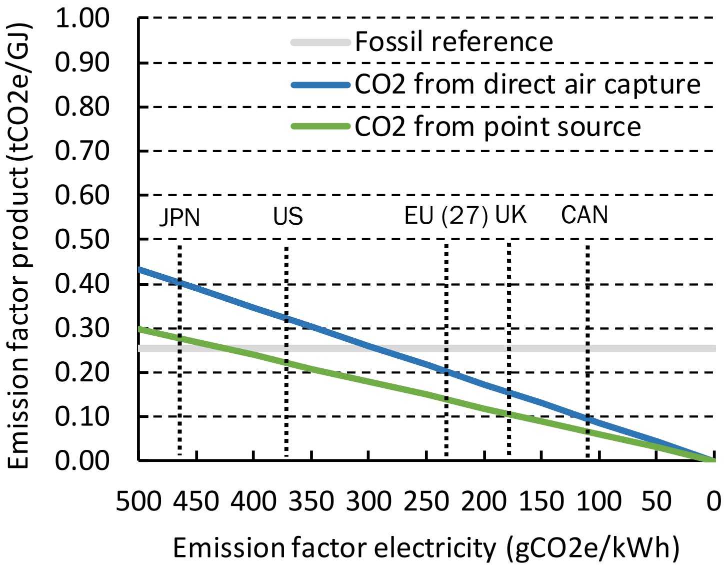
- The LT routes to produce CO and FA are currently already avoiding emissions if driven by grid electricity in the EU (27), even with CO_2 from direct air capture
- Electrochemical ethylene production becomes only competitive with the fossil benchmark if very low-carbon electricity can be used (< 50 $gCO_{2,e}$/kWh)



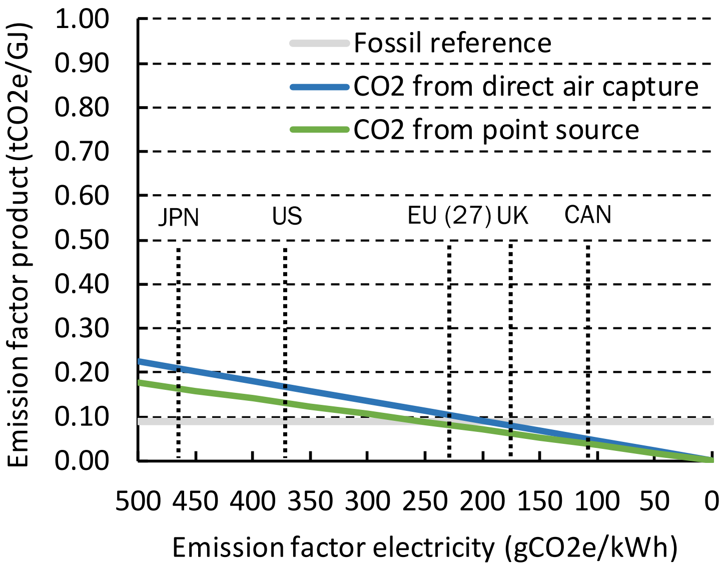
Emission reductions

- Compared to the fossil benchmark, HT CO production is currently already avoiding emissions if driven by grid electricity in the EU (27), for HT syngas production the emission factor should be slightly lower (<200 $gCO_{2,e}$/kWh), for ethylene production very low-carbon electricity is required (< 50 $gCO_{2,e}$/kWh)
- Notably, not all value chain emissions have been analyzed and full life cycle assessment is required to provide a more detailed comparison

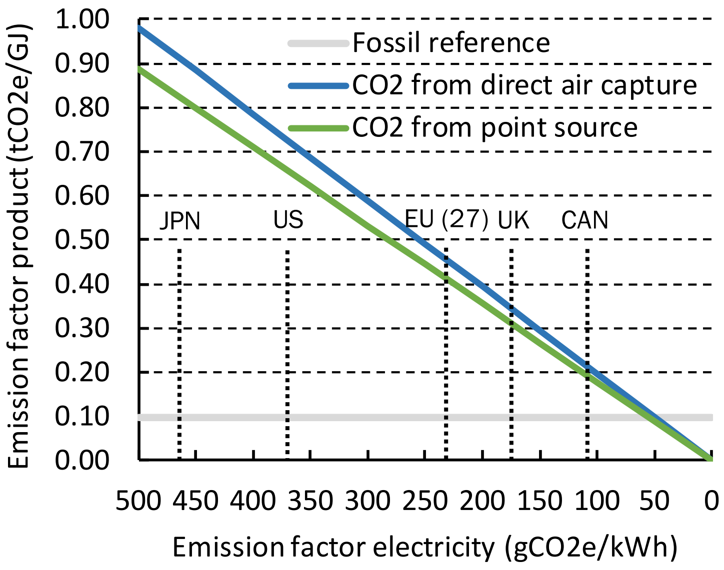
d) HT SOEC CO



e) HT SOEC CO/H2



f) TANDEM C2H4

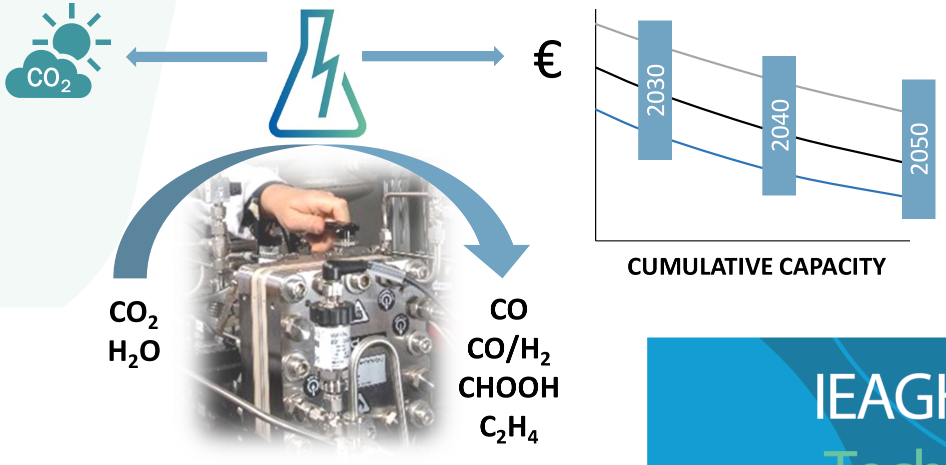


Conclusions

- Several electrochemical technologies are available to convert CO_2 into different products
- We analyzed six routes to produce CO, syngas, formic acid, and ethylene
- The economic performance of all routes is currently mainly determined by the CAPEX component
- Thanks to steep learning of the HT pathways, these routes are likely first to reach break-even levelized production cost in comparison to the fossil reference
- The most promising to reach break-even costs are LT formic acid production (CO_2 tax of 72 €/tCO_2) and HT CO production (CO_2 tax of 60 €/tCO_2)
- Once CAPEX has reduced thanks to learning, electricity and CO_2 prices strongly affect the production costs
- For ethylene production, saving GHG emissions by the electrochemical routes (3 and 6) becomes difficult if the efficiency and power density cannot be substantially improved without raising the investment costs
- All electrochemical production routes to produce CO, formic acid, and syngas avoid or can soon avoid CO_2 emissions when compared to fossil reference processes if only electricity use is considered
- Innovation and further development can substantially improve the process performance (efficiency, current density, purification) and, thus, competitivity

Still curious?

- More details can be found in the report and paper



From the journal:

Sustainable Energy & Fuels

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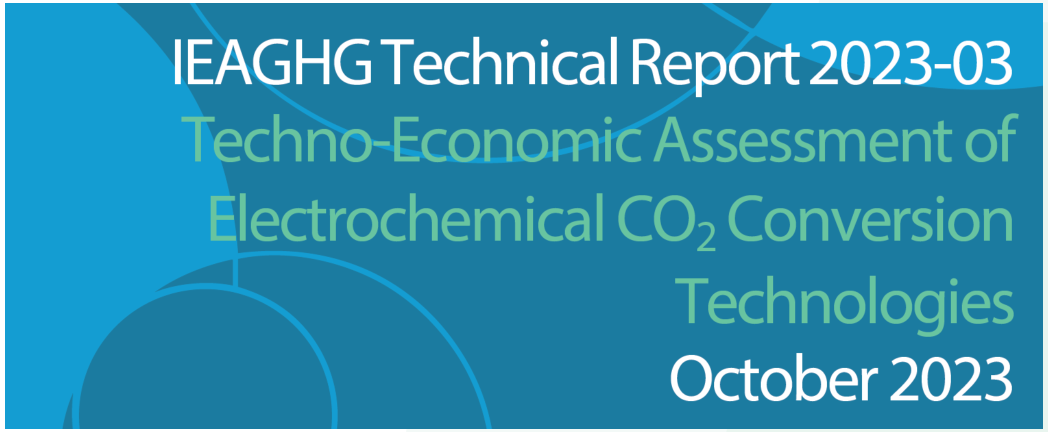

IEAGHG Technical Report 2023-03

Techno-Economic Assessment of Electrochemical CO_2 Conversion Technologies

October 2023

Thank you for your attention

Questions?

Please ask these in the chat

Remko Detz

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