TECHNISCHE UNIVERSITÄT WIEN

Economic and environmental aspects of energy systems (Winter/Summer School)

Carbon capture, storage and utilization

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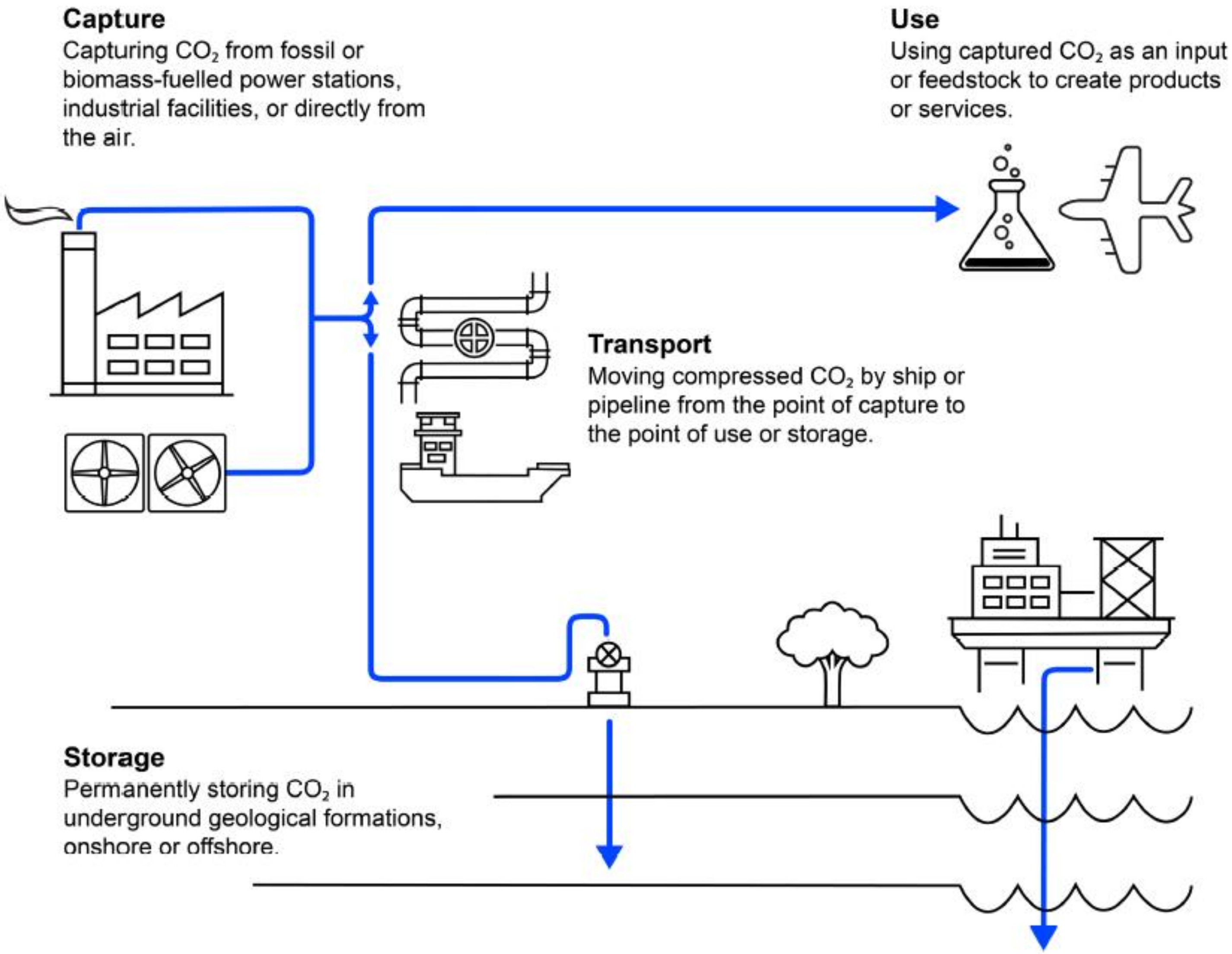
1. CCUS technologies and applications

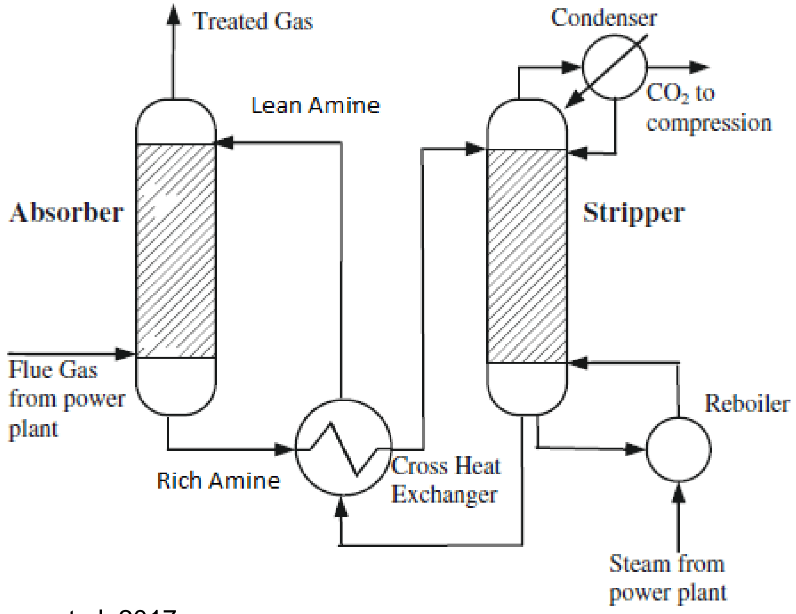
What is CCUS?



IEA 2020, Special report on CCUS

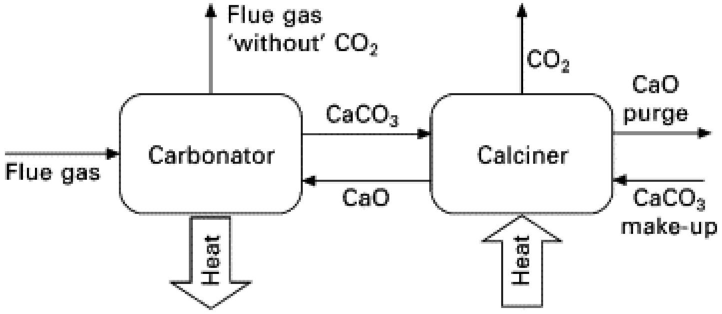
How does it work technically?

Chemical absorption



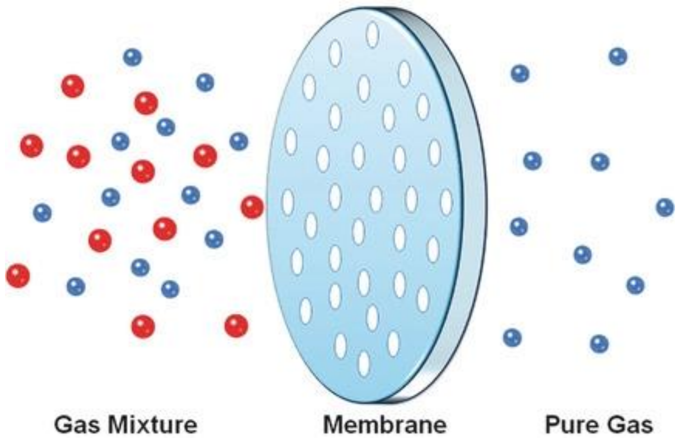
Zhang et al. 2017

Calcium looping



Abanades 2013

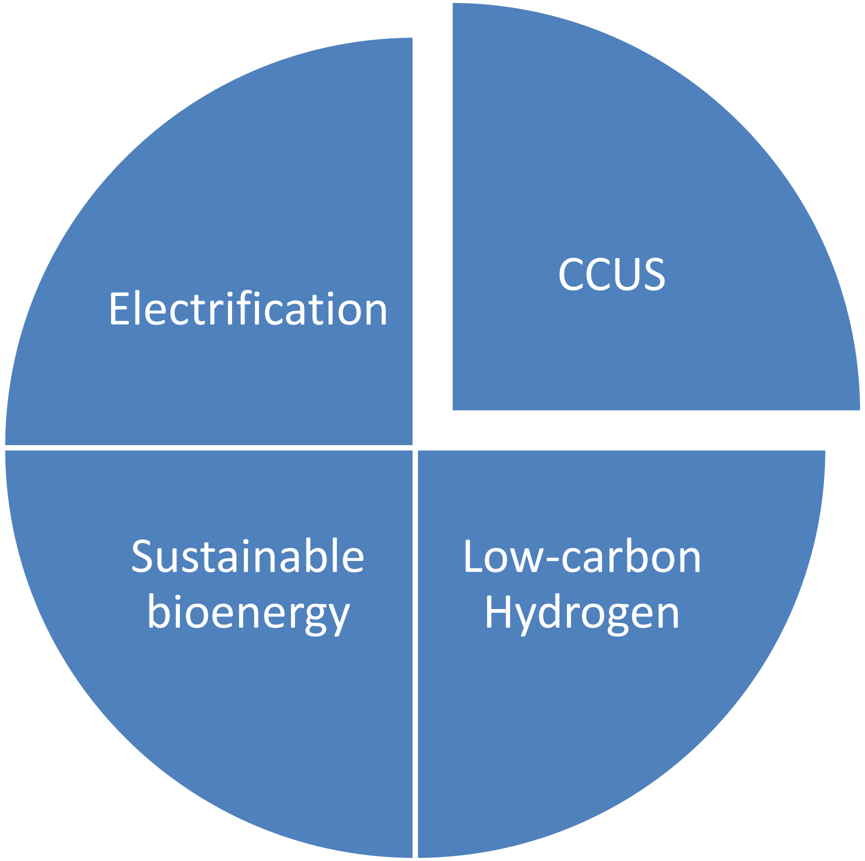
Membrane separation



Zou and Zhu 2017

Capture rates 60-99 %

Global energy transition



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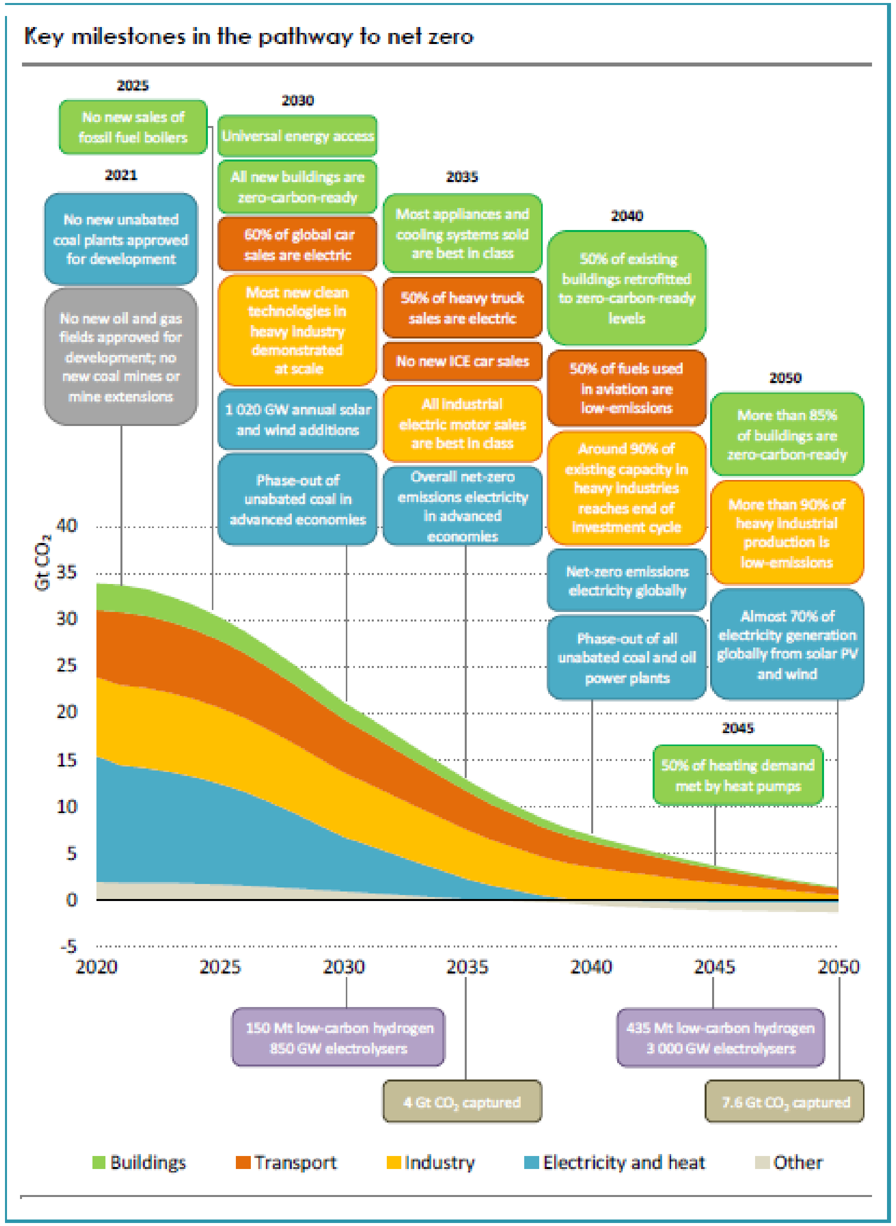
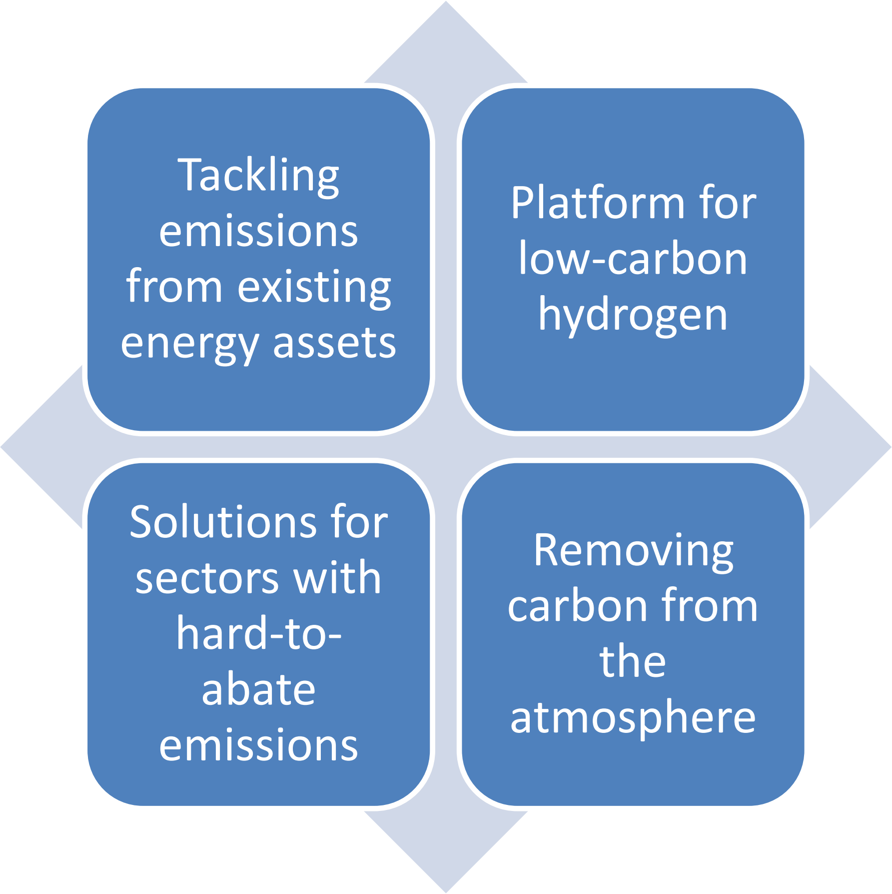
Path to net zero



IEA 2021 Net Zero by 2050

Zero-emission scenario



IEA 2020, Special report on CCUS

Emissions from energy assets

- Investment in modifications to existing equipment
  - less carbon-intense fuels or improve energy eff.
- Retire plants before the end of regular lifetime
- Retrofit CO_2 capture facilities

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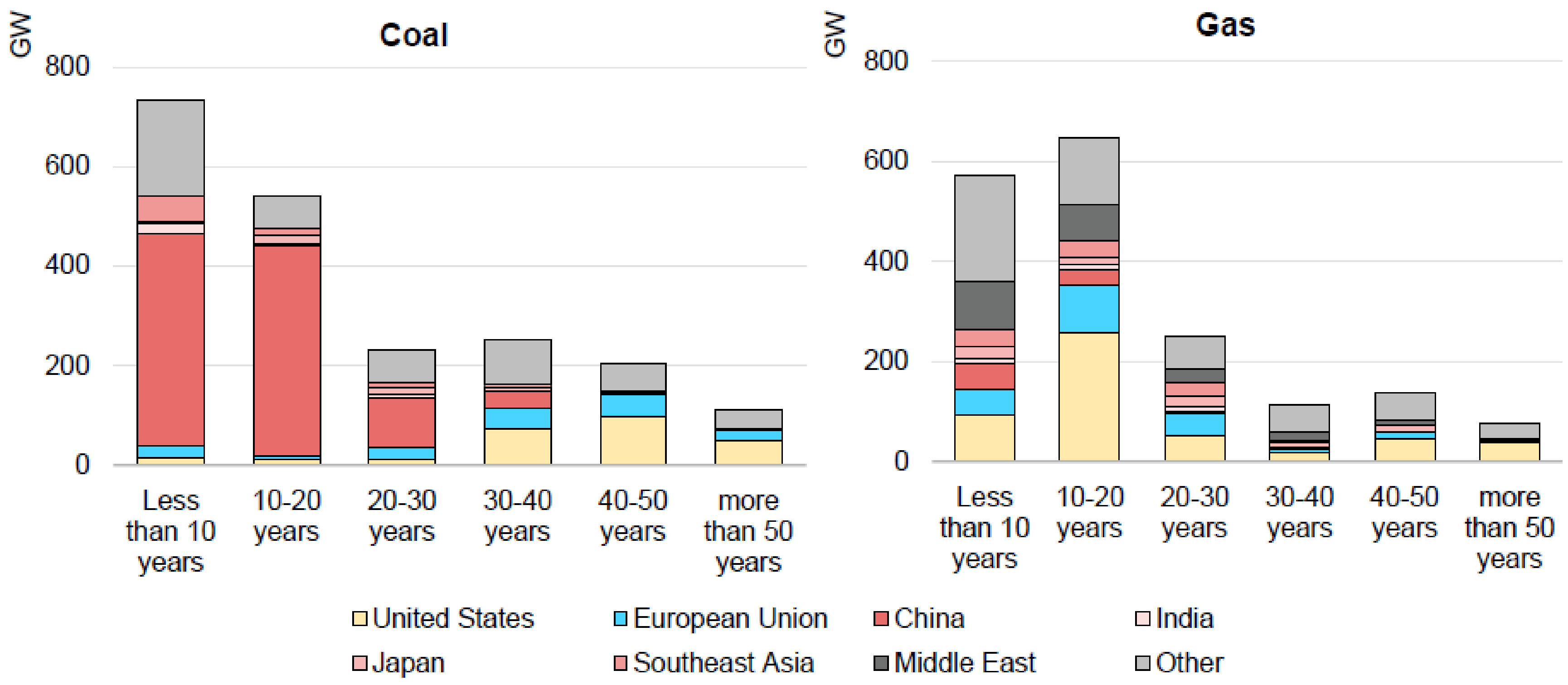
Emissions from energy assets



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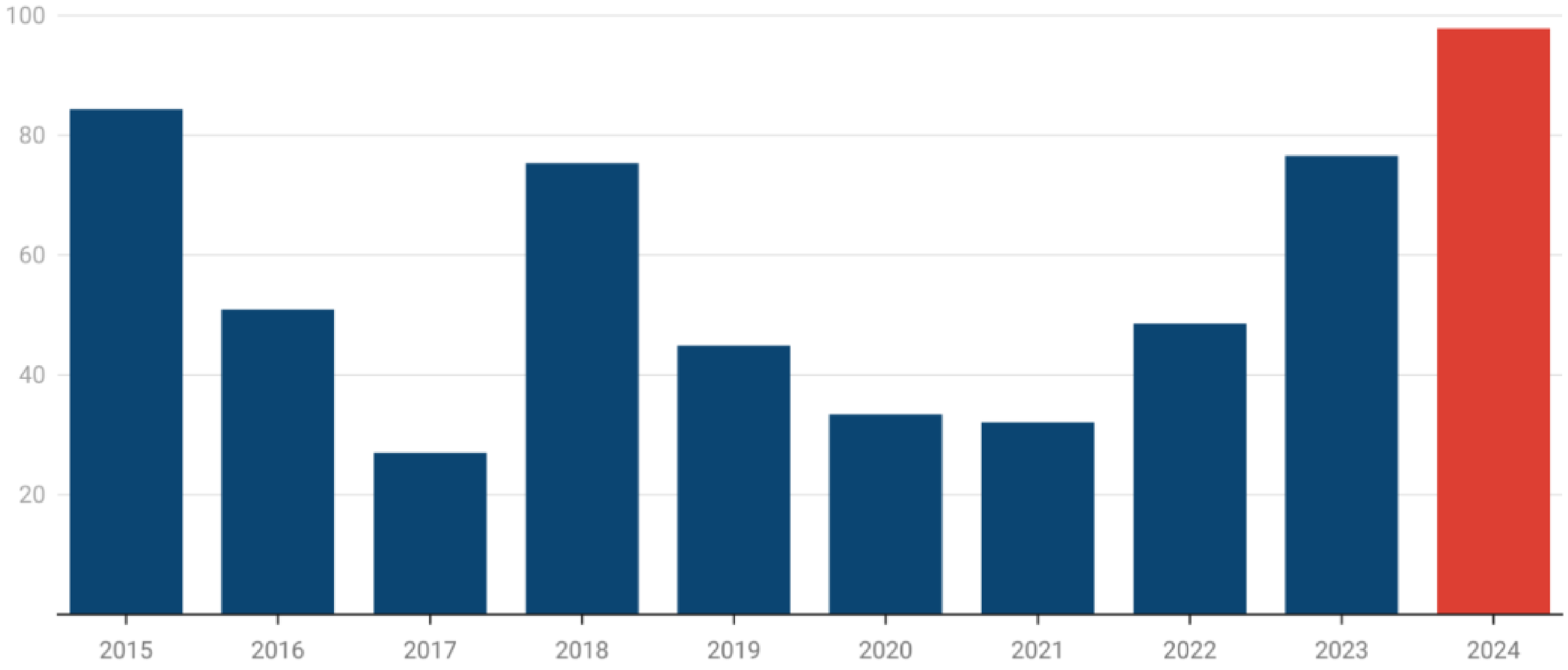
China's construction of new coal-power plants reached a 10-year high in 2024

New and resumed construction on coal plants in China between 2015-2024 (gigawatts)



Source: China Coal Power Biannual Review H2 2024

CarbonBrief CLEAR ON CLIMATE

https://www.carbonbrief.org/chinas-construction-of-new-coal-power-plants-reached-10-year-high-in-2024/

Hard-to-abate emissions

- Improvements of existing technologies
- Material efficiency
- Reduce transport emissions

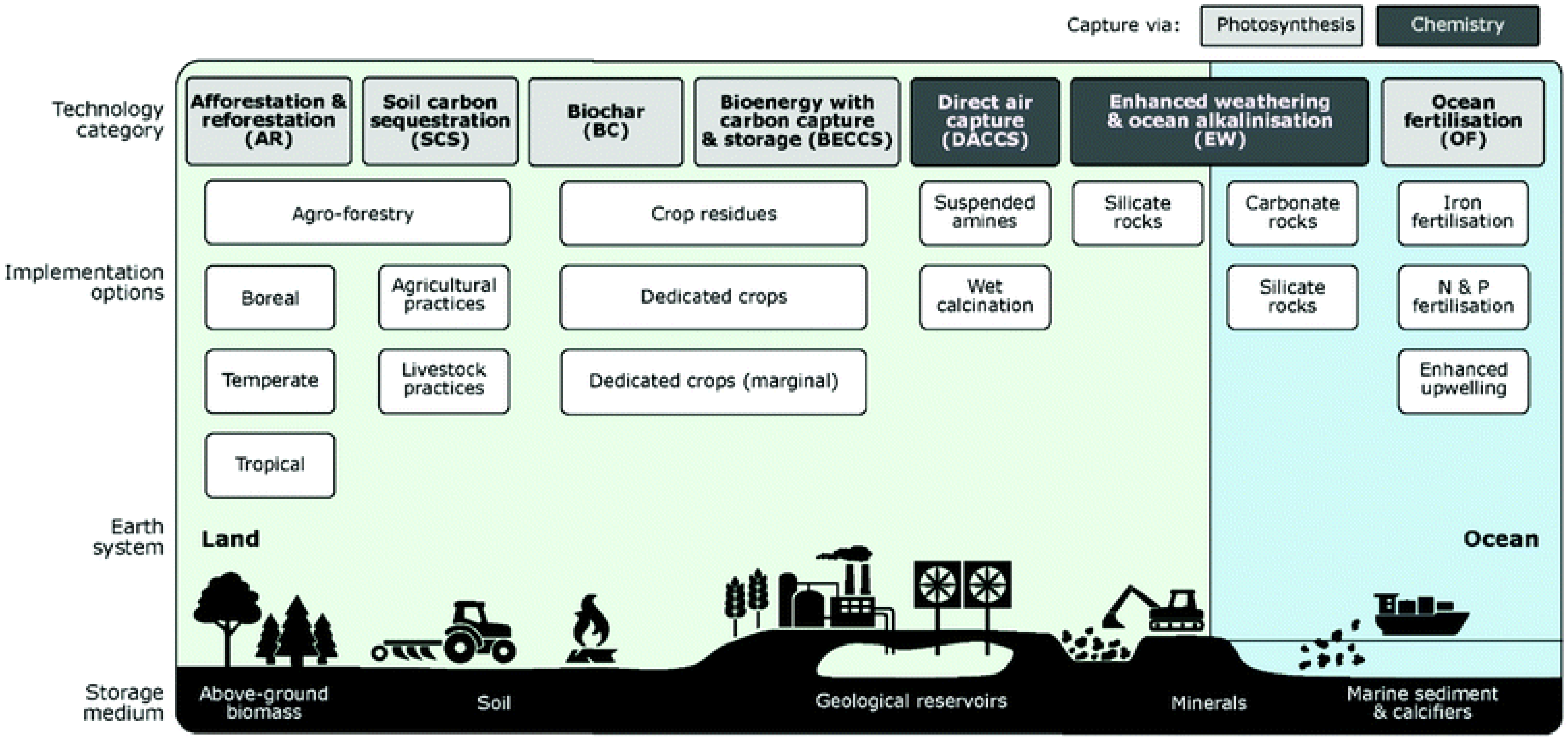
- Process related emissions remain:
  - Cement production
  - $CaCO_3$ -> $CaO + CO_2$

Removing carbon from the atmosphere

- Zero-emissions most probably require carbon removal
- Nature-based solutions: afforestation, biochar, etc.
- Technology-based solutions: CCUS, BECCS, DACS
- Compensation of emissions which are currently difficult to mitigate

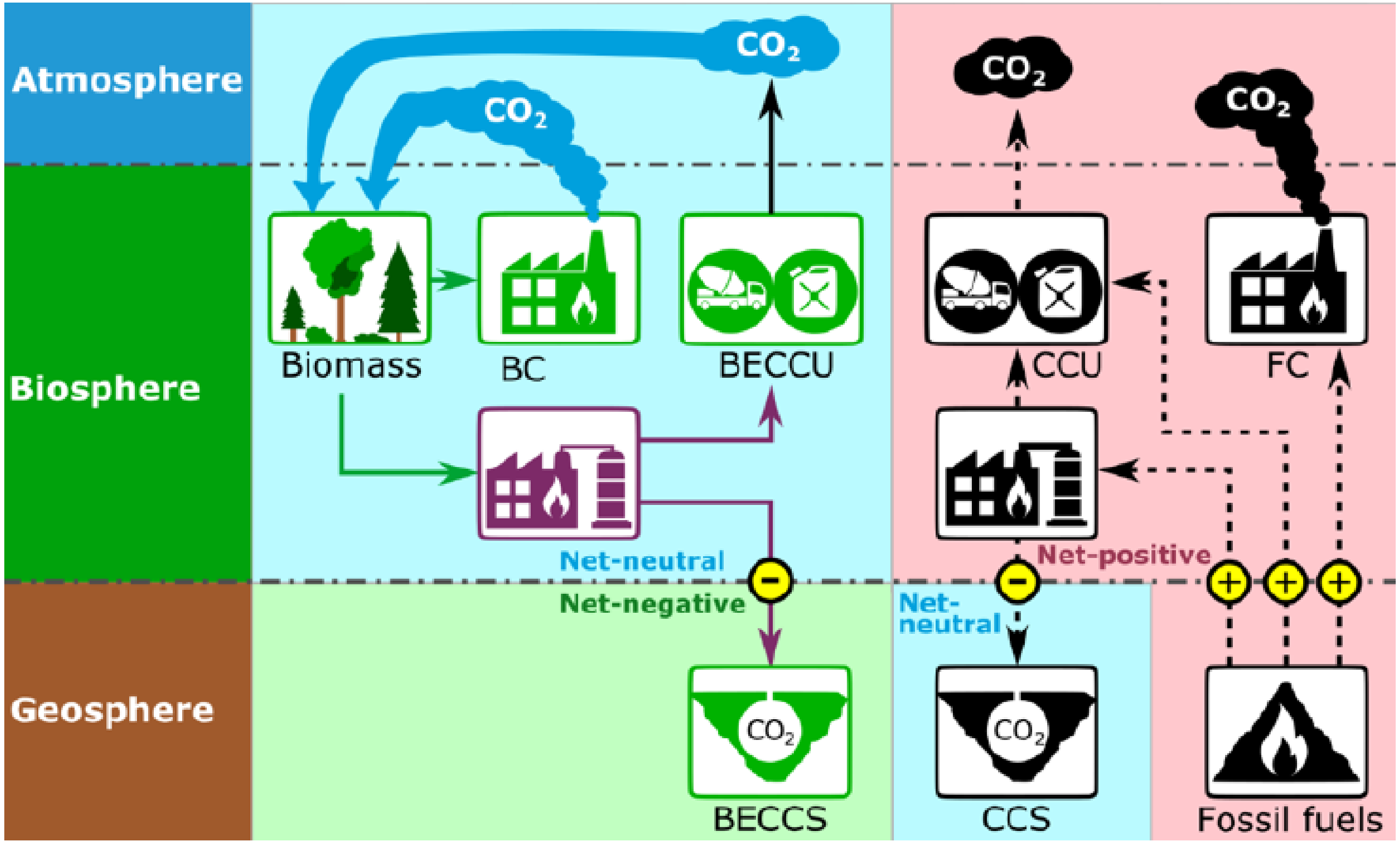
CCUS = Carbon capture utilization and storage, BECCS = Bioenergy carbon capture and storage, DACS = Direct air capture and storage

Removing carbon from the atmosphere



Erans et al. 2022

Bioenergy carbon capture and storage (BECCS)



Olsson et al. 2020

Carbon removal technologies

Approach	Approach type	Current maturity category	Carbon removal potential (cumul. to 2100, $GtCO_2$)*	CO_2 capture cost (USD/tCO_2)
Bioenergy with CCS	Technology	Demonstration	100-1170	15-85
Direct Air Capture and Storage	Technology	Demonstration	108-1000	135-345
Enhanced weathering of minerals	Enhanced natural processes	Fundamental research	100-367	50-200
Land management and biochar production	Enhanced natural processes	Early adoption	78-1468	30-120
Ocean fertilisation/alkalinisation	Enhanced natural processes	Fundamental research	55-1027	-
Afforestation/reforestation	Nature-based	Early adoption**	80-260	5-50

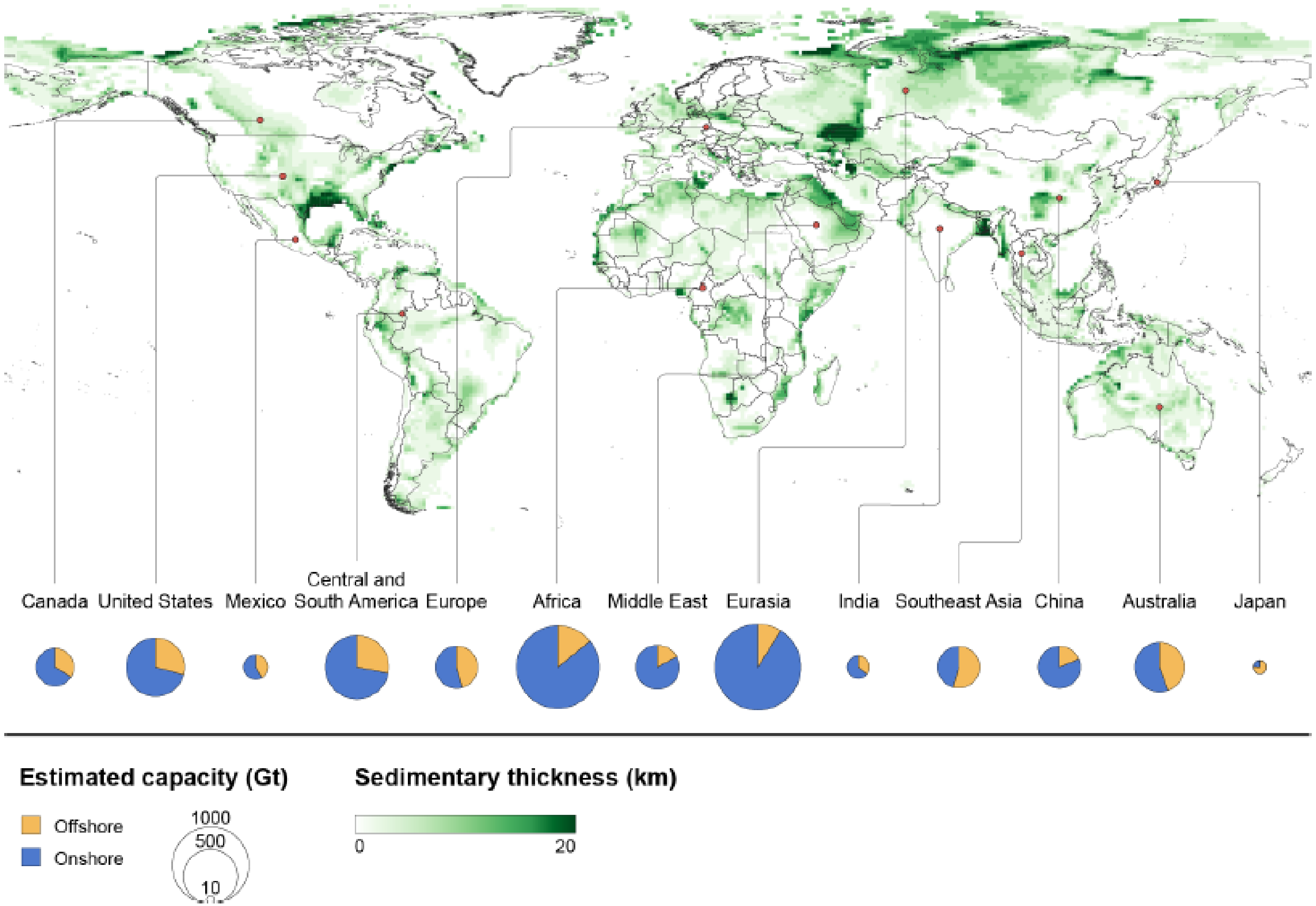
* Estimates for carbon removal potential are not additive, as CDR approaches partially compete for resources

** While afforestation/reforestation is an established practice, it is at early adoption in the context of carbon removal.

Sources: EASAC (2018), Fuss et al. (2018), Haszeldine et al. (2018), Keith et al. (2018), Minx et al. (2018), Nemet et al. (2018), Realmonte et al. (2019), Smith et al. (2015).

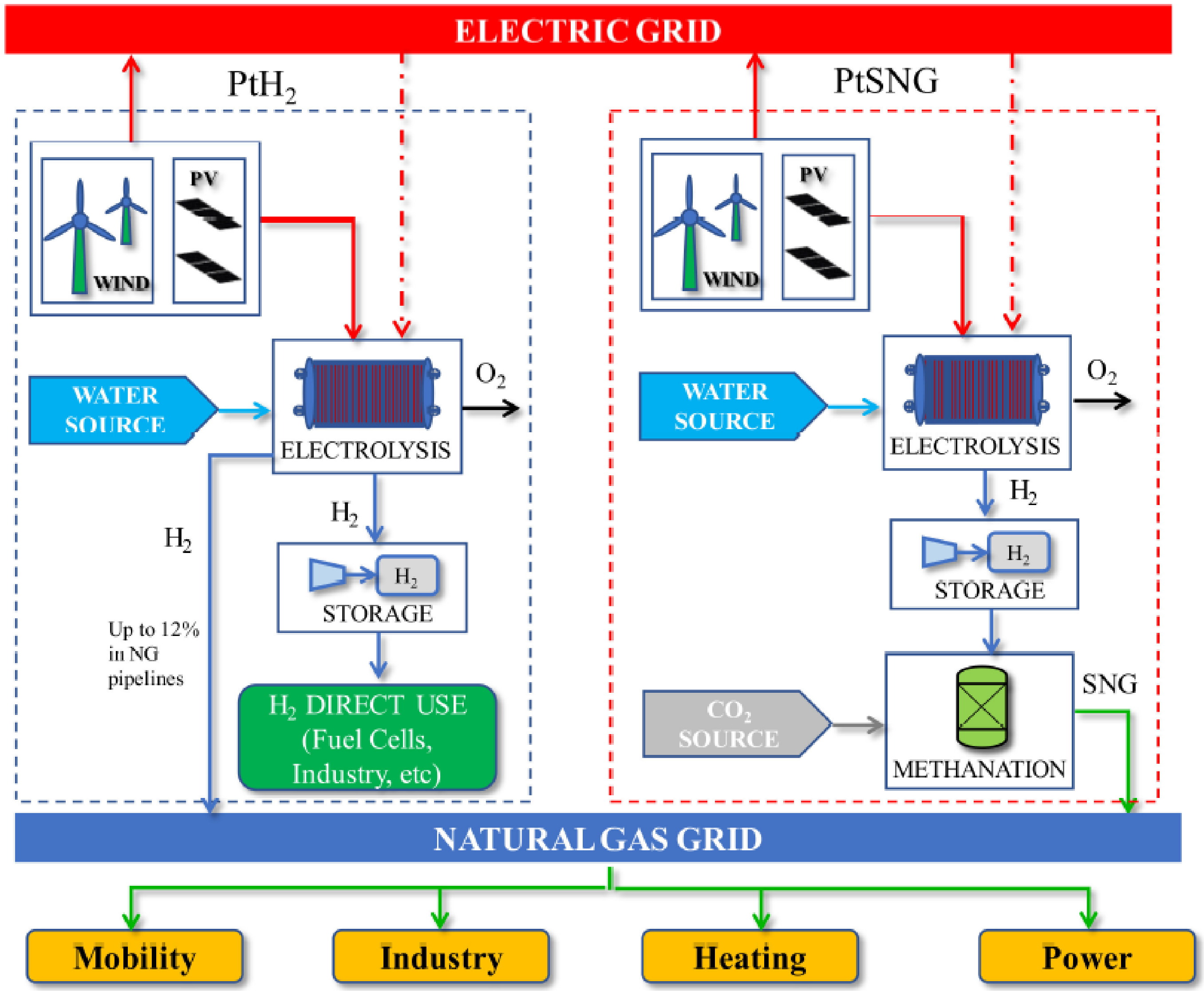
IEA 2020, Special report on CCUS

Storage sites



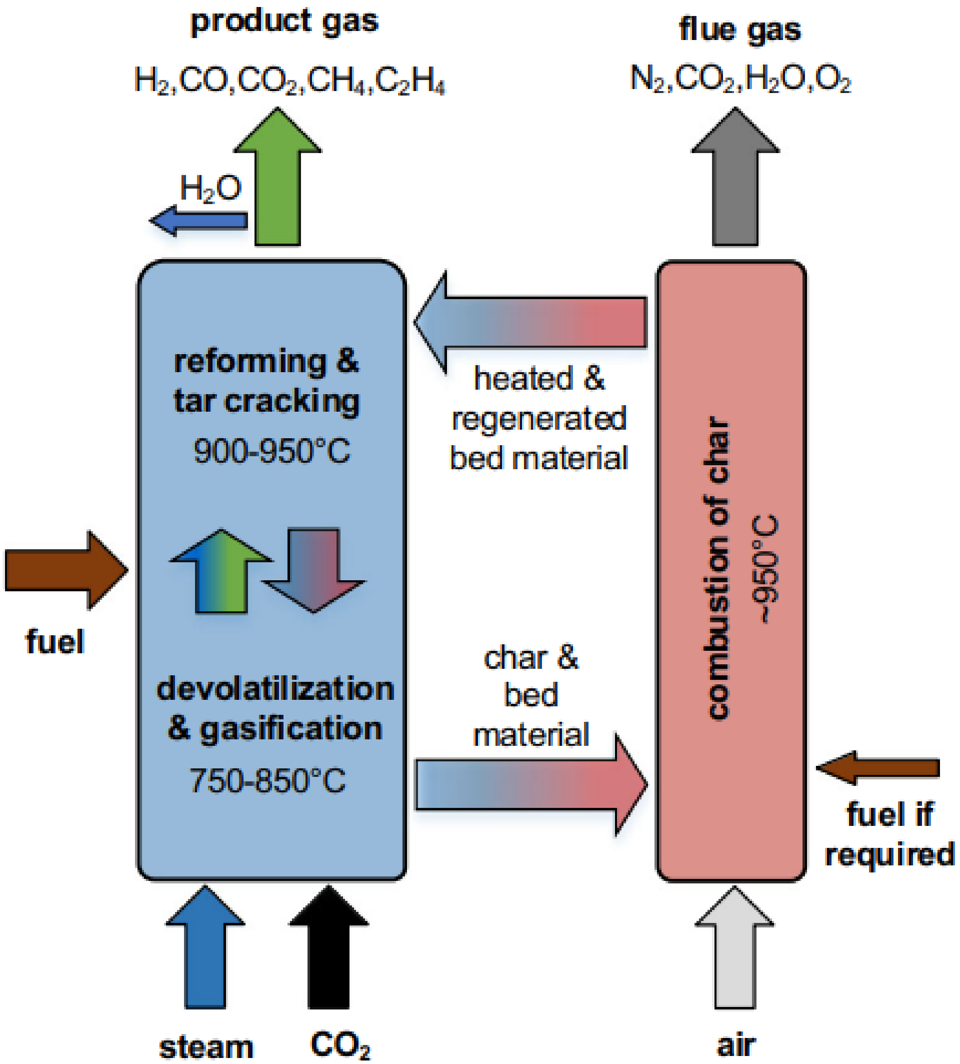
IEA 2020, Special report on CCUS

CCU: Power-to-gas



Perna et al. 2020

Biomass gasification with CO2



Bodouard reaction

$CO_2 + C \leftrightarrow 2CO$

Methanation

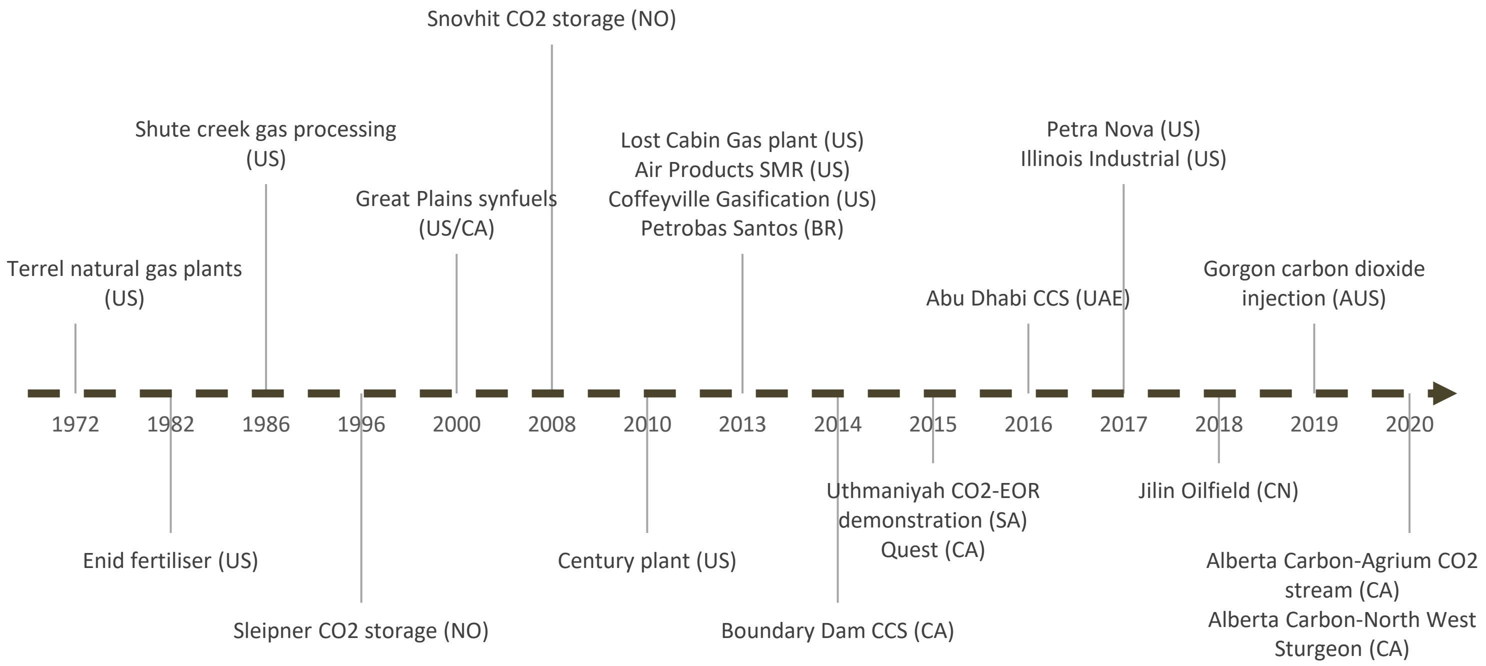
$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$

$CO + 3H_2 \leftrightarrow CH_4 + H_2O$

Mauerhofer et al. 2021

2. Overview on CCUS projects

Existing large-scale projects



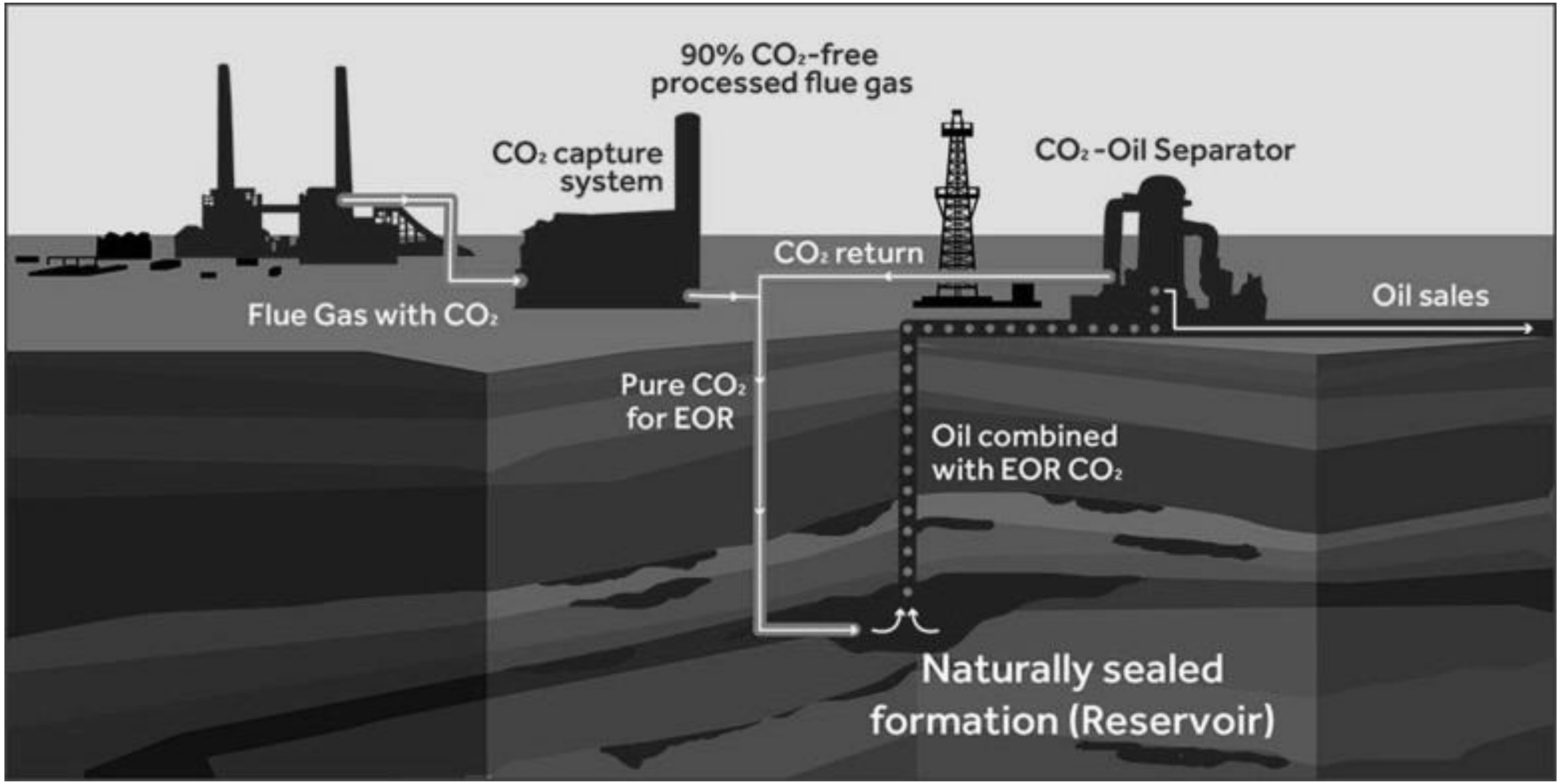
Source: IEA 2020, Special report on CCUS, own illustration

Large-scale projects (2020)

Country	Project	Operation date	Source of CO_2	Capture (Mt/ yr)	Primary storage
US	Terrell natural gas plants	1972	Natural gas	0.5	EOR
US	Enid fertiliser	1982	Fertiliser production	0.7	EOR
US	Shute creek gas processing facility	1986	Natural gas	7	EOR
Norway	Sleipner CO2 storage	1996	Natural gas	1	Dedicated
US/ CA	Great Plains Synfuels	2000	Synthetic natural gas	3	EOR
US	Snohvit CO2 storage	2008	Natural gas	0.7	Dedicated
US	Century plant	2010	Natural gas	8.4	EOR
US	Century plant	2013	Hydrogen production	1	EOR
US	Lost Cabin Gas plant	2013	Natural gas	0.9	EOR
Brazil	Petrobas Santos	2013	Natural gas	3	EOR
CA	Boundary Dam CCS	2014	Power generation	1	EOR
Saudi Arabia	Uthmaniyah CO2-EOR demonstration	2015	Natural gas	0.8	EOR
United Arab Emirates	Abu Dhabi CCS	2015	Iron and steel production	0.8	EOR
US	Petra Nova	2017	Power generation (coal)	1.4	EOR
US	Illinois Industrial	2017	Ethanol production	1	Dedicated
China	Jilin oilfield	2018	Natural gas	0.6	EOR
Australia	Gorgon Carbon Dioxide Injection	2019	Natural gas	3.4-4.0	Dedicated
Canada	Alberta Carbon Trunk Line (ACTL) with Agrium CO2 stream	2020	Fertiliser production	0.-0.6	EOR
Canada	ACTL with North Sturgeon Refinery CO2 stream	2020	Hydrogen production	1.2-1.4	EOR

IEA 2020, Special report on CCUS

Enhanced oil recovery (EOR)



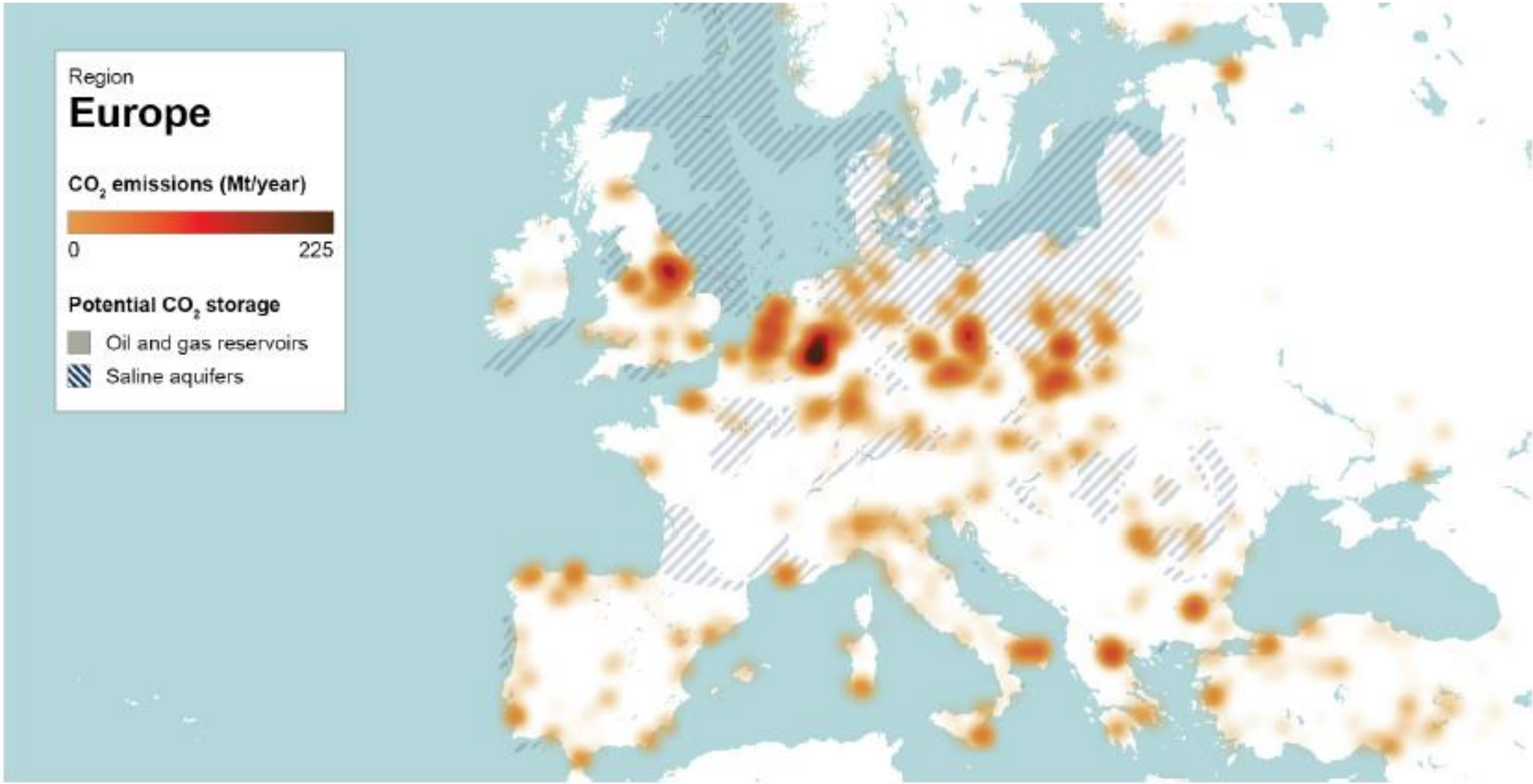
Wang et al. 2018

Potential CO_2 hubs in Europe

Country	Hub	CO2 sources	Emissions (Mt/yr)
Germany	North Rhine- Westphalia/Ruhr	Refining, (petro)chemicals, cement, iron and steel, waste incineration	35
France	Fos-Berre/Marseille	Refining, (petro)chemicals, cement, iron and steel	31
Netherlands	Rotterdam	Refining, (petro)chemicals, cement, iron and steel, waste incineration, bio-based industries	28
Belgium	Antwerp	Refining, (petro)chemicals, cement, iron and steel	20
France	Le Havre	Power, refining, (petro)chemicals, cement, iron and steel	14
Scandinavia	Skagerrak/Kattegat	(Petro)chemicals, fertilisers, refinery, cement, pulp and paper	14
UK	Humberside	Refining, (petro)chemicals, cement, iron and steel	12.4
UK	South Wales	Refining, (petro)chemicals, cement, iron and steel, waste incineration, bio-based industries	8.2
UK	Grangemouth/Fifth of Five	Power, refining, (petro)chemicals	4.3
UK	Teesside	Refining, (petro)chemicals	3.1
UK	Merseyside	Refining, (petro)chemicals, pulp and paper, glass	2.6
UK	Southampton	Refining, (petro)chemicals, cement	2.6

IEA 2020, Special report on CCUS

Possible storage in Europe

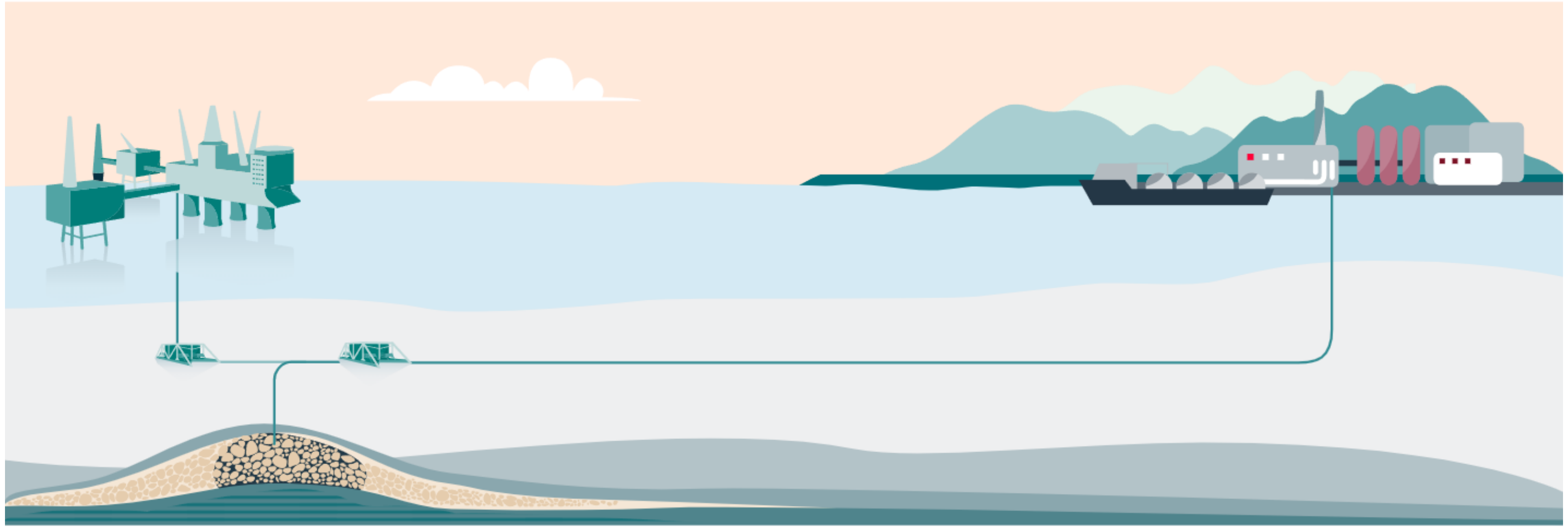


Source: CO_2 storage data based on CO2StoP (2020), European CO_2 storage database, CO_2 Storage Potential in Europe (CO2StoP).

IEA 2020, Special report on CCUS

Longship project

- Industrial CCS storage project
- Open access infrastructure: storing significant amounts of CO2 from across Europe
- More than 20 years experience for CCS in Norway
- Subsidies for capital and operational costs by the government



https://www.equinor.com/energy/northern-lights

Longship project

- Waste incineration plant
- Capture of 400kt CO_2/ year
- 200kt removed from atmosphere

- Cement manufacturing
- Capture of 400kt CO_2/ year

https://ccsnorway.com/capture-fortum-oslo-varme/

https://ccsnorway.com/capture-norcem/

CO2RYLUS

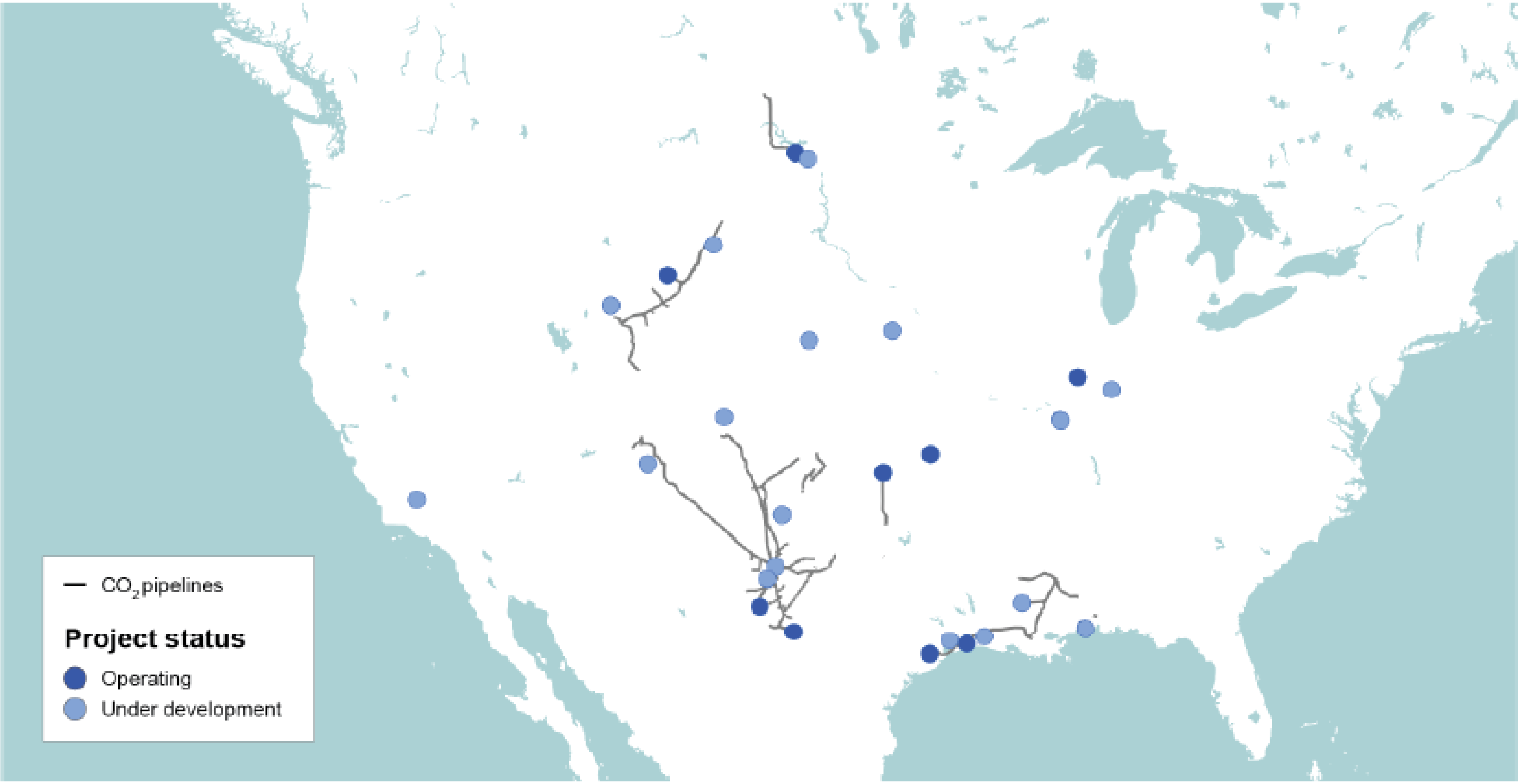
https://geoexpro.com/europes-first-full-scale-onshore-co2-storage-project/

Governmental priorities for CCUS projects

- Create conditions for investment -> put a value on reducing emissions and direct support for CCUS projects
- Development of industrial hubs wit shared CO_2 infrastructure
- Identify and encourage development of CO_2 storage in key regions
- Innovations to reduce capture cost

IEA 2020, Special report on CCUS

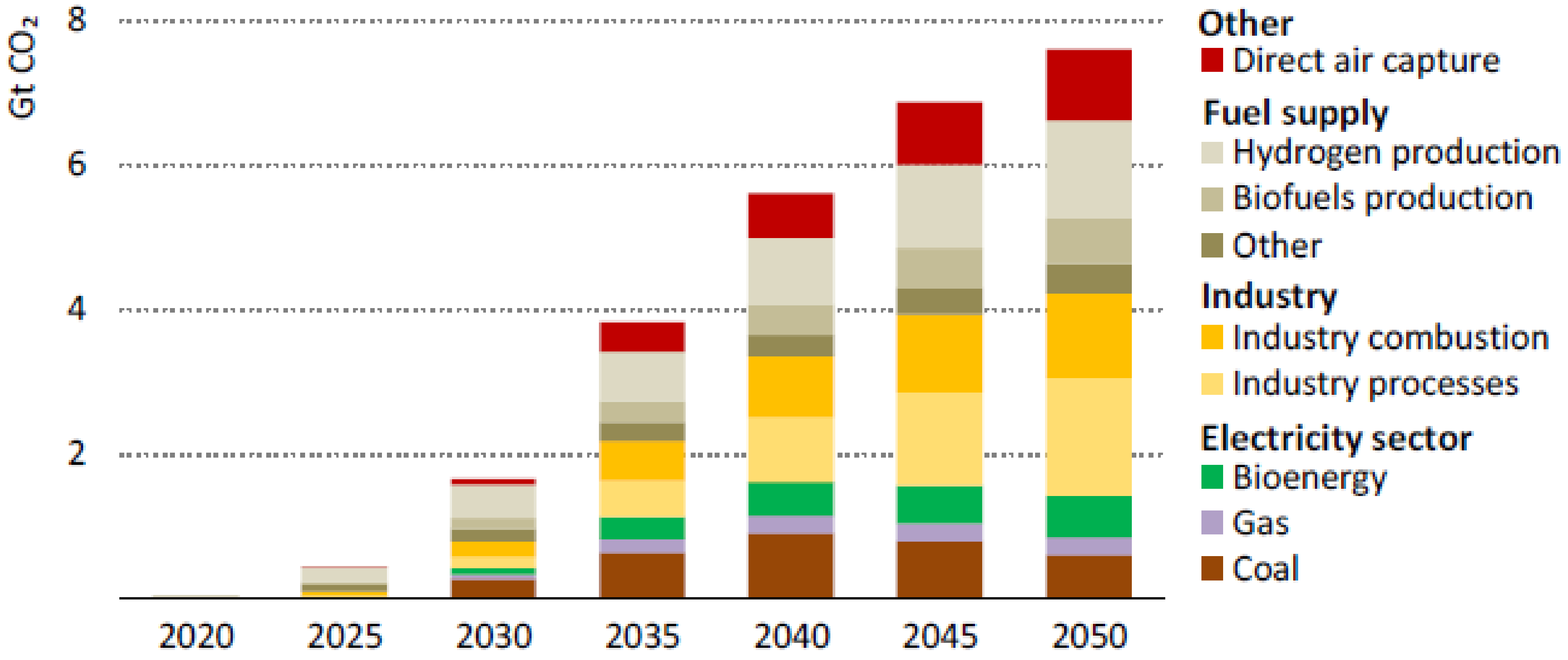
CO_2 transport in the USA



Source: Transport infrastructure based on Edwards, R. and Celia, M. (2018), Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States.

IEA 2020, Special report on CCUS

Outlook



IEA 2021 Net Zero by 2050

3. Positive and negative aspects
Causal loops
Costs

Pros and Cons of CCUS

Pros

- Reduction of GHG emissions from existing processes
- Compensation of remaining emissions in the future
- CO_2 source for fuel and chemical production

Cons

- Almost no commercial interest without incentives or emission penalties
- Shift of climate change mitigation into the future
- Cause for further usage of fossil fuels
- Concerns about escape of stored CO_2

Carbon budget

Carbon Budget: The cap on total greenhouse gas emissions to limit global warming to a certain temperature threshold (e.g., 1.5°C or 2°C).

Calculation --Estimation Basis: Derived from the linear relationship between cumulative CO_2 emissions and the global temperature increase.

Remaining Budget for 1.5°C Goal

Starting Point (2020): Approximately 400 gigatonnes(Gt) of CO_2 (67th percentile).

Current Estimate: Roughly 183 Gt CO_2 remaining (Source: Mercator Research Institute on Global Commons and Climate Change (MCC)).

Probabilistic Nature

Probability vs. Uncertainty: The budget reflects the likelihood of staying within the temperature target, rather than a fixed uncertainty margin.

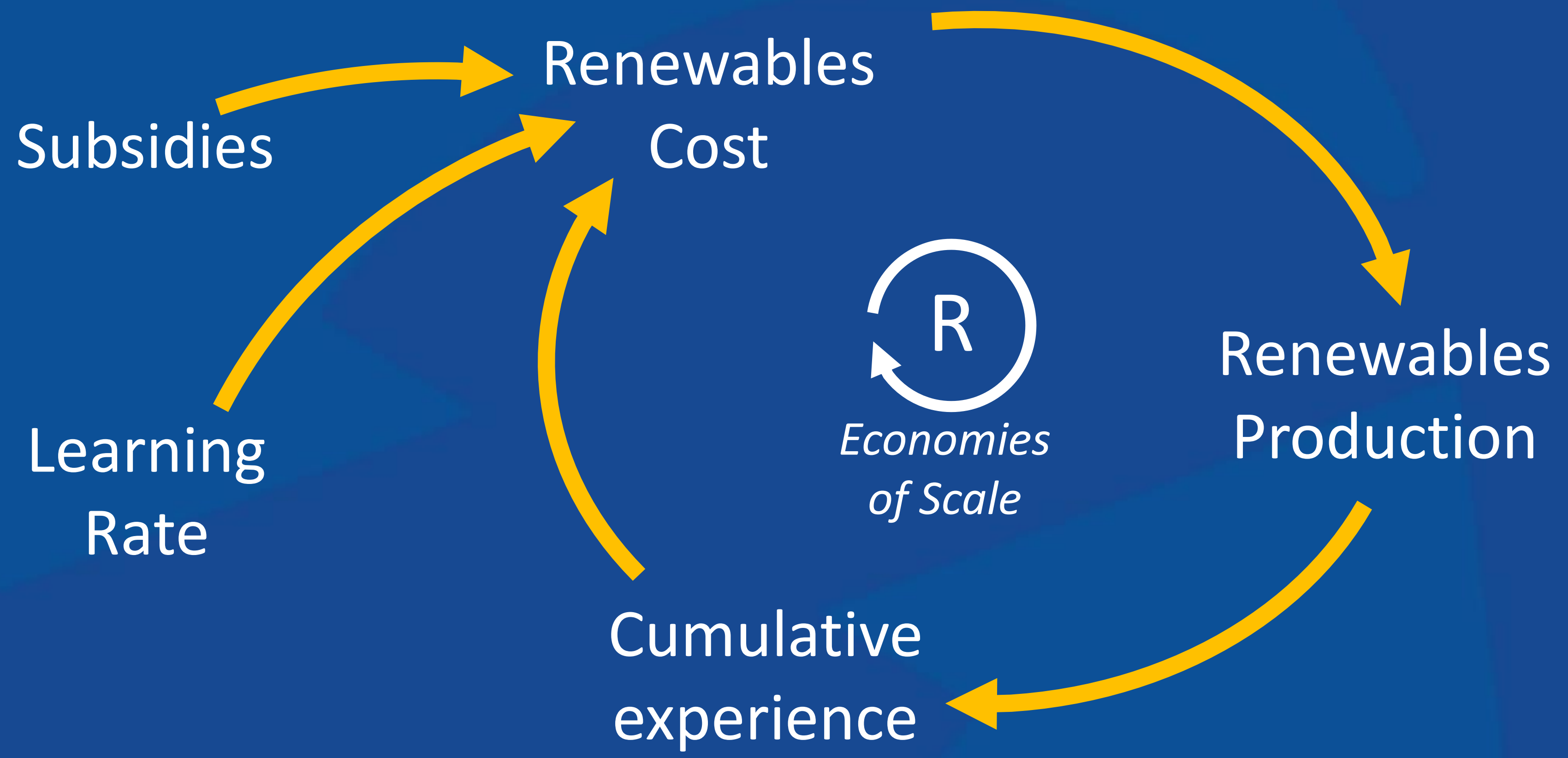
Budget Longevity

Emissions Rate Dependence: The duration of the remaining budget varies based on current and future rates of greenhouse gas emissions.

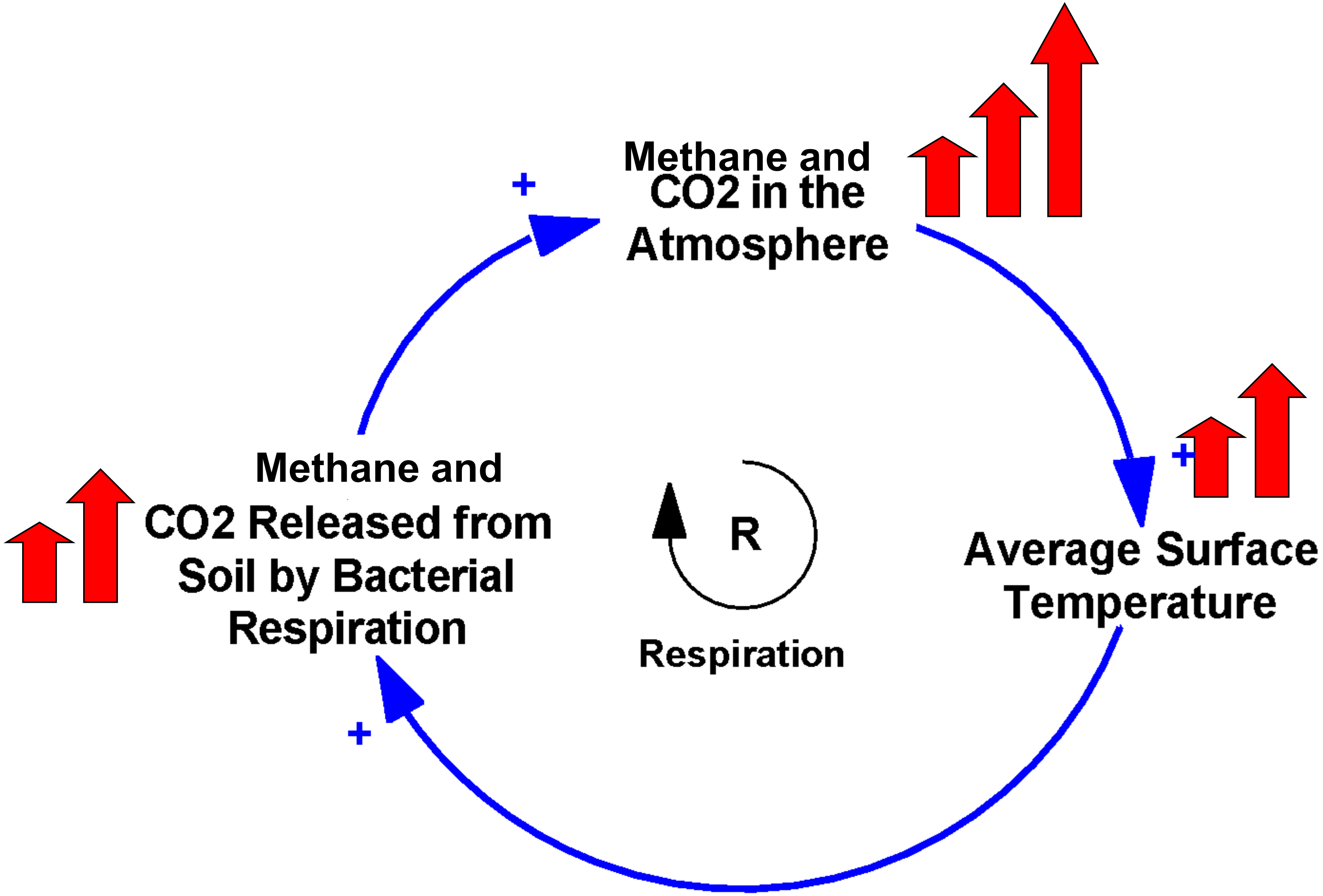
Mitigation Pathways: Different strategies and policies will alter the time frame of the carbon budget.

External Factors: Unanticipated events, like the COVID-19 pandemic, can affect emissions and thus the carbon budget lifespan.

Subsidies externally reduce price and *increase growth* in the loop

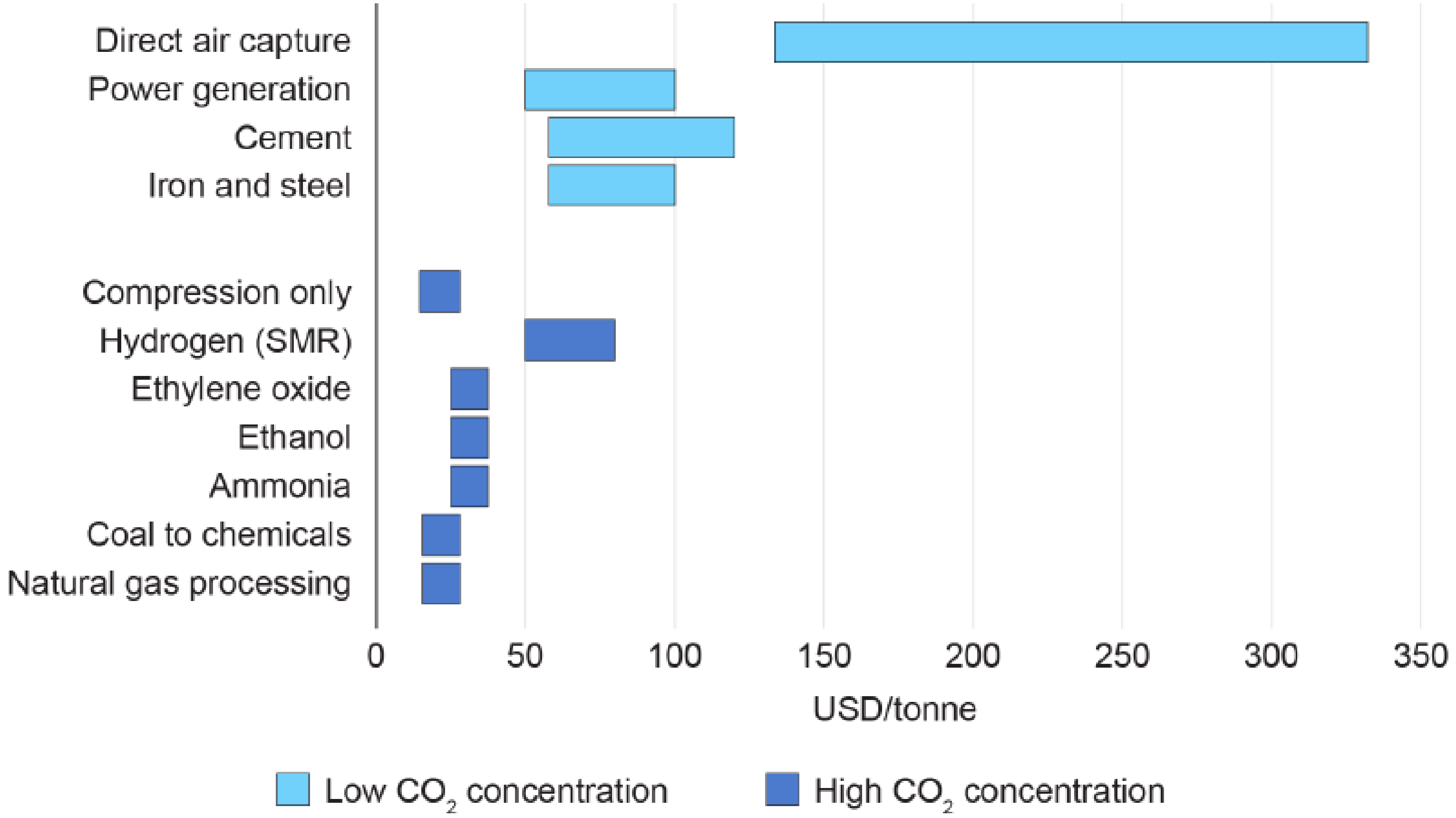


Reinforced feedback



3. Costs of carbon capture

Capture cost



IEA 2020, Special report on CCUS

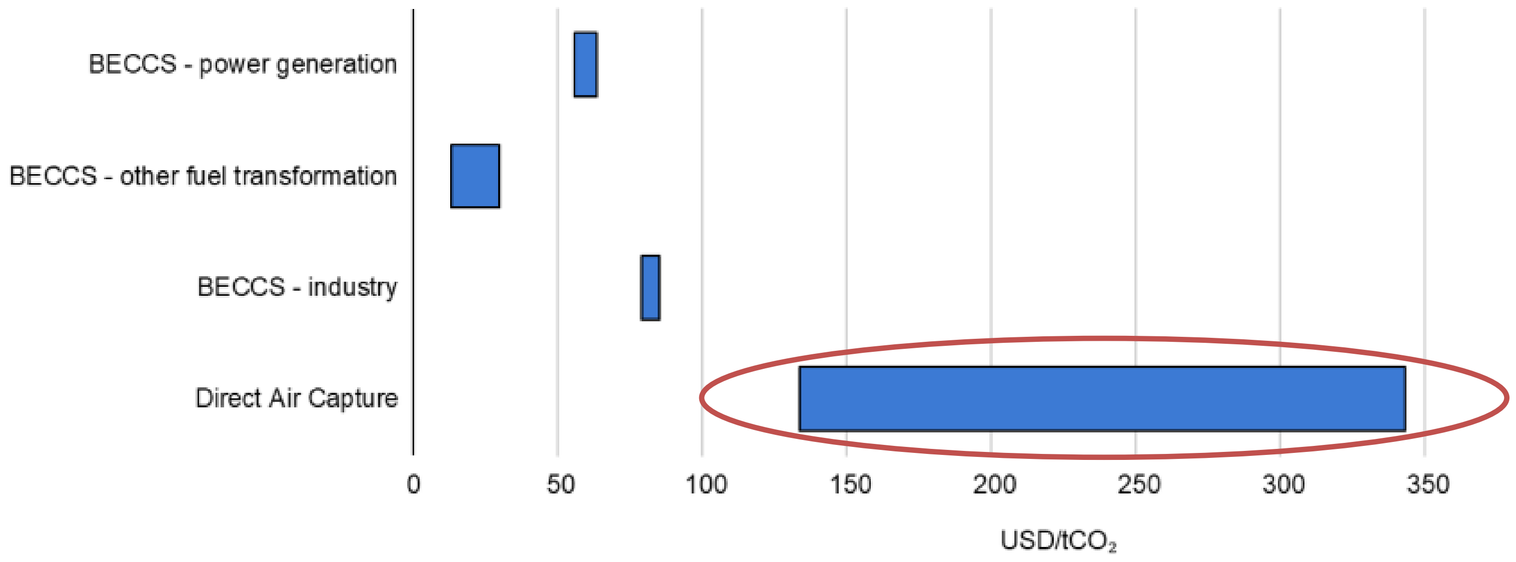
Capture cost

Capital and operational fix costs

Energy costs

$$C_{DAC} = \frac{C_C + C_{OF}}{t_{CO_2}} + c_{var} + DAC_{ele.in} * c_{ele} + DAC_{th.input} * c_{th}$$

Variable costs



Notes: CO_2 capture costs are based on the following assumptions: technical lifetime = 25 years; representative discount rate = 8%; the price of fuel = USD 7.50/GJ; the price of electricity = USD 6.7/GJ. BECCS applied to industrial processes is based on chemical absorption.

Sources: EASAC (2018), Fuss et al. (2018), Haszeldine et al. (2018), Keith et al. (2018), Realmonte et al. (2019).

IEA 2020, Special report on CCUS, Fasihi et al. 2019

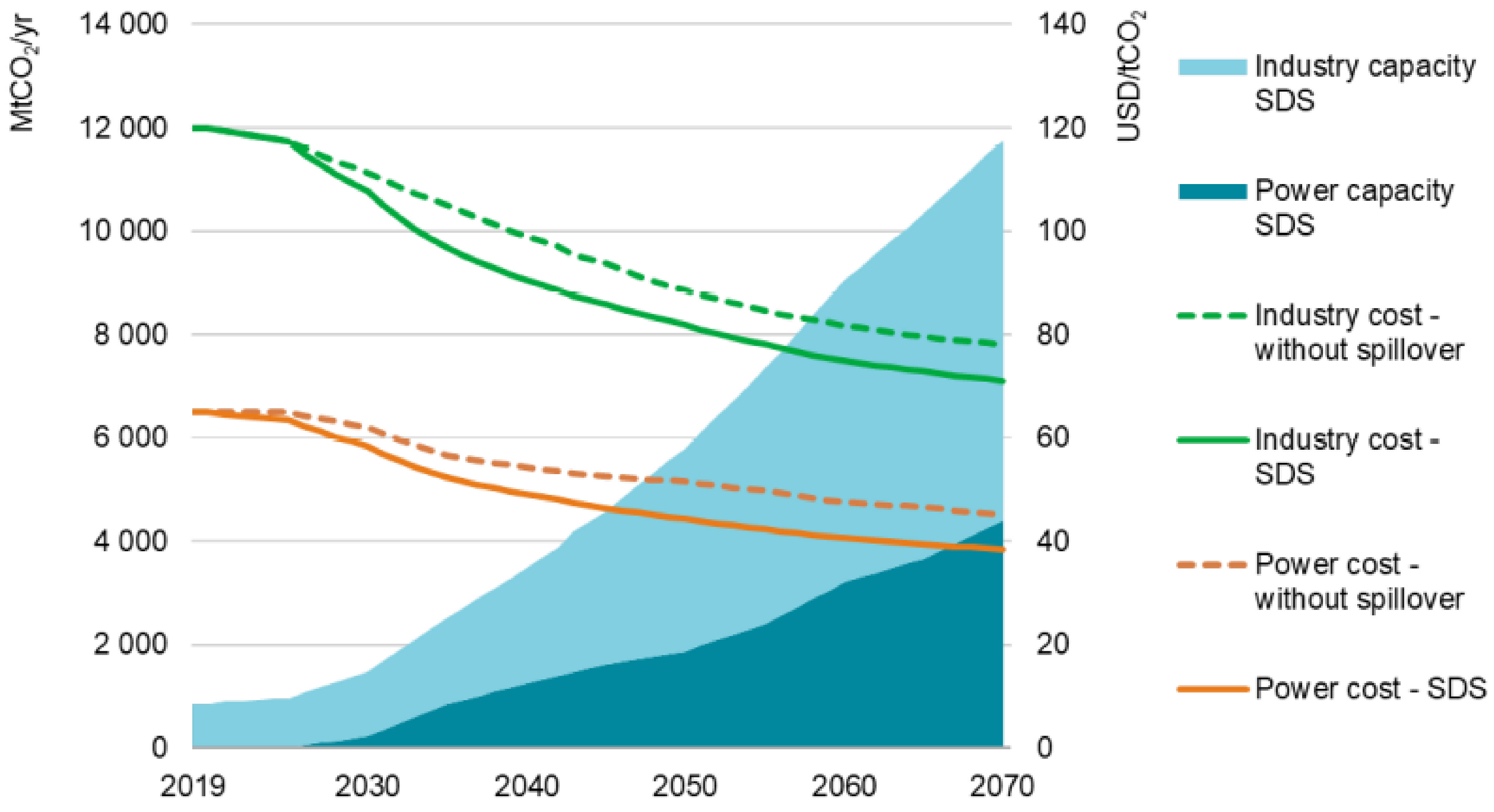
Energy demand and costs

Biogas upgrading	Water scrubbing	Amine scrubbing	PSA	Membrane
Methane recovery	98%	99.9%	98%	99.5%
Energy demand [kWh/Nm³]	0.2-0.5	0.05-0.18	0.16-0.43	0.18-0.35
Temperature level		120-160°C		
100 Nm³/h	5060	4765	5220	3810
250 Nm³/h	2760	2510	2710	2450
500 Nm³/h	1750	1760	1860	1860

Fajrina et al. 2023

Direct air capture	Solid-DAC	Liquid-DAC	PSA	Membrane
Electricity demand [MWh/ton CO2]	0.22-0.6			
Heat demand [MWh/ton CO2]	1.11-3.27			
Temperature level		900		

Cost reductions for the sustainable development scenario



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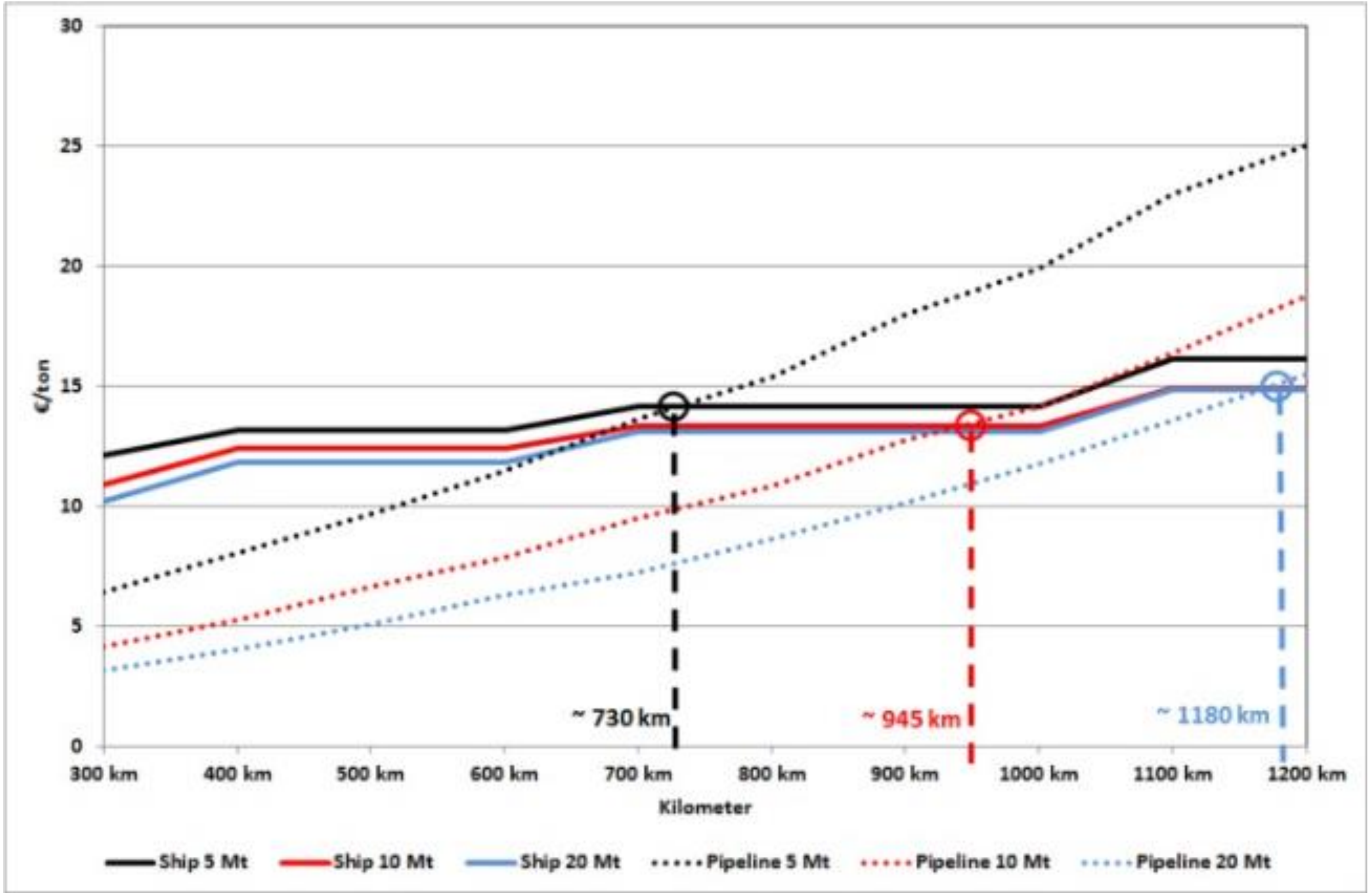
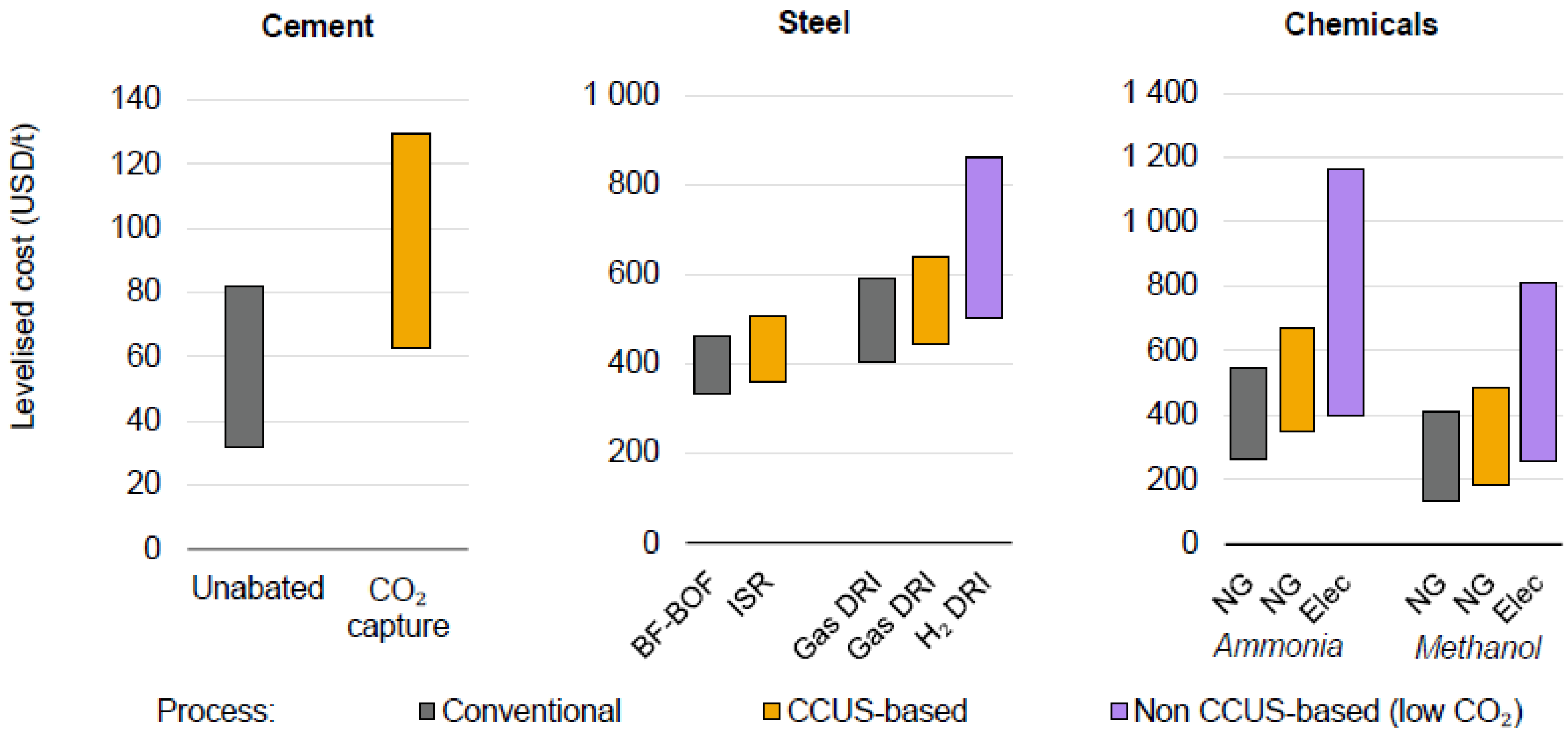
CO_2 transport cost



Kjärstad et al. 2016

Cost increase of products



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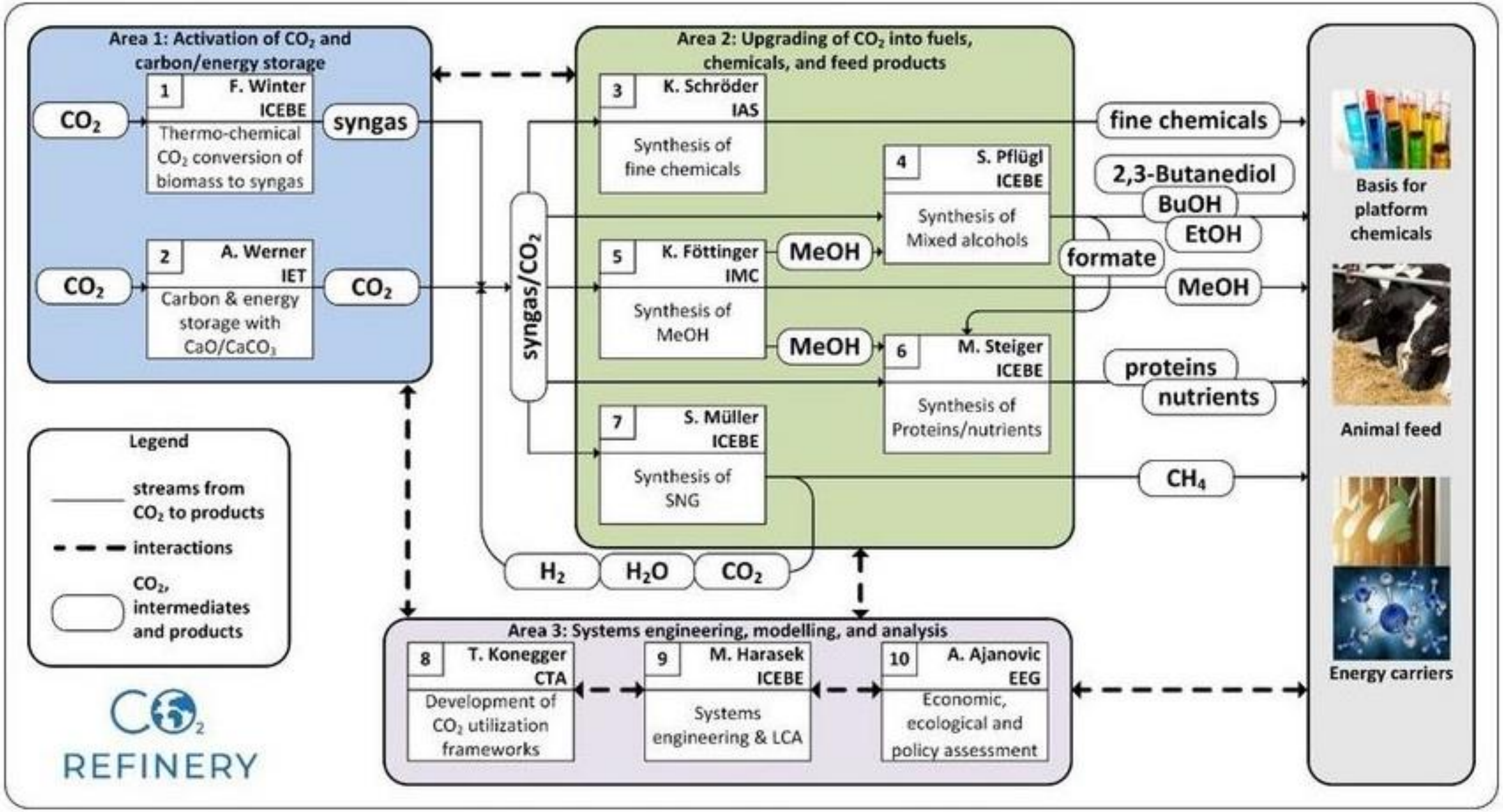
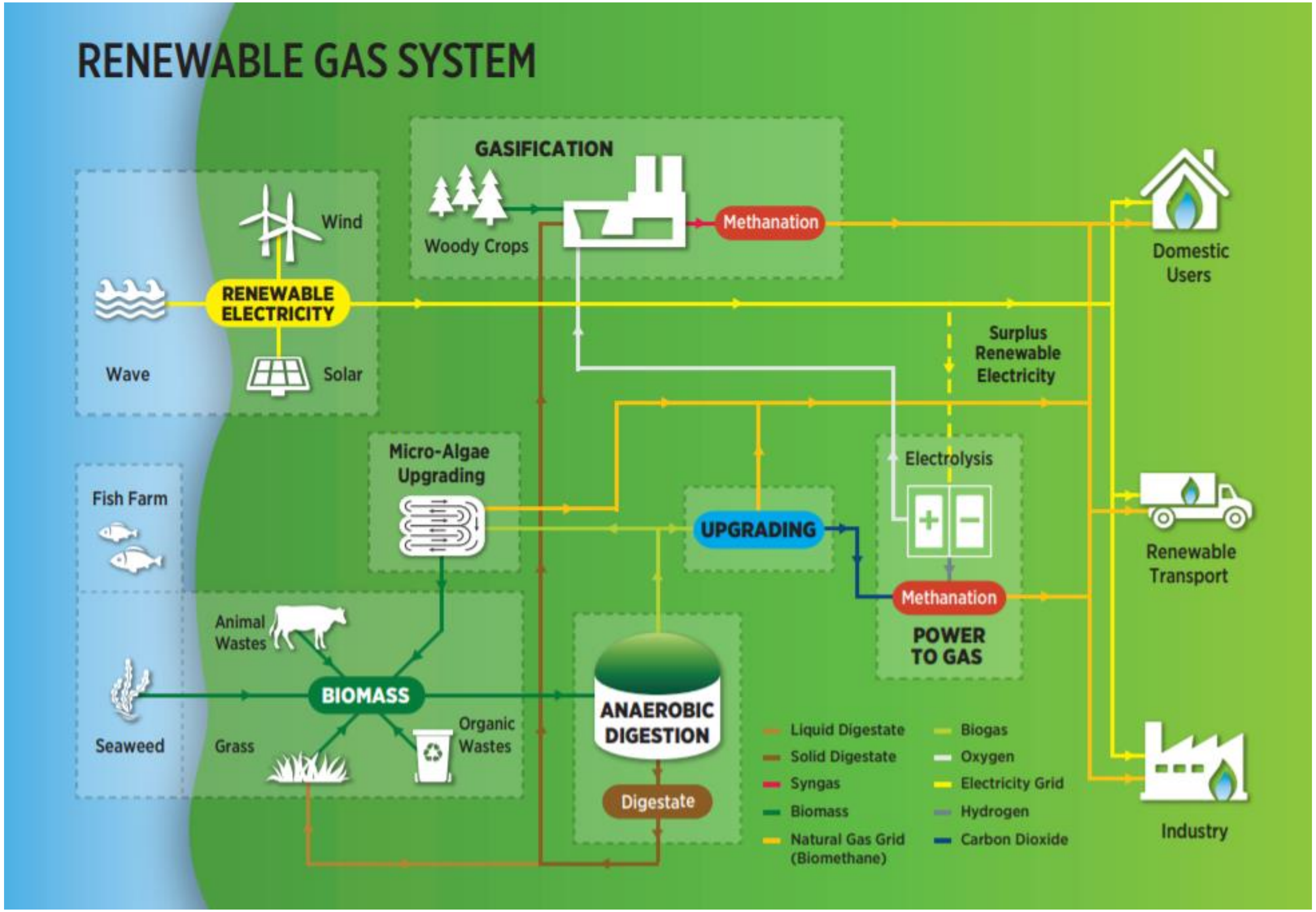
4. Selected CCU applications

E-Methanol and synthetic natural gas

CO2Refinery

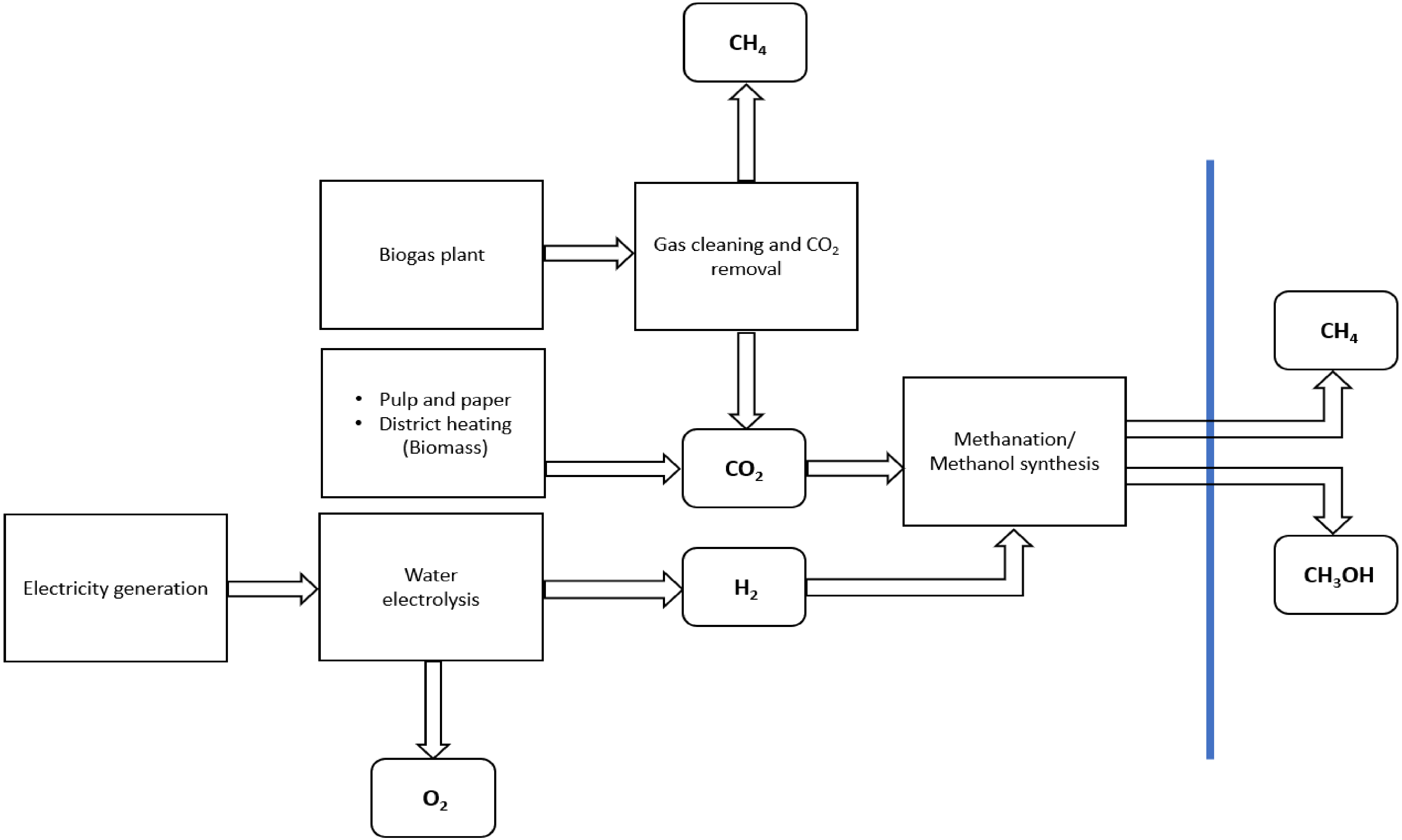


Renewable gas system



Source: Green Gas Brochure, www.MaREI.ie

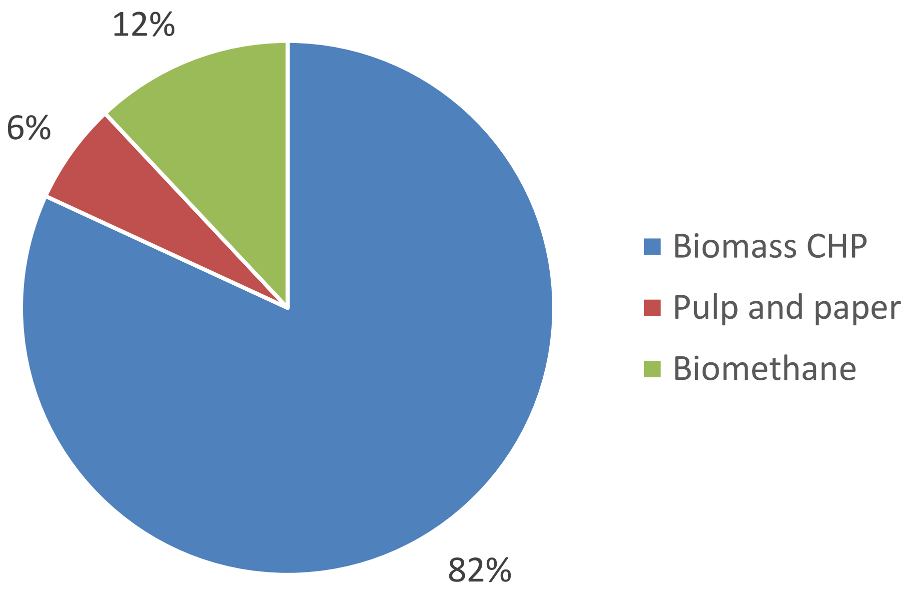
Process chains



Biomass-derived CO_2 potentials in 2030

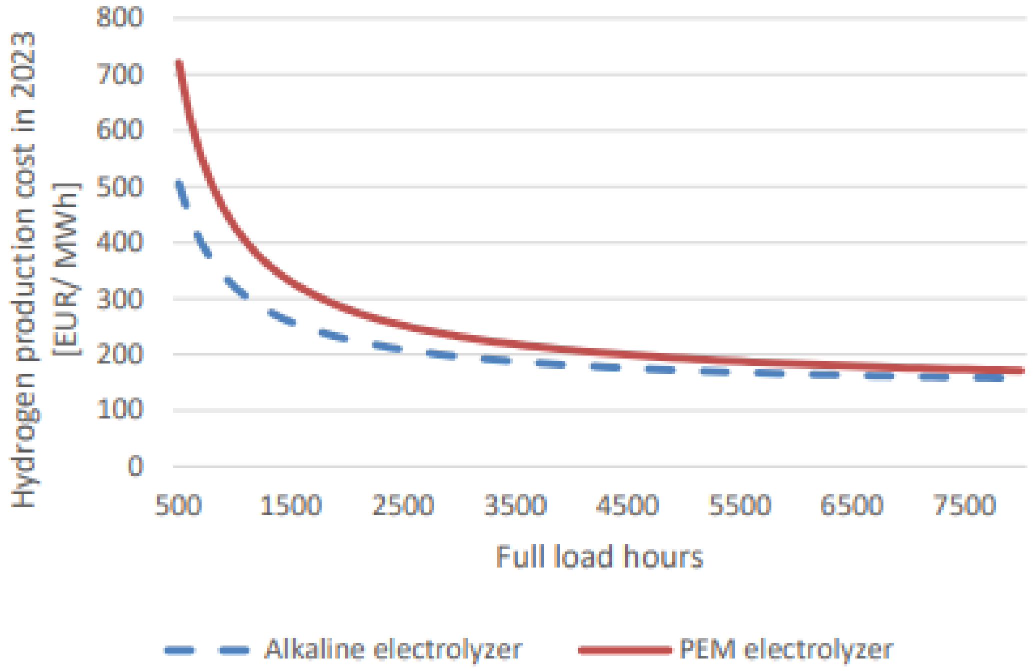
- Target of 35 bcm biomethane
  - 41-69 Mt CO_2/ a
- Pulp and paper
  - 25 Mt direct CO_2 emissions
- 99 Mtoe of solid biofuels for heating and electricity
  - 354-396 Mt CO_2/ a

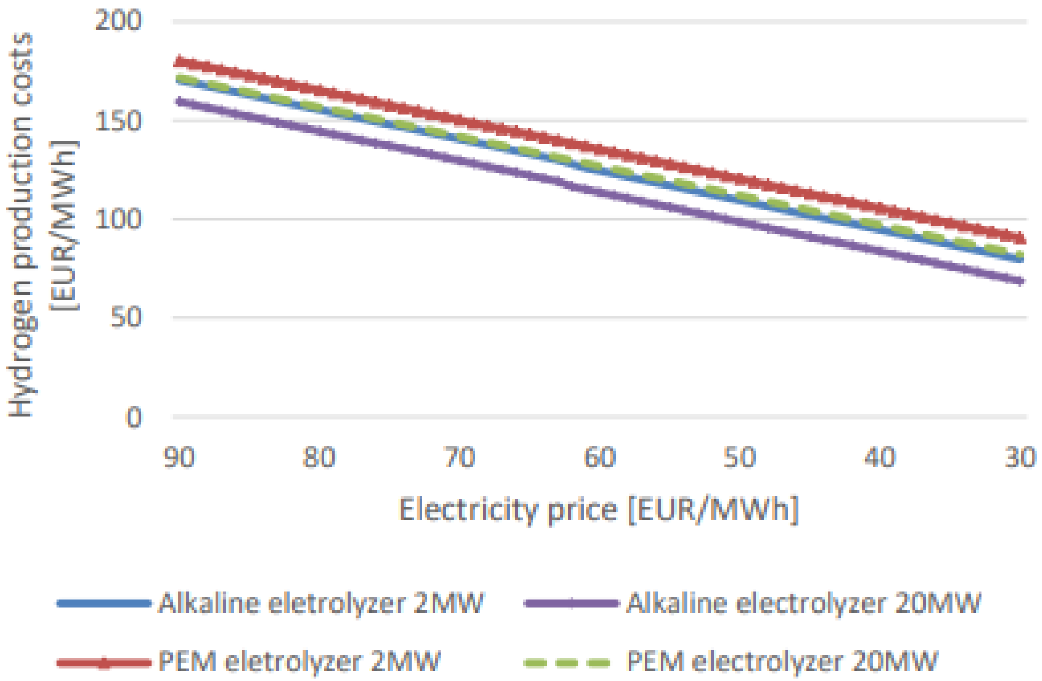
- Total: 420- 490 Mt CO_2/ a



Koytsoumpa et al. 2021, CEPI 2022, https://bip-europe.eu/

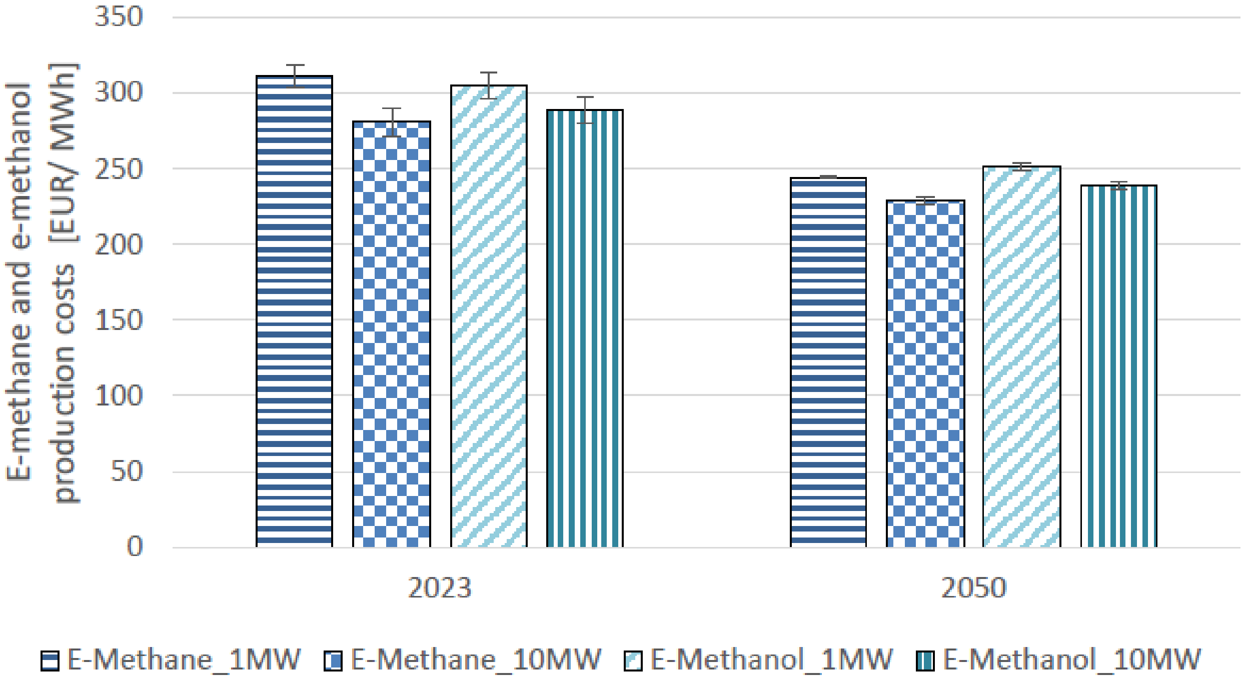
Hydrogen production costs

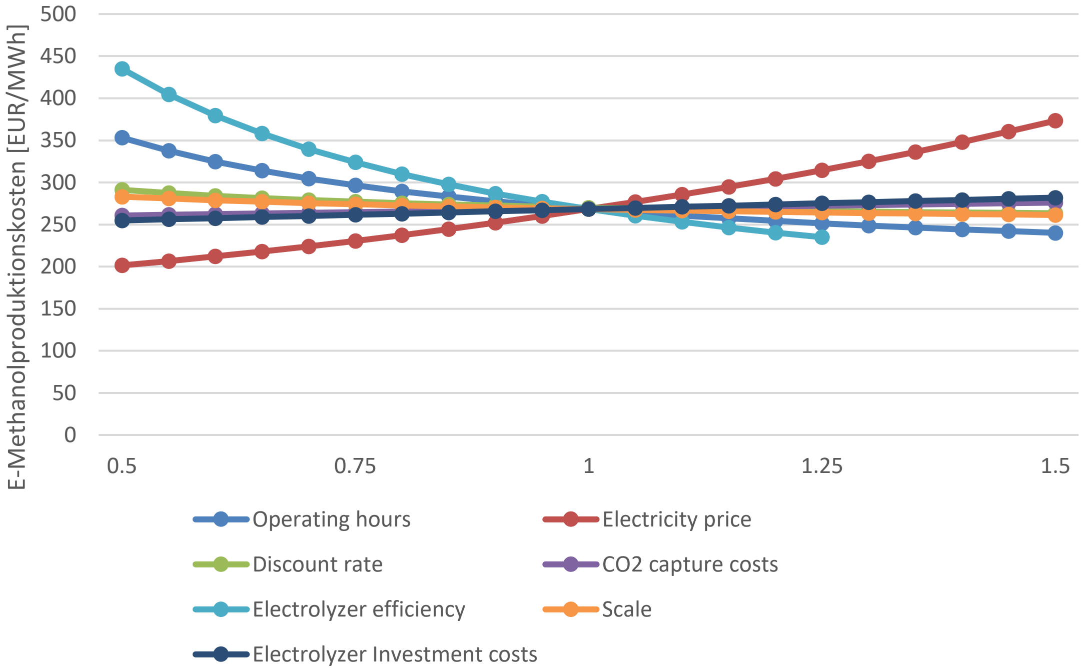




Radosits et al. 2024

Small-scale e-methanol and e-methane



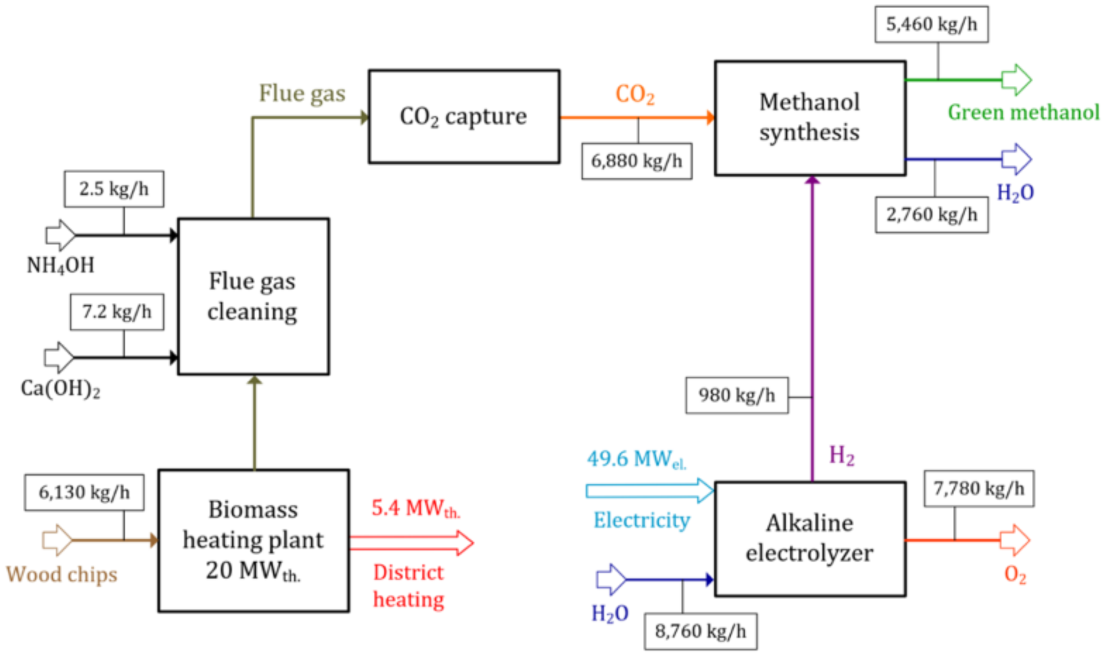


Radosits et al. 2024

Strompreis 90 EUR/MWh,
8000 Volllaststunden

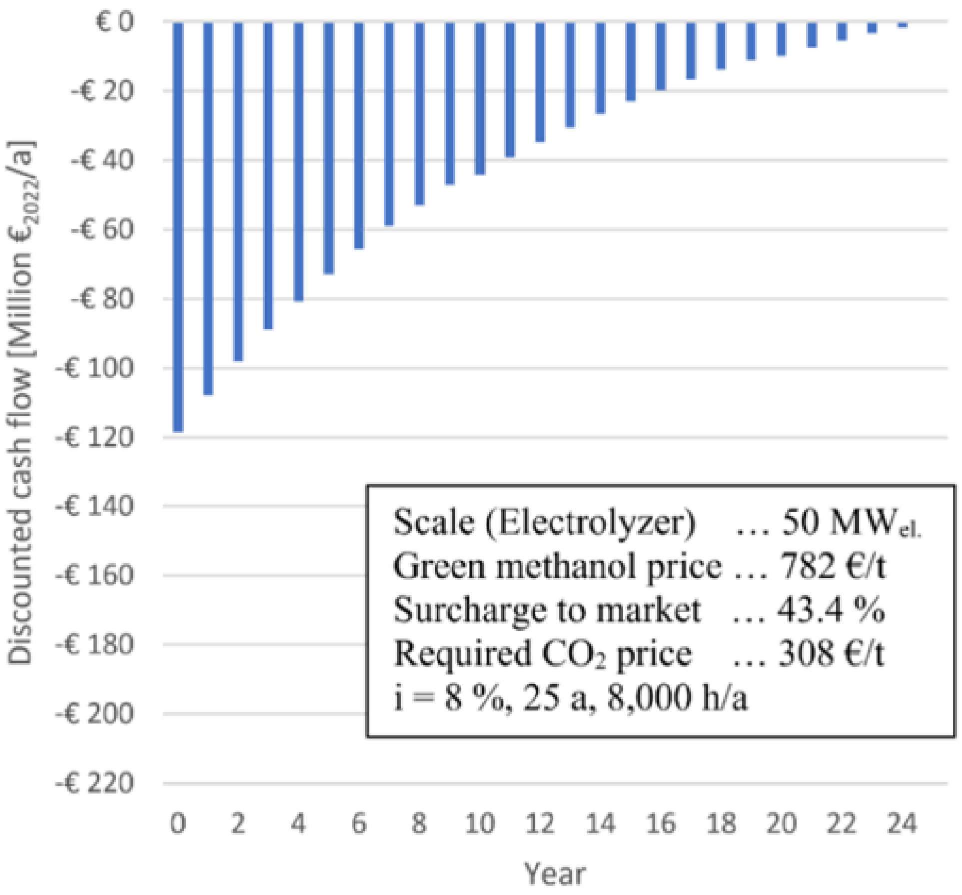
Power-to-green methanol

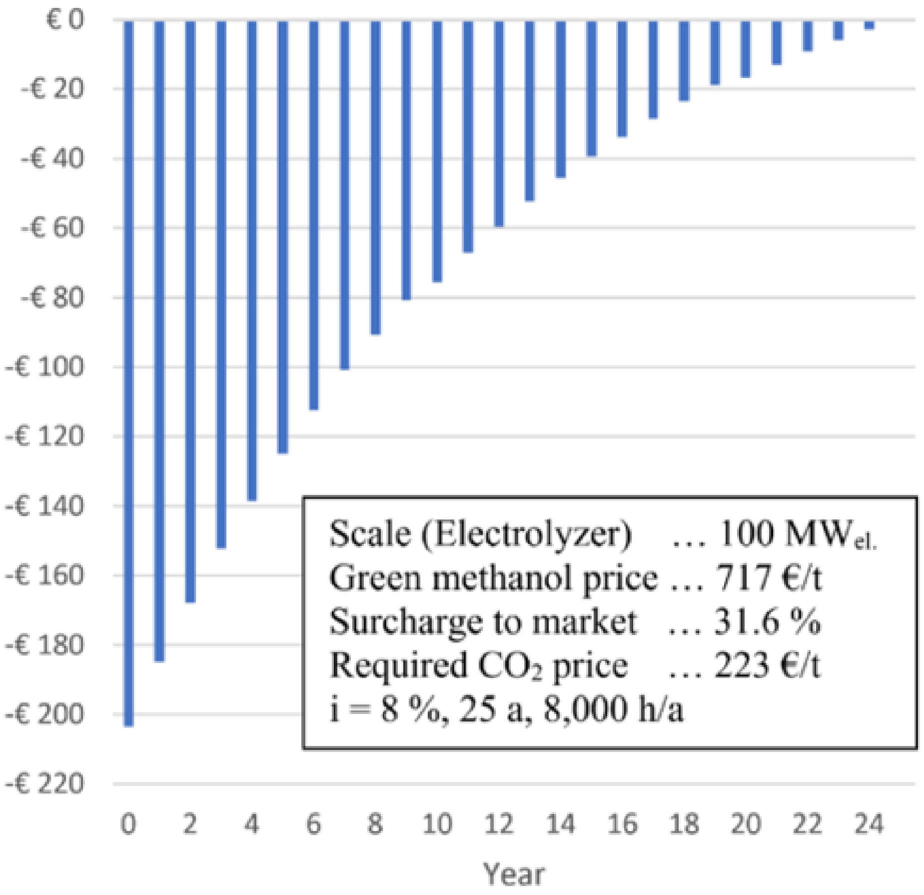
Pratschner et al. 2021



Pratschner et al. 2023

Power-to-green methanol





Pratschner et al. 2023

SWOT-analysis e-methanol

Strengths

High volumetric energy density at room temperature compared to H_2 and e-methane

Very low storage losses

Easy to handle

Weaknesses

Lower energy density than diesel and gasoline

Low overall process efficiency

Combustion engines need to be adapted

Currently high production costs

Opportunities

Methanol terminals are already existing

CO_2 utilization

Platform chemical in the chemical industry

Creation of a new industry in Europe

Threats

Optimization of transport and fueling systems necessary

Higher storage capacities on board needed

Radosits et al. 2024

Conclusions

- Emission reductions of power plants
- Solution for hard-to-abate emissions
- Removing carbon from the atmosphere
- Capture costs depend on the CO_2 concentration, plant characteristics, electricity price, etc.
- Risk of seeing CCUS as miracle solution against climate change.

Sources

Jan Kjärstad, Ragnhild Skagestad, Nils Henrik Eldrup, Filip Johnsson, 2016, Ship transport—A low cost and low risk CO2 transport option in the Nordic countries, International Journal of Greenhouse Gas Control, Volume 54, Part 1, Pages 168-184,

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