Unlocking Tomorrow’s Decarbonization Potential:

A Techno-Economic Assessment of Carbon Capture Diffusion in the European Industrial Landscape

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Agenda

- Motivation
- Research Questions
- Method
- Results
- Conclusion

Unlocking Tomorrow’s Decarbonization Potential:

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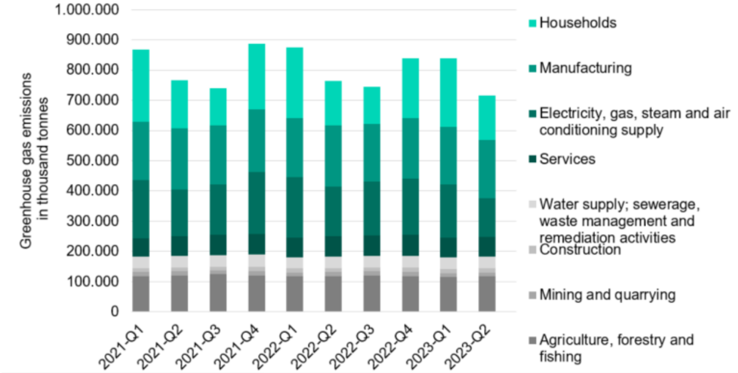
Motivation

- EU points out significance of decarbonizing Industry in European Green Deal
- Industry accounts for 20 % of EU's emissions
- Net zero → account for process emissions

- carbon capture technologies (CCT) to reach climate mitigation goals
- despite urgency, widespread roll-out of CCS remains slower than anticipated (IEA, 2016)
- significant cost of implementing such large-scale facilities
  - → Share costs
  - → Legislative frameworks and policies to support the implementation
- Also unclear, which carbon capture technology is feasible for the respective hard-to-abate industry sector

- Need for a techno-economic assessment of potential future carbon capture technologies in hard-to-abate industry sectors



Greenhouse gas emissions by sector (Eurostat, 2023)

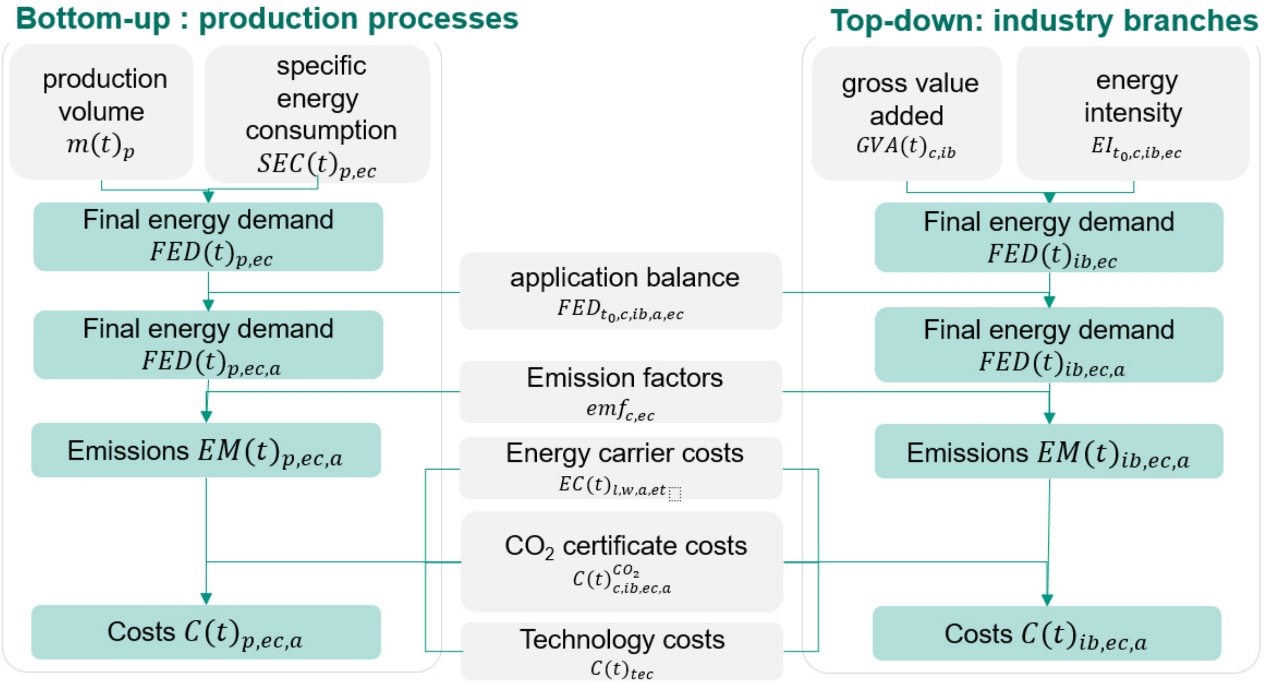
Research Objective

- Extend an industry demand simulation model by competing carbon capture technologies in hard-to-abate sectors
- Implement a discrete choice model

Research Questions/Research Objective

- What is the **techno-economic potential** of employing **carbon capture technologies** across various emission intensive industry sectors?
- How can a **discrete choice model** be effectively utilized to analyze **competition among carbon capture technologies**?

Industry demand simulation model
Model Structure I



Bottom-up : production processes

production volume $m(t)_p$

specific energy consumption $SEC(t)_{p,ec}$

Final energy demand $FED(t)_{p,ec}$

Final energy demand $FED(t)_{p,ec,a}$

Emissions $EM(t)_{p,ec,a}$

Costs $C(t)_{p,ec,a}$

application balance $FED_{t_0,c,ib,a,ec}$

Emission factors $emf_{c,ec}$

Energy carrier costs $EC(t)_{l,w,a,et}$

CO_2 certificate costs $C(t)^{CO_2}_{c,ib,ec,a}$

Technology costs $C(t)_{tec}$

Top-down: industry branches

gross value added $GVA(t)_{c,ib}$

energy intensity $EI_{t_0,c,ib,ec}$

Final energy demand $FED(t)_{ib,ec}$

Final energy demand $FED(t)_{ib,ec,a}$

Emissions $EM(t)_{ib,ec,a}$

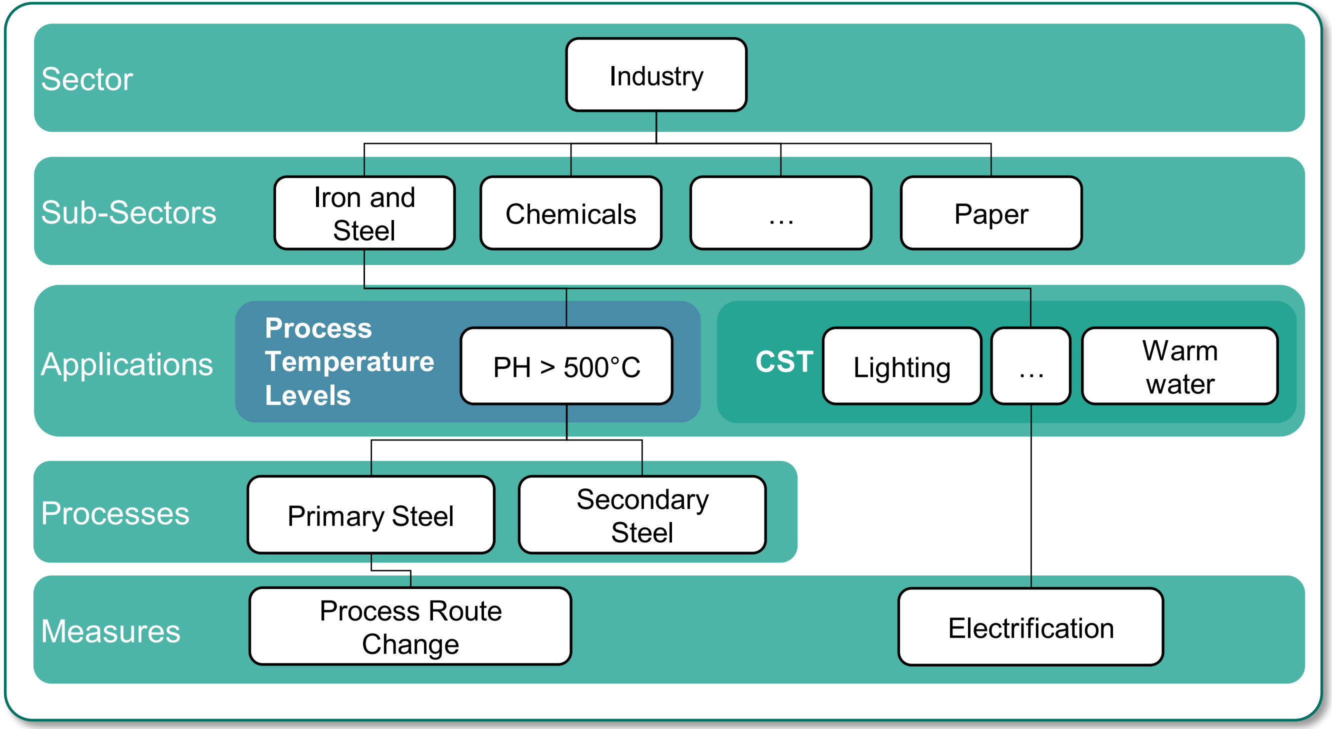
Costs $C(t)_{ib,ec,a}$

Input

Output

Industry demand simulation model
Model Structure II

- **Countries**
  (EU27 +CH, NO, IS, UK, XK, GE, BG, RO, EU candidate countries)
- **Industry Sectors** (13)
- **Processes** (16)
- **Process Temperature** (3)
- **CST** (6)
- **Applications** (13)
- **Energy carriers** (10)
- **Decarbonization Measures** (134)
- **Decarbonization strategies**
  - Reduction of material demand
  - Material efficiency
  - Circular economy and industrial waste
  - Energy efficiency
  - Electrification and fuel switch
  - CCU, CCS and biogeneous raw materials



Industry Structure (own illustration after Fleiter et al. 2018)

Methodology – Discrete Choice Model
Competing Carbon Capture Technologies I

Technology choice

$$MS_j(t) = \frac{\frac{e^{\frac{-lp*c^{CA}}{\overline{c^{CA}}}}}{n_g^{CCTG}}}{\sum_g \sum_{CCTG} \frac{e^{\frac{-lp*c^{CA}}{\overline{c^{CA}}}}}{n_g^{CCTG}}}$$

Carbon avoidance cost

$$c^{CA}(j) = c^{CC}(j) + c^{down}(j) + c^{tr}(j) + c^{seq}(j)$$

Exchange rate

$$er(t)_j \;=\; er_{pr} * MS_j(t)$$

Measure implementation

$$MP(t)_j = af_{pr} * r(t)_{pr} * m(t-1)_{pr} + \left(m(t)_{pr} - m(t-1)_{pr}\right) * er(t)_j$$

$MS_j(t)$	market share of alternative j in %
c^{CA}	carbon avoidance cost in €/t_{CO_2}
n_g^{CCTG}	no. of carbon capture technologies per CCTG (varies per group and process route)
CCTG	Carbon capture technology group (pre-combustion, post-combustion, oxyfuel combustion, looping technologies)
lp	logit parameter
$c^{CC}(j)$	carbon capture cost
$c^{down}(j)$	cost increase due to retrofitting downtime
$c^{tr}(j)$	transportation cost
$c^{seq}(j)$	sequestration cost
$er(t)_j$	exchange rate per technology j
$MP(t)_j$	production volume from measure

Methodology – Discrete Choice Model
Competing Carbon Capture Technologies II

Captured process emissions:

$$CC_j^p(t) = m(t)_j * emf_{pr}^p * cr(j)$$

Carbon avoidance cost of process route:

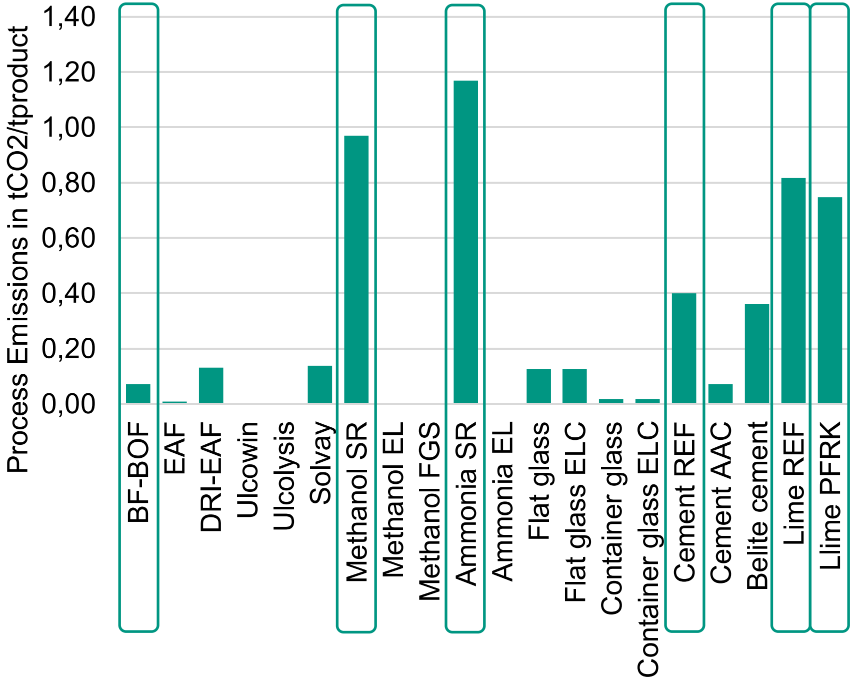
$$c_{pr}^{ca}(t) = \sum_j \left(CC_j^p(t) + CC_j^f(t)\right) * c_j^{CA}(t)$$

Total monetary savings considering CO_2 certificate costs:

$$s^{tca}(t) = \sum\nolimits_j \left(CC_j^p(t) + CC_j^f(t)\right) * (c_j^{CA}(t) - c^{CO_2})$$

$CC_j^p(t)$	Captured process emissions in t_CO2
$c_{pr}^{ca}(t)$	Carbon avoidance cost per process route in €
$s^{tca}(t)$	Total savings (incl. CO_2 certificate costs)
$cr(j)$	Capture rate of CCT
$m(t)_j$	Production volume of CCT

Process Emissions



Process emissions per production route (own illustration from literature data[1])

Process Route	Exchange Rate	Application Factor	Reference
BF-BOF	0.03	0.85	Lerede et al, 2021
Methanol SR	0.04	0.9	Assumption based on (Guminski, 2022)
Ammonia SR	0.04	0.9	Guminski, 2022
Cement REF	0.1	1	Guminski, 2022
Lime REF	0.1	1	Guminski 2022
Lime PFRK	0.1	1	Assumption based on (Guminski, 2022)

Process routes and technological specifications

[1] Guminski, 2022; West, 2020; US Environmental Protection Agency, 2009; Mignard et al., 2003; Ecofys, 2009; Alsalman et al., 2021; Kotsay et al. 2019; Simoni et al. 2022

Carbon Capture Technologies

- **Cement REF, Lime REF, Lime PFRK**
- Monoethanolamine (MEA)
- Oxyfuel
- Chilled Ammonia Process (CAP)
- Membrane-Assisted CO2 Liquefaction (MAL)
- Calcium Looping (CAL)
- Low Emissions Intensity Lime And Cement (LEILAC)

→ 6 CCTs

- **Ammonia SR, Methanol SR**
- Indirect Calcination (IndCalc)
- Oxyfuel
- Monoethanolamine (MEA)
- Vacuum Swing Adsorption (VSA)

→ 4 CCTs

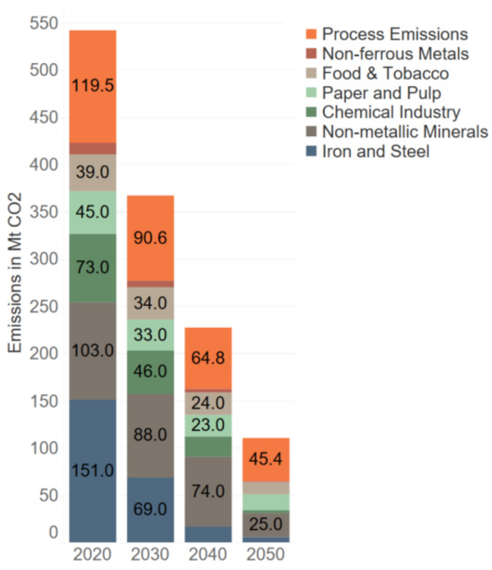
- **BF-BOF steel**
- Pre-combustion capture with chemical absorption (Pre-chem)
- Pre-combustion capture with chemical adsorption (Pre-adsor)
- Sorption Enhanced Water Gas Shift (SEWGS)
- Post-combustion capture with membranes (Post-memb)

→ 4 CCTs

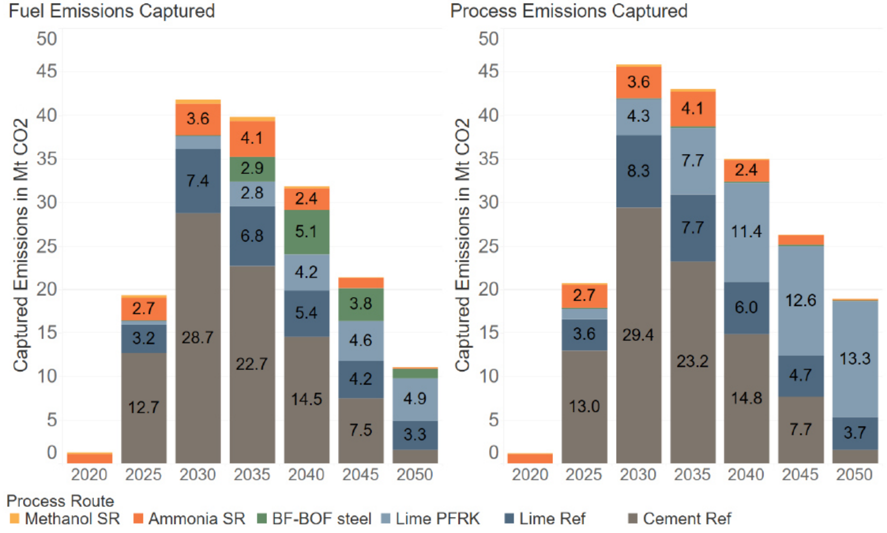
Input Data
Cement REF, lime REF and lime PFRK

CCT	Carbon avoidance cost in $€/t_{CO_2}$	Technology readiness level	Captured CO_2 in %	Reference
MEA	93	4	90	Gardarsdottier et al. 2019, Subraveti et al. 2021
Oxyfuel	58.2	4	90	Gardarsdottier et al. 2019, Yan et al. 2020
CAP	79	6	90	Gardarsdottier et al. 2019
MAL	96.3	6	90	Gardarsdottier et al. 2019
CaL	68.2	7	90	Gardarsdottier et al. 2019
Leilac	39	6	95	Leilac 2021 (Case A3)

Results – Captured Emissions

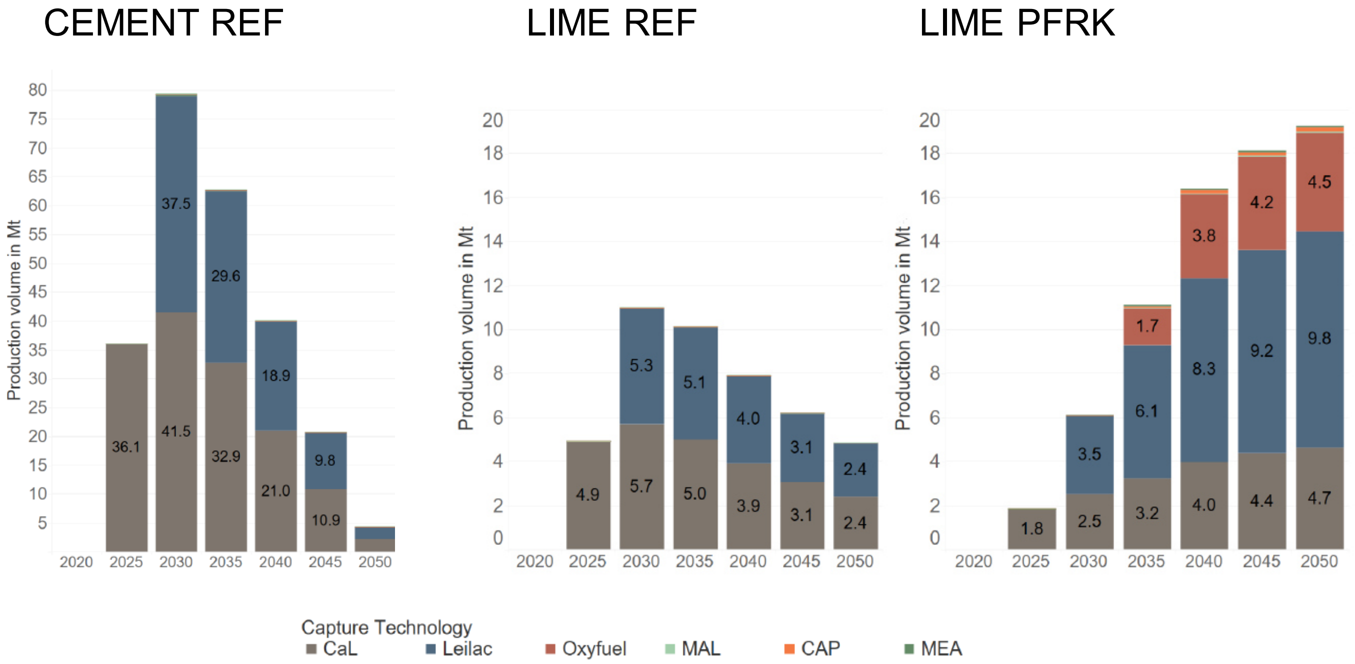


Aggregated process emissions and fuel emissions by sector from bottom-up modelled processes

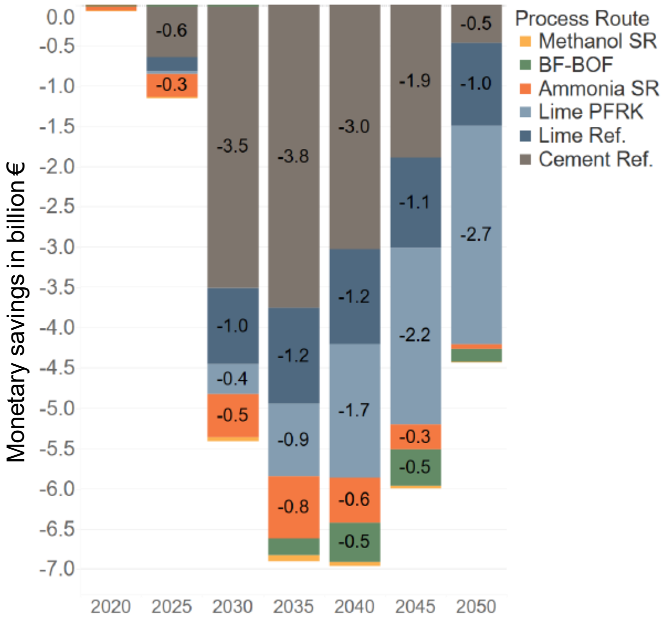


Captured fuel and process emissions by process route

Results – Carbon Capture Technology Diffusion



Potential monetary savings from the deployment of carbon capture



Potential savings in the process routes with carbon capture in billion EUR

Conclusion and Outlook

Conclusion

- Non-metallic mineral industry shows highest carbon capture potential (cement, lime)
- Technology readiness significantly influences the diffusion of CCTs
- Rising CO_2 certificate prices make carbon capture technologies a viable option

Outlook

- Extension of discrete choice model by energy price sensitivity of carbon capture technologies abatement costs and BECCS
- Potential model coupling to consider spatial aspects of transport and sequestration

Thank you!

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Input Data – Carbon avoidance cost

BF-BOF process route:

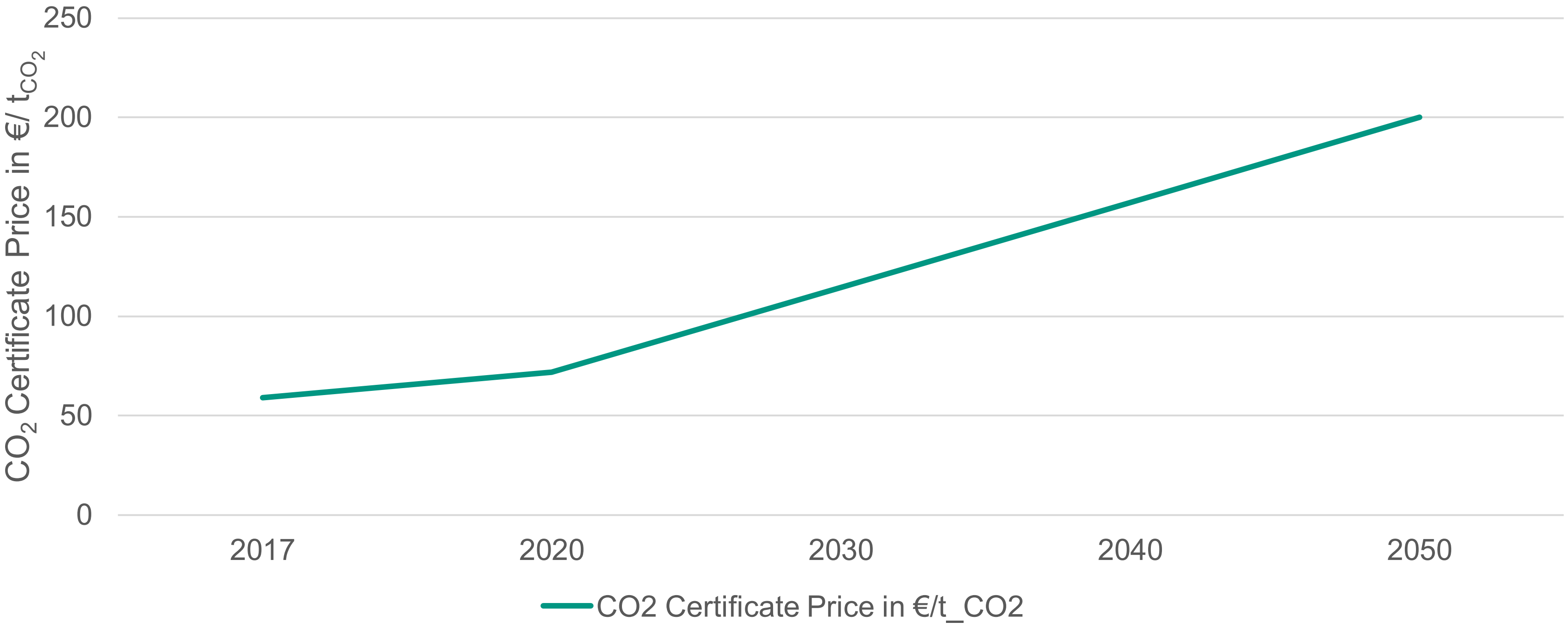
CCT	Carbon avoidance cost in $€/t_{CO_2}$	Captured CO_2 in %	Reference
Pre-chem	76.91	50	Perpiñán et al., 2023
Pre-adsor	71.59	50	Perpiñán et al., 2023
SEWGS	57.85	50	Perpiñán et al., 2023
Post-memb	67.26	50	Perpiñán et al., 2023

Input Data - Carbon avoidance cost

Ammonia and Methanol SR process route:

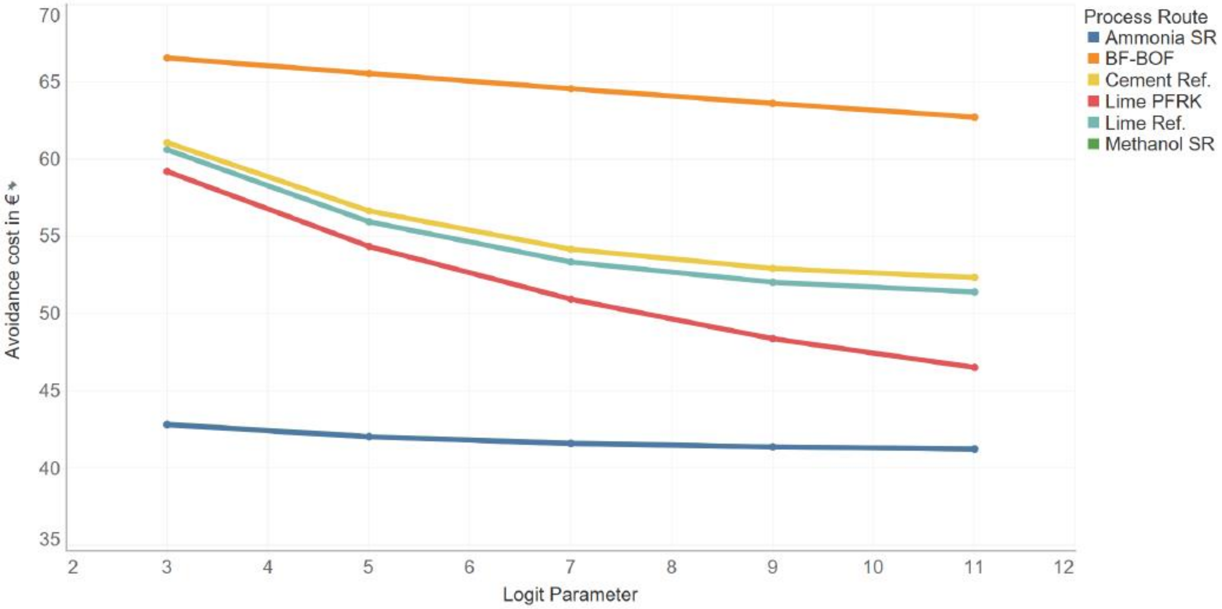
CCT	Carbon avoidance cost in $€/t_{CO_2}$	Captured CO_2 in %	Reference
IndCalc	43.8	61.1	Yan et al. 2020
Oxyfuel	68.1	100	Yan et al. 2020
MEA	40.9	54.4	Subraveti 2021a
VSA	50.3	91.4	Subraveti 2021b

CO_2 Certificate Price



Limitations: Logit parameter

2040



Sensitivity analysis of the avoidance cost per process route to varying logit parameters for the year 2040