Electrifying Post Combustion Carbon Capture:

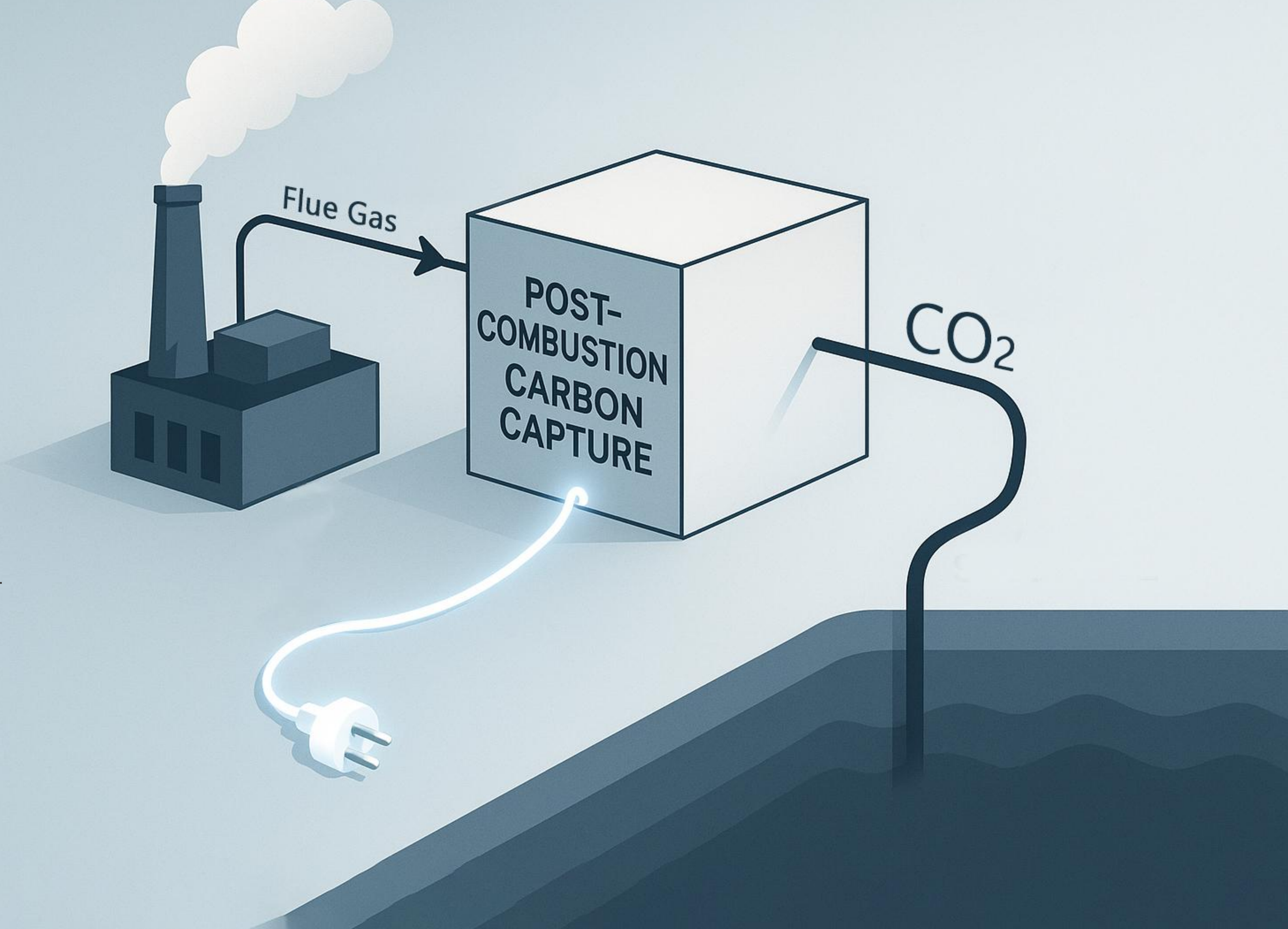
How Future Energy Scenarios Reshape Techno-Economic Performance

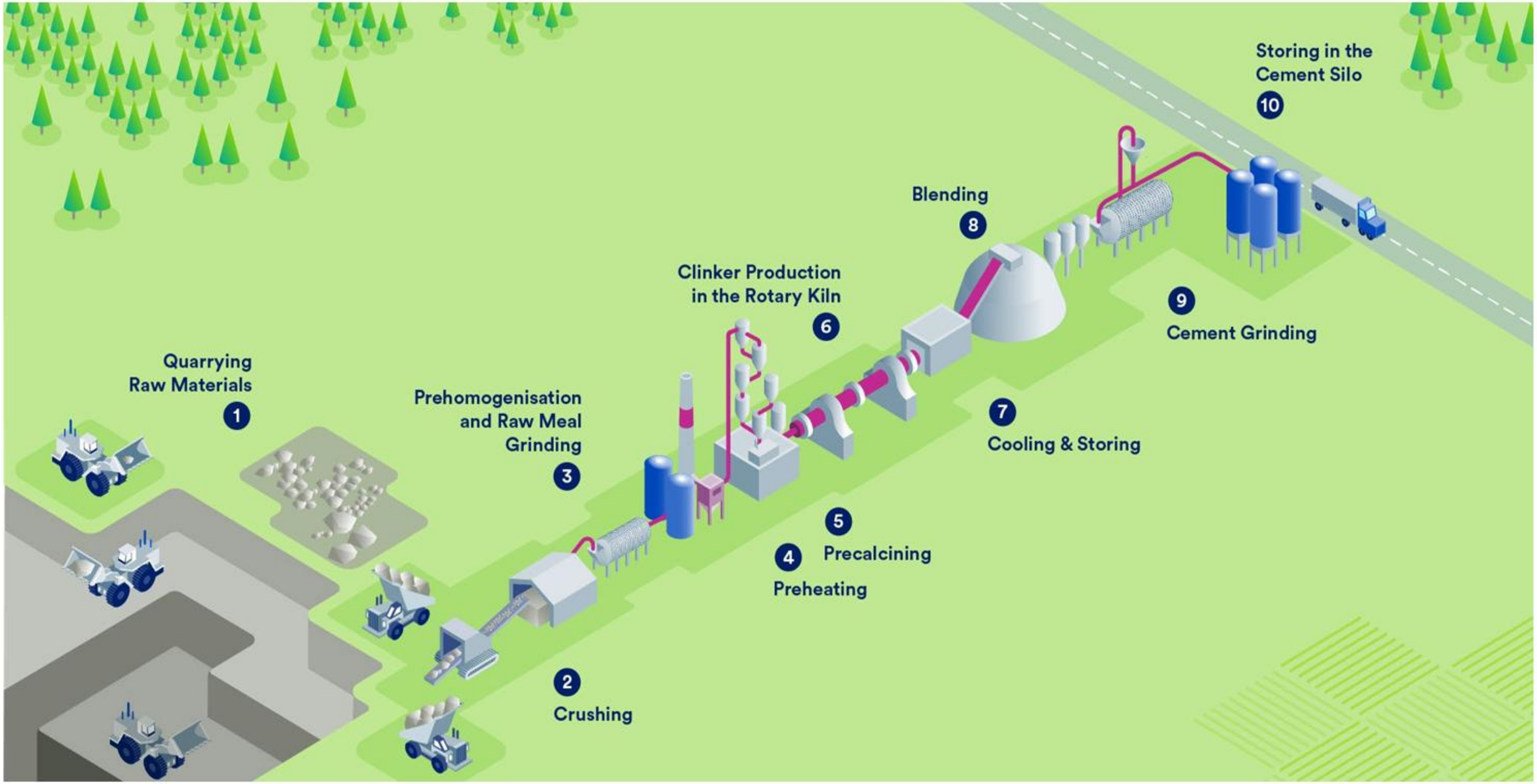
---

Muhammad Salman[a]

Alexis Costa[b], Rafailia Mitraki[a], So-mang Kim[a], Salar Fakhraddinfakhriazar[a], Brieuc Beguin[a], Daniel Flórez-Orrego[c], Guy De Weireld[b], François Maréchal[c], **Grégoire Léonard[a]**

[a] Université de Liège
[b] Université de Mons
[c] École Polytechnique Fédérale de Lausanne





Cement Production Process

https://www.catf.us/resource/role-carbon-capture-storage-decarbonising-europes-cement-sector/

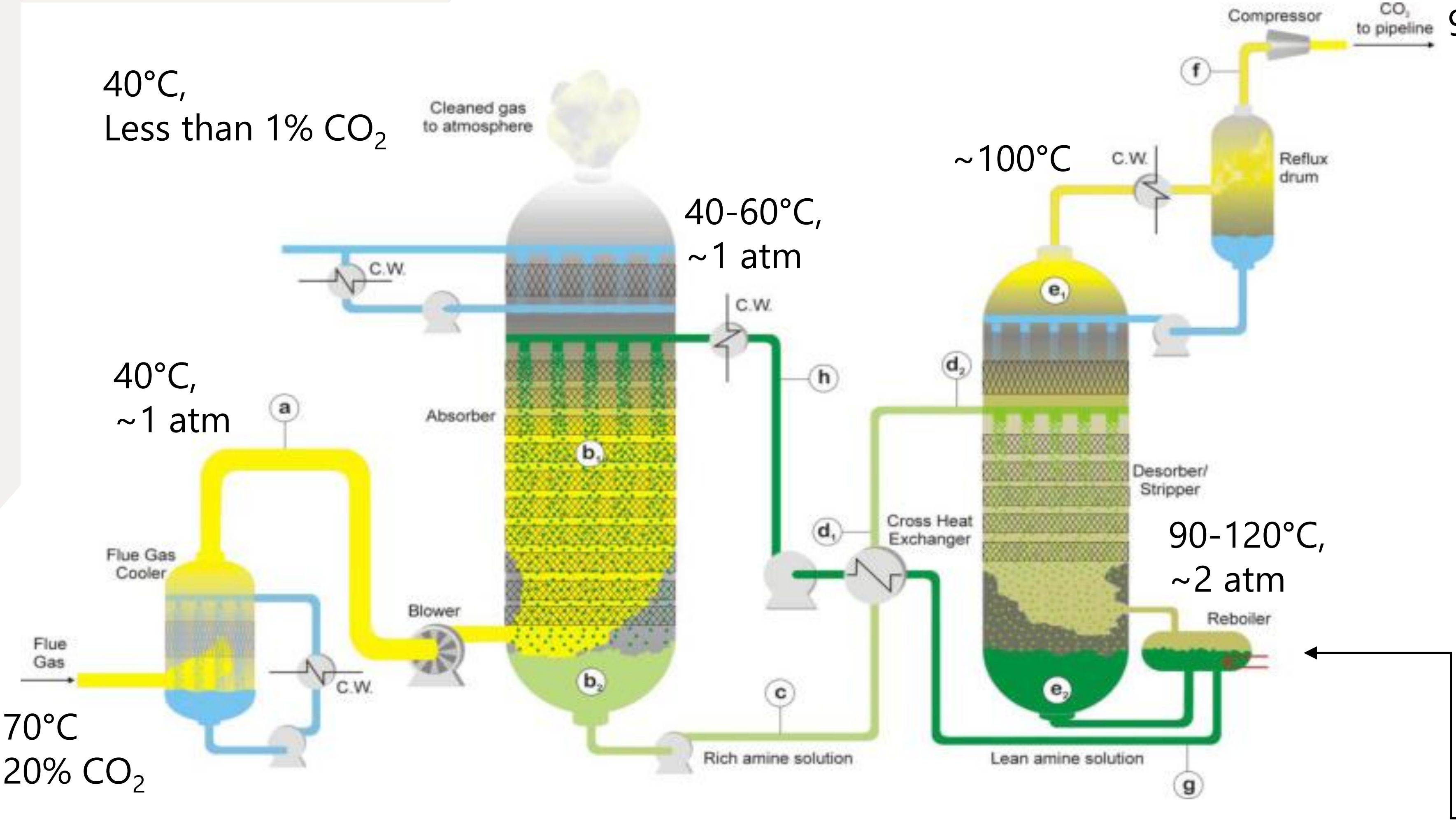
Introduction

- Why Cement?
  - ○ A **hard-to-abate** sector, central to infrastructure and development
  - ○ Responsible for **~7–8% of global CO_2 emissions**
  - ○ Emissions arise from both:
    - Calcination (**process emissions** from limestone decomposition)
    - Fossil fuel **combustion** (heat for kilns)

- What Are the Key Challenges?
  - ○ Highly energy- and carbon-intensive process
  - ○ EU ETS price increases can impact **competitiveness**
  - ○ Risk of **industrial relocation** (carbon leakage & deindustrialisation)

- What Do We Need to Do?
  - ○ Conduct a **systematic evaluation** of various carbon capture options levers
  - ○ **Identify** cost-effective and low-risk options

Post Combustion MEA-based Chemical Absorption Capture



40°C,
97% CO_2

40°C,
Less than 1% CO_2

~100°C

40-60°C,
~1 atm

40°C,
~1 atm

90-120°C,
~2 atm

70°C
20% CO_2

Steam at
~130°C

Fossil fired
steam boiler

This results in
- High Energy needs: ~3.5 GJ/tCO_2

When Integrated with a cement plant:
- 27% higher Cement cost
- 47% higher total energy
- When fossil fired, increase capture size

Solvent: 70%$_w$ water + 30%$_w$ MEA

Sanpasertparnich et al. (2010)

Why Electrify?

- **Electrification** is emerging as a **key pathway** for industrial **decarbonisation**.
- Beyond direct process electrification, **carbon capture itself can be electrified**.
- Fully electrified capture **avoids fossil fuel use** and eliminates additional emissions.
- Electrification lowers the **energy penalty** of capture systems.
- With **renewable electricity**, emissions are further reduced while supporting flexibility and integration with intermittent supply.

Questions

1. What are the options for electrification of PCCC?

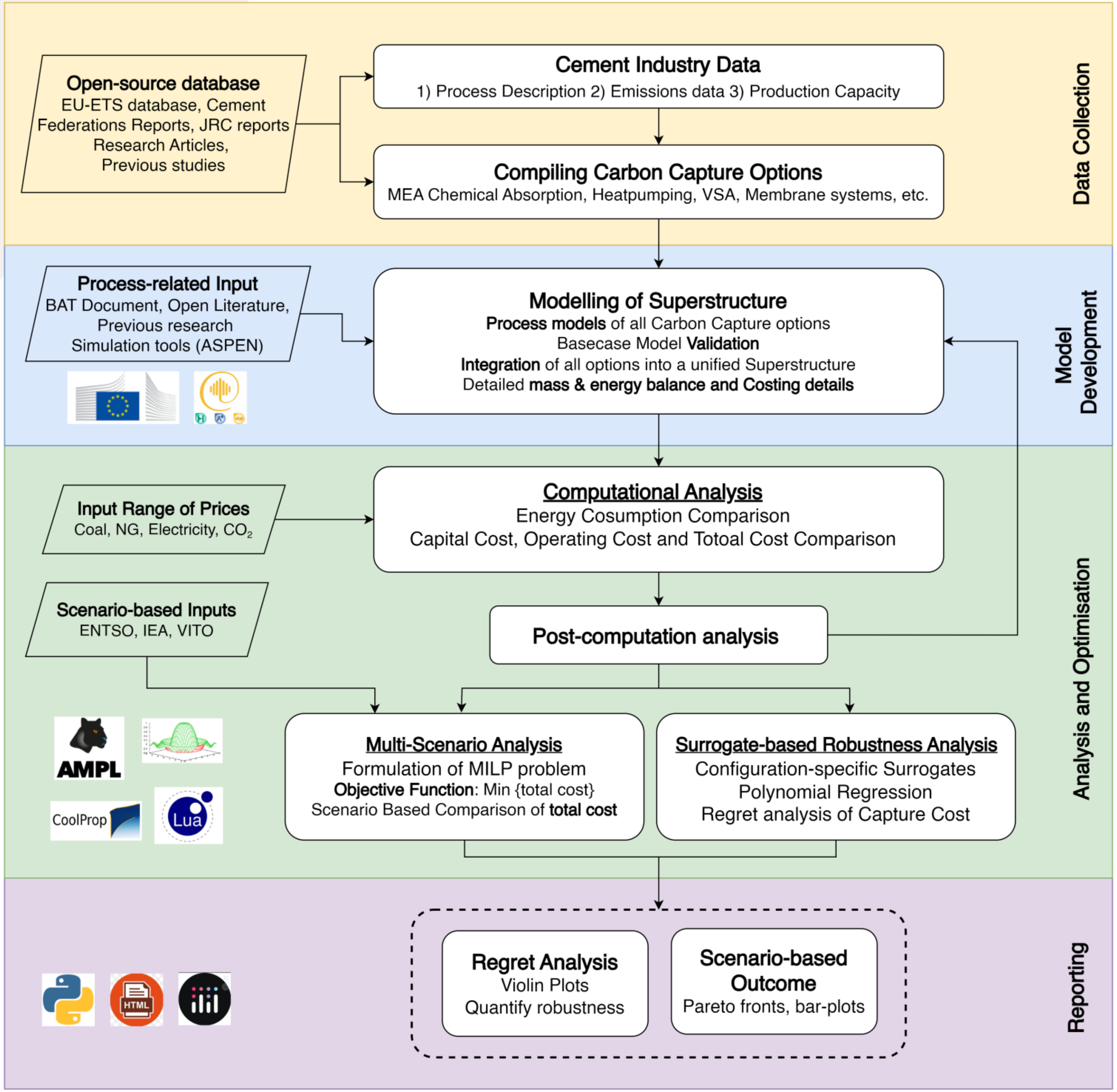
2. Can these options compete with conventional CC-MEA from a techno-economic point of view?

3. Where different electrification options lie in the future energy scenarios?

Methodology

Electrifying Post Combustion Carbon Capture

4-step Methodology of the Analysis



Data Collection

Open-source database
EU-ETS database, Cement Federations Reports, JRC reports
Research Articles,
Previous studies

Cement Industry Data
1) Process Description 2) Emissions data 3) Production Capacity

Compiling Carbon Capture Options
MEA Chemical Absorption, Heatpumping, VSA, Membrane systems, etc.

Model Development

Process-related Input
BAT Document, Open Literature,
Previous research
Simulation tools (ASPEN)

Modelling of Superstructure
Process models of all Carbon Capture options
Basecase Model **Validation**
Integration of all options into a unified Superstructure
Detailed **mass & energy balance and Costing details**

Analysis and Optimisation

Input Range of Prices
Coal, NG, Electricity, CO_2

Computational Analysis
Energy Cosumption Comparison
Capital Cost, Operating Cost and Totoal Cost Comparison

Scenario-based Inputs
ENTSO, IEA, VITO

Post-computation analysis

Multi-Scenario Analysis
Formulation of MILP problem
Objective Function: Min {total cost}
Scenario Based Comparison of **total cost**

Surrogate-based Robustness Analysis
Configuration-specific Surrogates
Polynomial Regression
Regret analysis of Capture Cost

Reporting

Regret Analysis
Violin Plots
Quantify robustness

Scenario-based Outcome
Pareto fronts, bar-plots

OSMOSE Lua
Process & Energy Systems Optimisation Framework

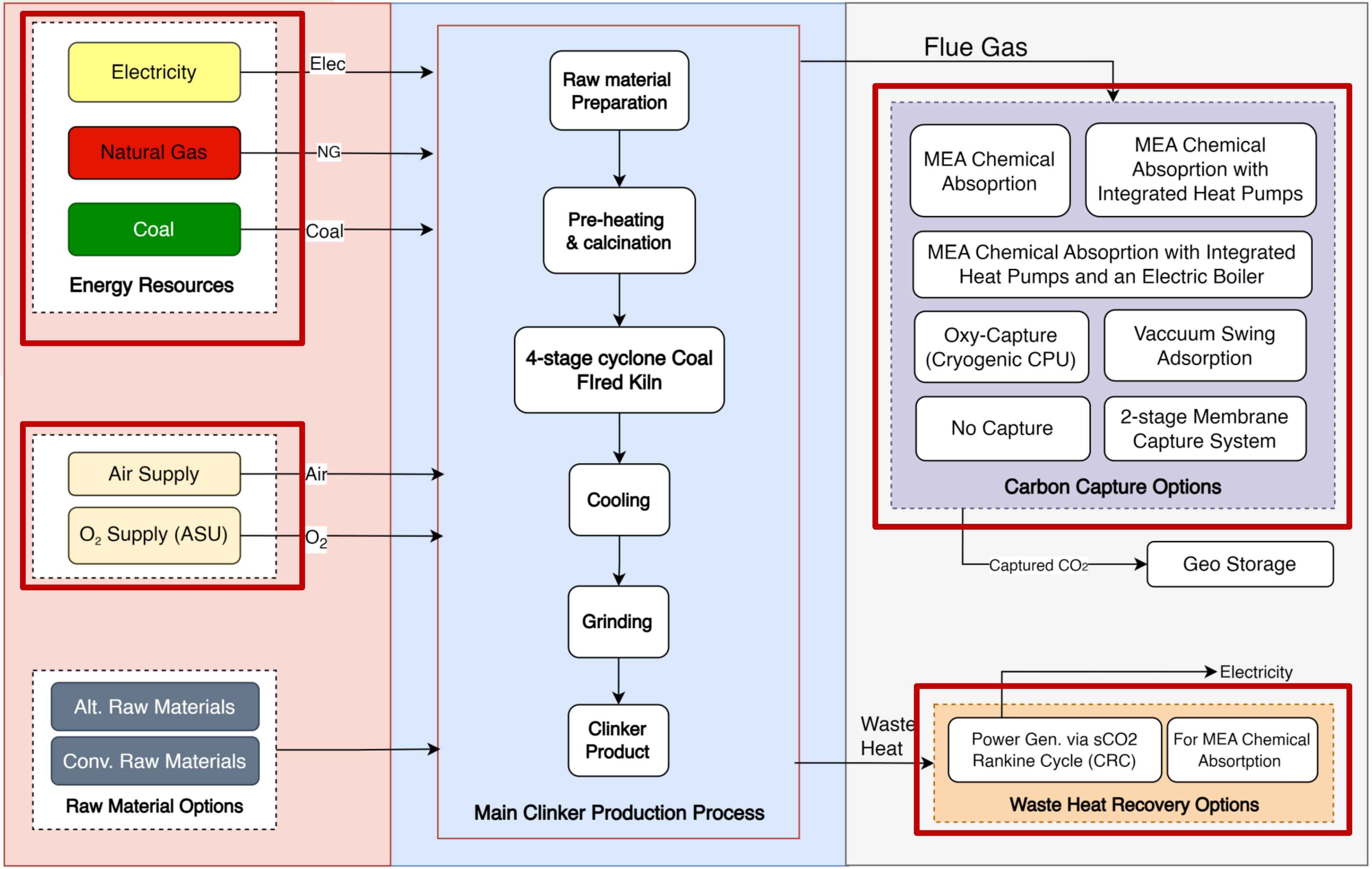
IPESE
Industrial Process and Energy Systems Engineering

EPFL

Salman et al.

Superstructure of Carbon Capture Options For the Cement Industry

5000 tpd of Clinker production



Capture Options

No.	Configuration	Abbreviation	Validation
1	Coal fired kiln (Base-case with no capture)	Base_case	Schorcht et al., (2013)
2	MEA Chemical Absorption Capture for Kiln	CC_MEA	Kim & Léonard (2025), Salman, M. et al. (2024).
3	MEA Chemical Absorption Capture for Kiln w/ Heat Pumps	CC_MEA_HP	Zühlsdorf, B. (2023).
4	MEA Chemical Absorption Capture w/ Electric Boilers and Heat Pumps	CC_MEA_EL_HP	Zühlsdorf, B. (2023)., Lyons et al. 2018
5	Coal-oxy-fired kiln with cryogenic CO_2 compression and purification unit (CPU)	CC_Oxy	Costa et al. (2024), Jamali et al. (2018) (CEMCAP)
6	Vacuum swing adsorption capture	CC_VSA	Zanco, S. E., et al. (2021)
7	Membrane-based capture	CC_Membrane	Rahimalimamaghani, A., et. al (2023)

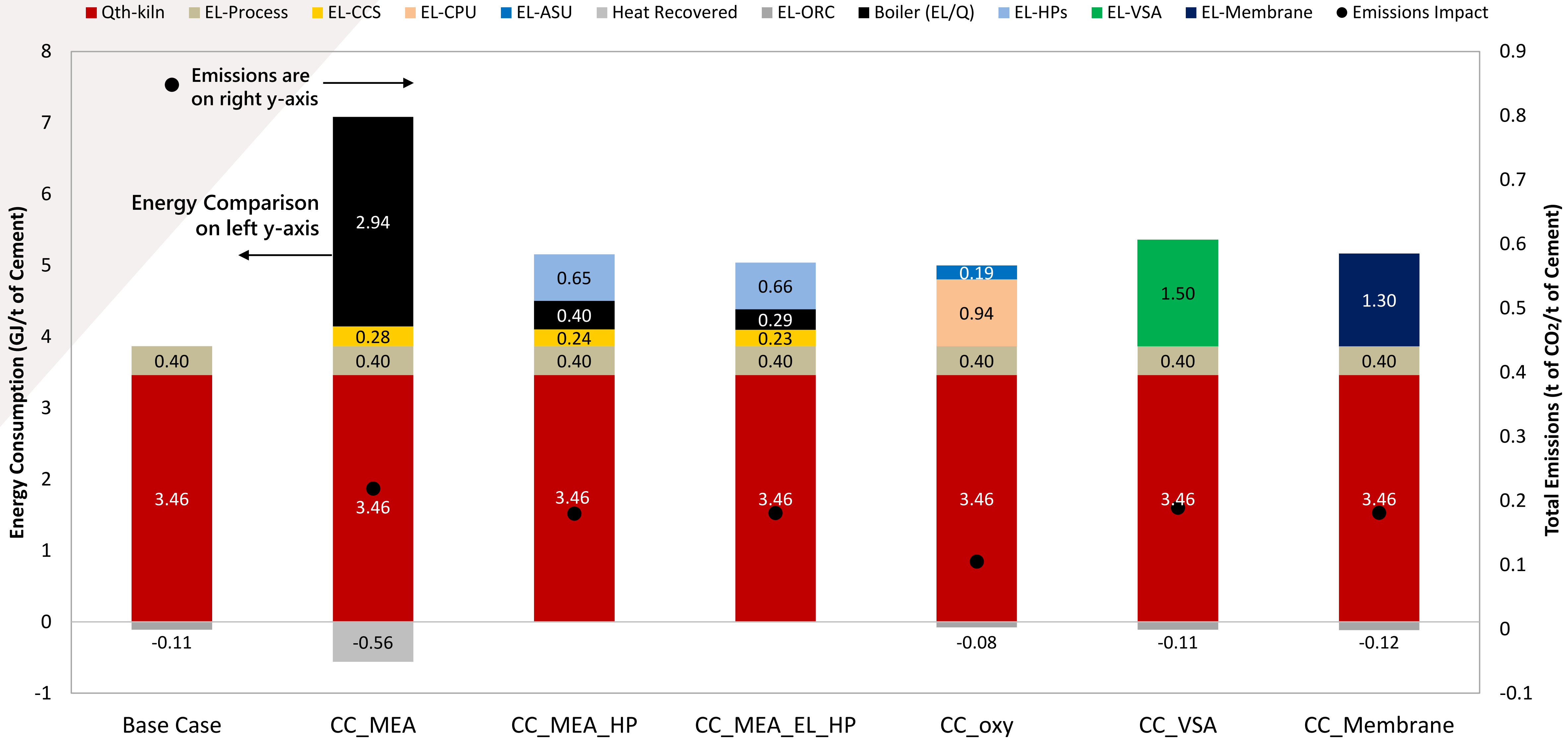
Parameters & assumptions

Parameter	**Value / Source**
Plant capacity	5000 tpd clinker → 1.3 Mtpa CO_2
Flue gas CO_2 concentration	20 mol% air-fired, 79 mol% oxy-fired
Emissions Impact	Direct (combustion + process) + Indirect (fuel/electricity)
CCS Cost	Capture + compression (110 bar) + T&S
Commodity prices	Commodity prices (electricity, NG, coal, CO_2 tax, T&S; 2025–2050)
OPEX	Raw materials, energy, CO_2 tax & T&S cost
CAPEX	Greenfield, 40 yrs lifetime, 6% discount
Heat pumps	25 MW max. condenser capacity (Zühlsdorf, B. (2023)).

Techno-Economic Analysis

Decarbonization of the Cement Industry

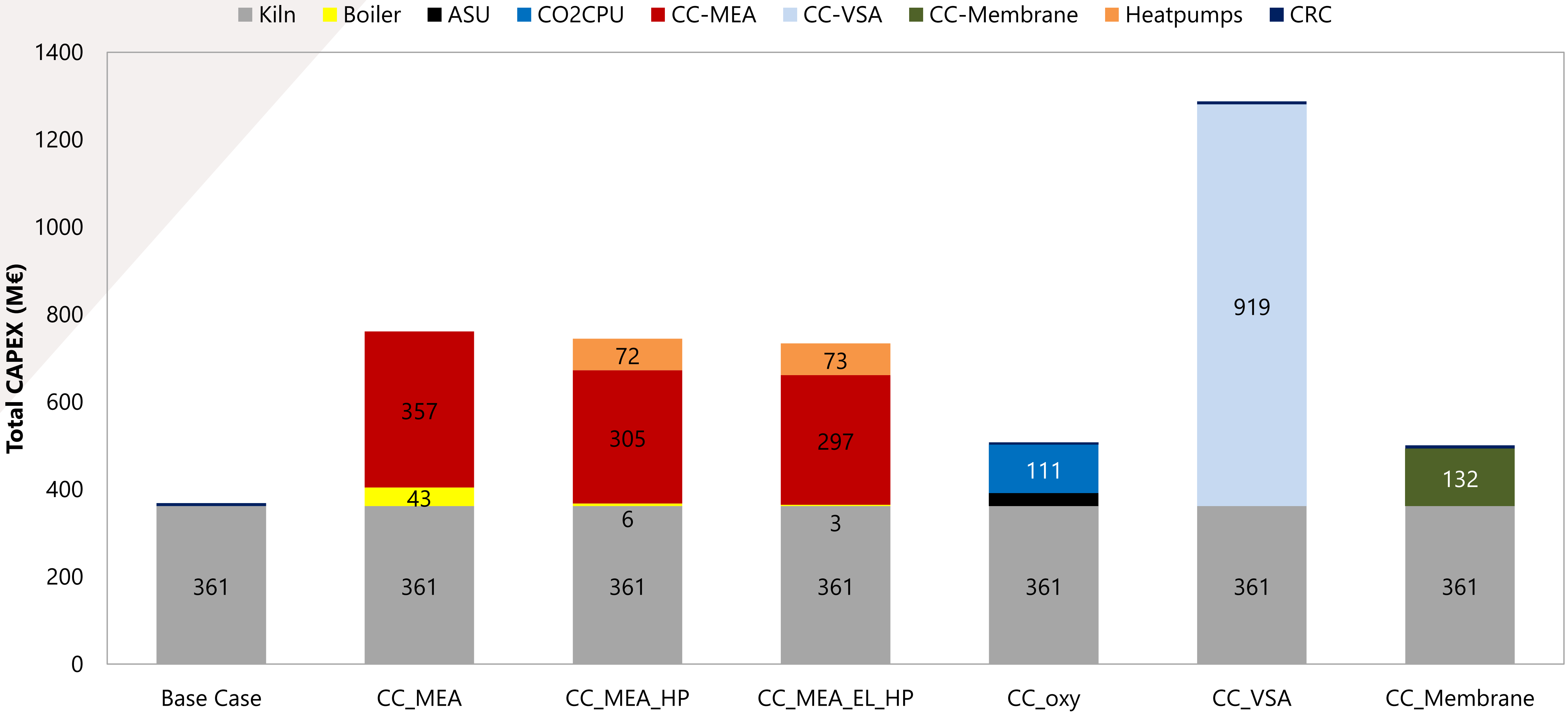
Energy Consumption Analysis



Emissions are on right y-axis

Energy Comparison on left y-axis

Total CAPEX



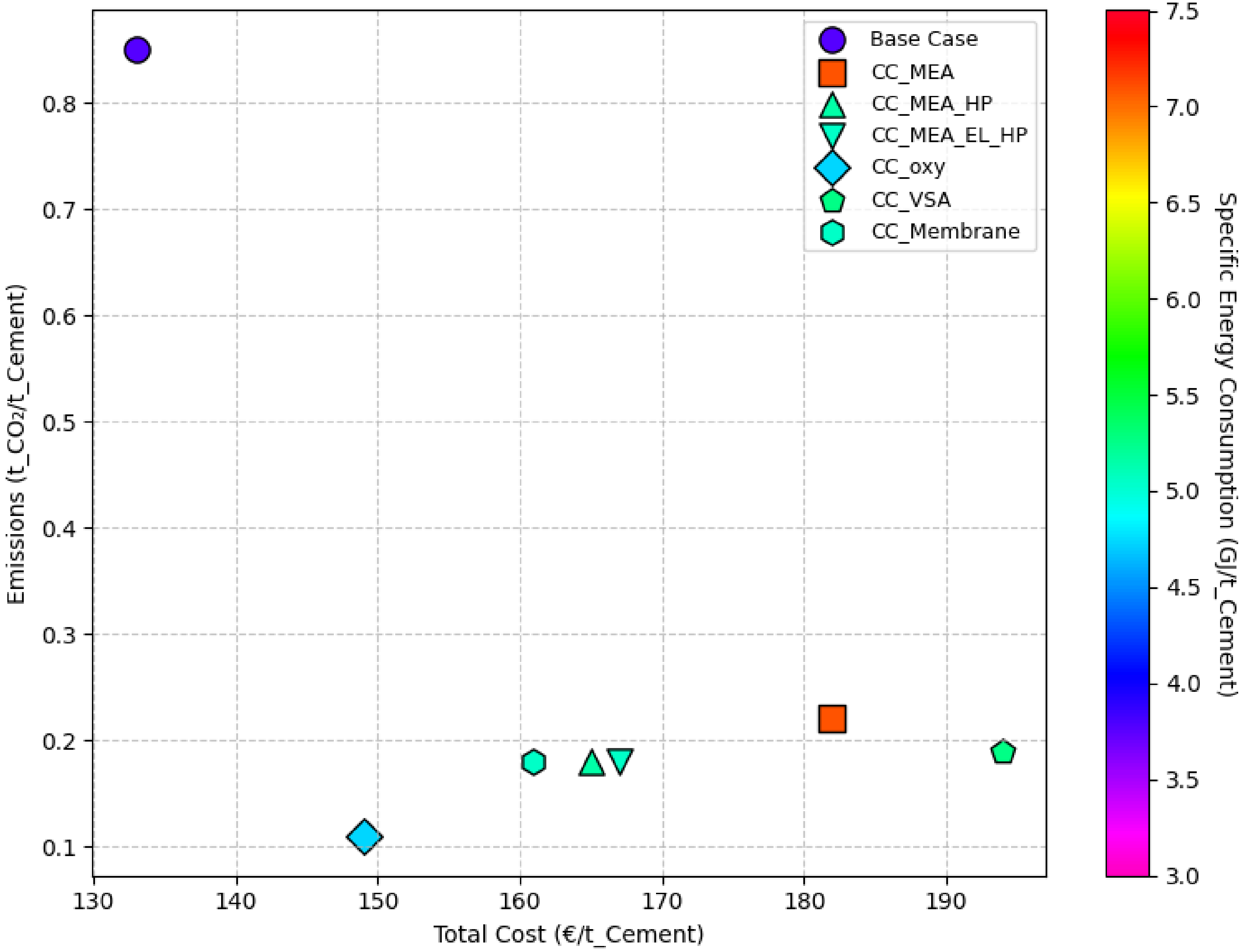
Kiln
Boiler
ASU
CO2CPU
CC-MEA
CC-VSA
CC-Membrane
Heatpumps
CRC
Total CAPEX (M€)
1400
1200
1000
800
600
400
200
0
361
361
43
357
361
6
305
72
361
3
297
73
361
111
361
919
361
132
Base Case
CC_MEA
CC_MEA_HP
CC_MEA_EL_HP
CC_oxy
CC_VSA
CC_Membrane

Assumed Scenarios

(benchmarked to VITO, IEA, ENTSO, Roussanaly et al. CCSA, CATF)

Variable	**Unit**	**2025**	**2040**	**2050**
Electricity	(€/MWh)	100	65	30
Natural Gas	(€/MWh)	35	35	35
Coal	(€/MWh)	13	12	12
CO_2 tax	(€/tCO_2)	80	140	200
CO_2 T&S	(€/tCO_2)	60	40	20
Electricity Impact	(kgCO_2/MWh)	139	56	49

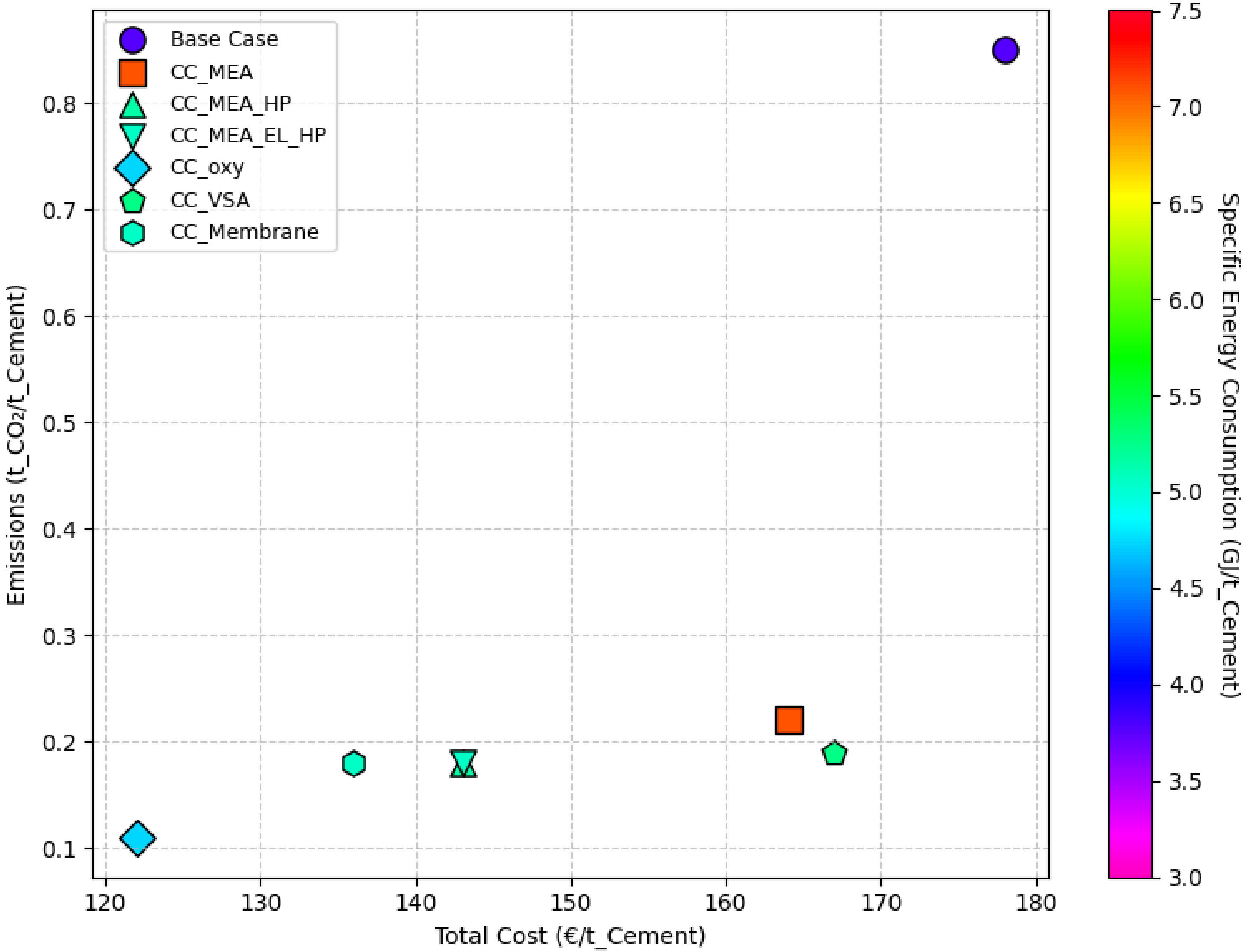
cEE = 100 €/MWh, **cNG** = 35 €/MWh, **cCoal** = 11 €/MWh, **cCO$_2$Tax** = 80 €/tCO$_2$, **cCO$_2$TnS** = 60 €/tCO$_2$,
Indirect Emissions Electricity = 138 kgCO$_2$/MWh



Total Cost per ton of Cement vs Total Emissions – **Scenario 2025**

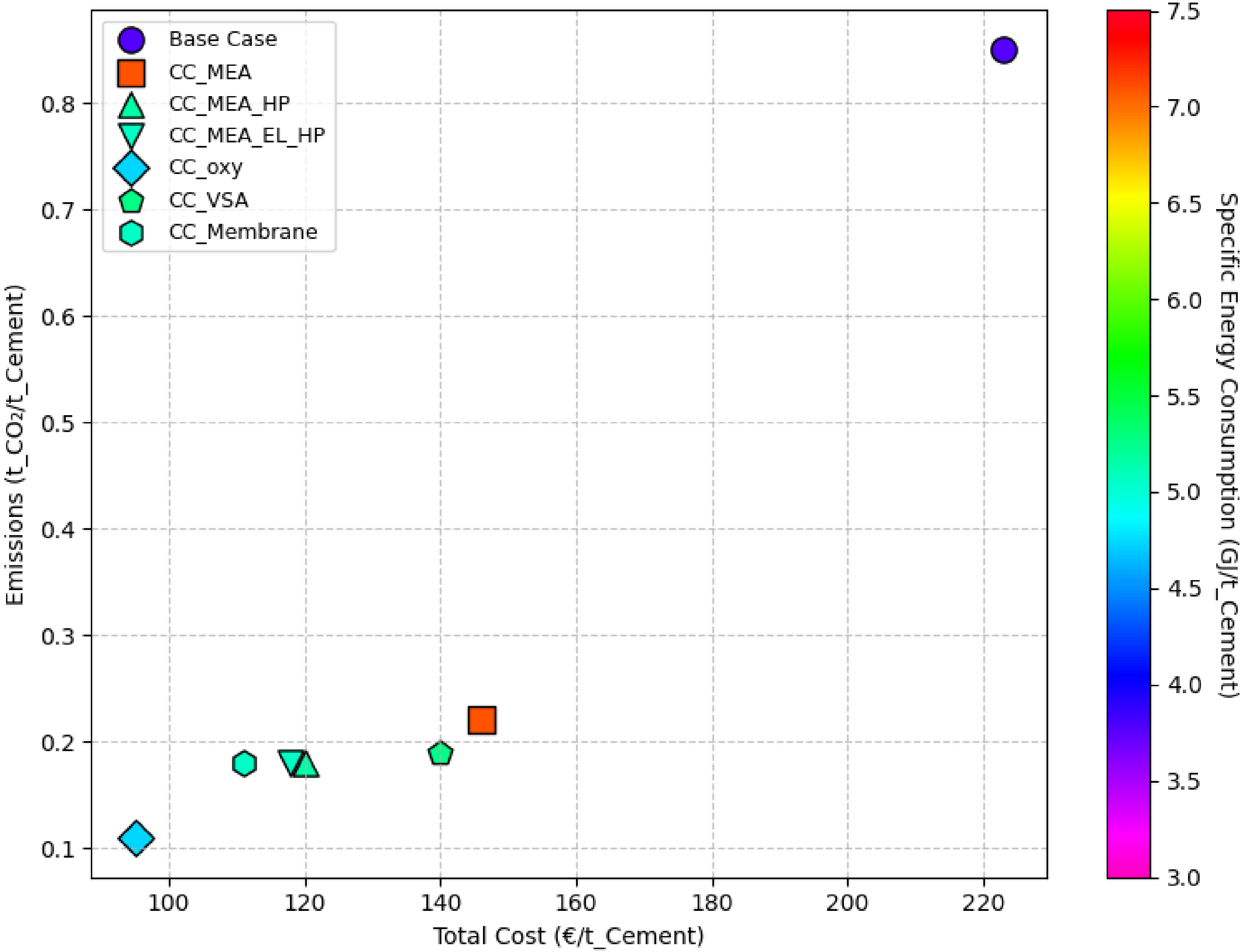
cEE = 65 €/MWh, **cNG** = 35 €/MWh, **cCoal** = 11 €/MWh, **cCO_2Tax** = 140 €/tCO_2, **cCO_2TnS** = 40 €/tCO_2

Indirect Emissions Electricity = 60 $kgCO_2$/MWh



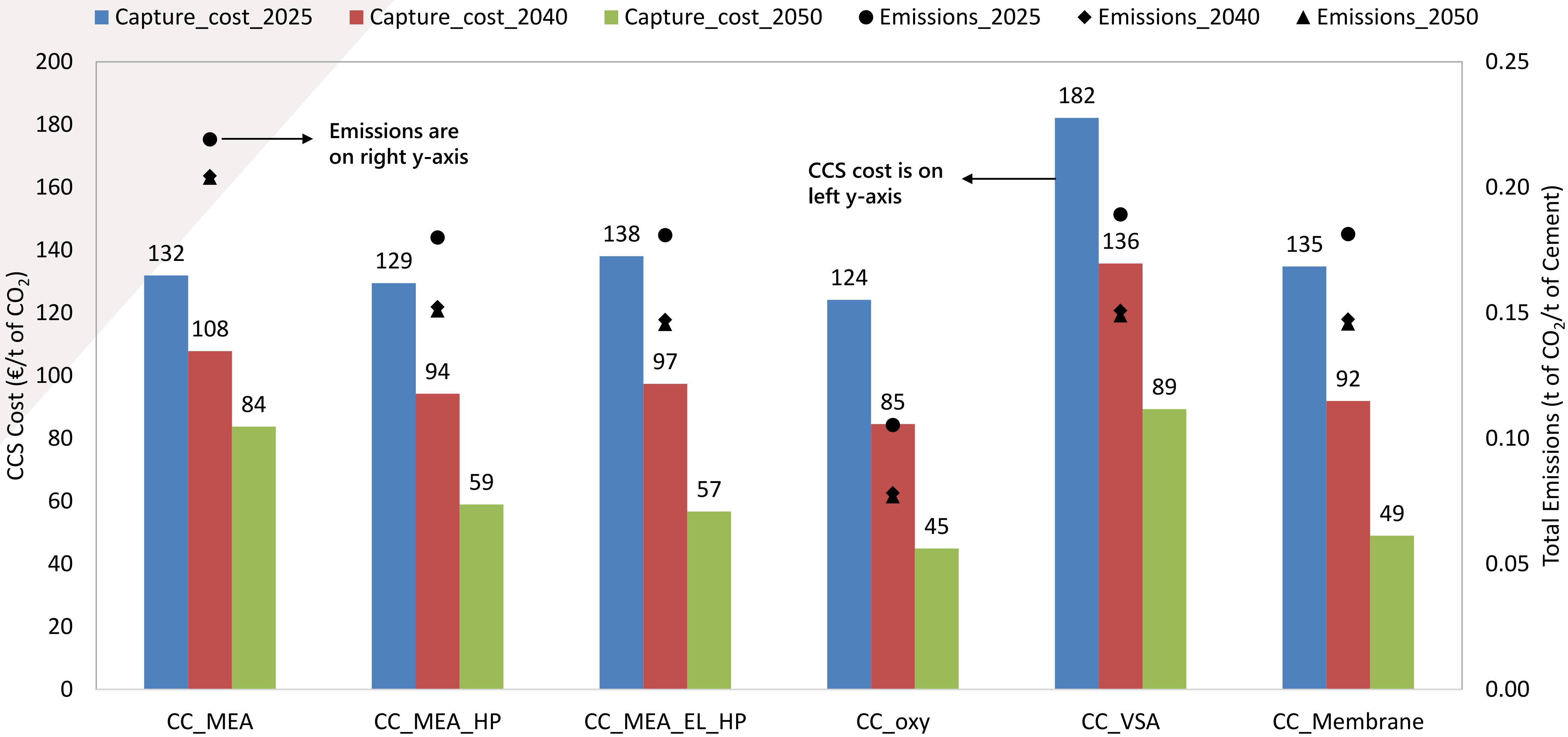
Total Cost per ton of Cement vs Total Emissions – **Scenario 2040**

cEE = 30 €/MWh, **cNG** = 35 €/MWh, **cCoal** = 11 €/MWh, **cCO_2Tax** = 200 €/tCO_2, **cCO_2TnS** = 20 €/tCO_2
Indirect Emissions Electricity = 57 $kgCO_2$/MWh



Total Cost per ton of Cement vs Total Emissions – **Scenario 2050**

Cost of CCS



Emissions are on right y-axis

CCS cost is on left y-axis

Salman et al.

Question: *How to test the robustness???*

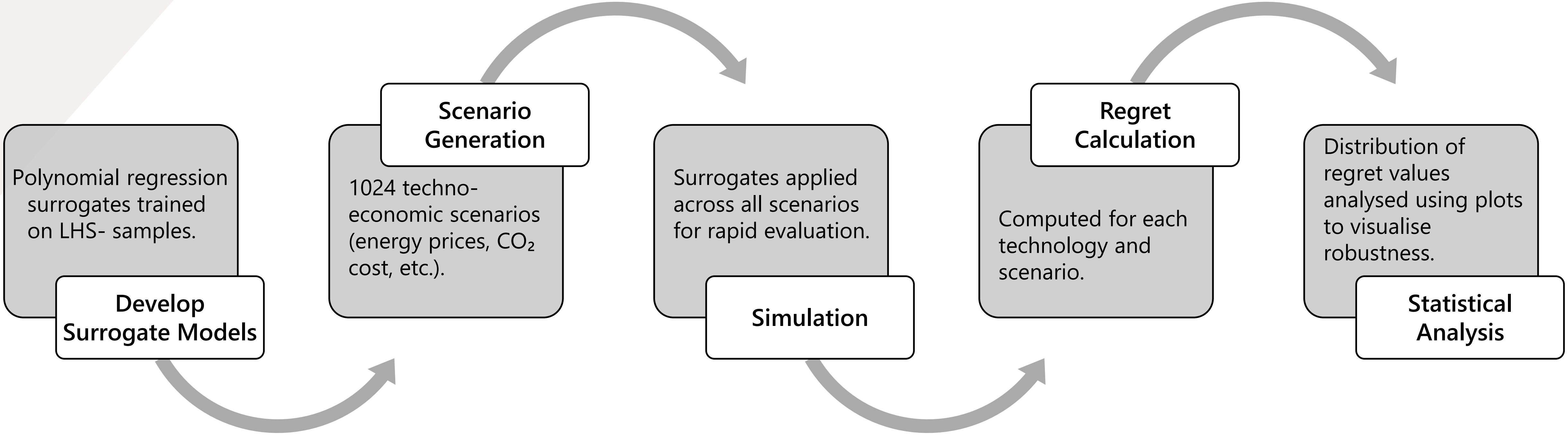
"Your energy scenarios are not realistic bro"

"This price of electricity is too low"

"CO_2 tax (or ETS price) is way too high"

Regret Analysis – *to evaluate robustness of options*

- **Quantifies the performance loss** of a given option compared to the best-performing option under each scenario.
- Purpose
  - **Evaluates robustness** of technologies under uncertainty.
  - **Highlights solutions** that consistently perform well across many scenarios.



Develop Surrogate Models

Polynomial regression surrogates trained on LHS- samples.

Scenario Generation

1024 techno-economic scenarios (energy prices, CO_2 cost, etc.).

Simulation

Surrogates applied across all scenarios for rapid evaluation.

Regret Calculation

Computed for each technology and scenario.

Statistical Analysis

Distribution of regret values analysed using plots to visualise robustness.

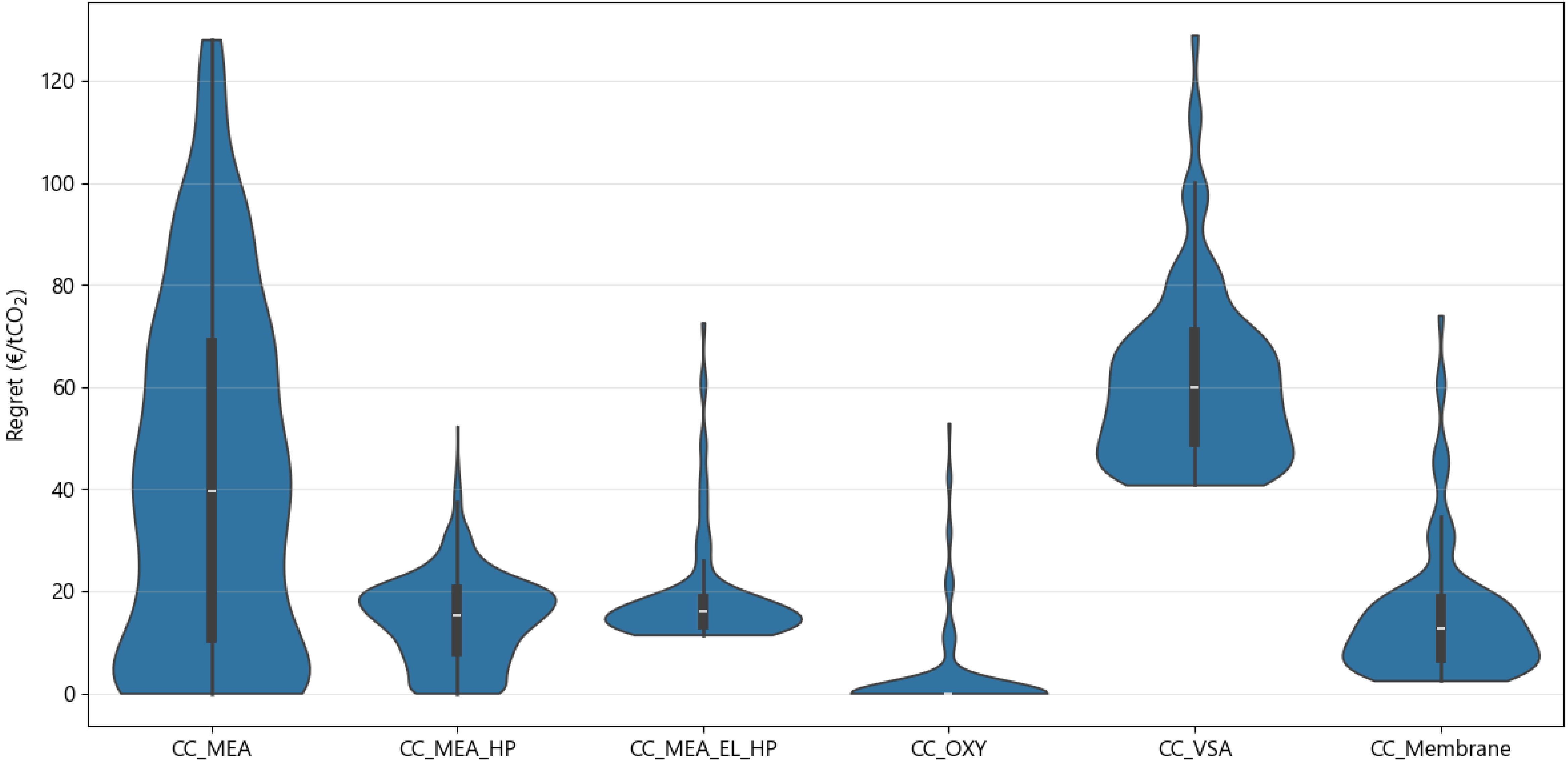
Regret Analysis

Variables

Electricity:	10 – 200 €/MWh
Natural Gas:	10 – 100 €/MWh *(2.78 – 27.8 €/GJ)*
Coal:	10 – 100 €/MWh (*0.08 – 0.82 €/kg*)
CO_2 emissions:	75 – 250 €/tCO_2
CO_2 T&S:	20 – 100 €/tCO_2

- **1024 Scenarios**

Distribution of Capture Cost Regret



Conclusion - *Electrification is decisive.*

- **Integrating Heat pumps** with MEA cuts capture cost by ~54–59% in different scenarios, while it results in 60% total energy.
- **Oxyfuel is the most robust option**. It reaches ~45 €/tCO_2 by 2050 (−64% vs 2025), delivers the lowest energy requirement, and shows the **lowest regret** across 1000+ scenarios.
- **Membranes are highly competitive** as the grid decarbonizes: ~49 €/tCO_2 by 2050 (−65%); ~35% lower total CAPEX than MEA today.
- **Standalone MEA lags**: −36% capture-cost improvement by 2050 and the **widest regret**, because the reboiler remains the dominant penalty.
- **VSA is rarely optimal**: even with cheaper power its capture cost is ~89 €/tCO_2 in 2050 (still the highest), and total CAPEX is +56% vs MEA.

- **Decision support**:
  - ○ **Near-term**: Deploy **MEA+HP (-EL)** where oxycombustion integration is constrained, 2–4% lower total CAPEX than MEA and much better OPEX/emissions;
  - ○ **Medium/long-term**: Oxyfuel can be priortised; consider Membranes where electricity is cheap/clean or for incremental retrofits. Improve TRL of membranes.

References

- CATF, “The cost of carbon capture and storage in europe,” [Online]. Available: https://www.catf.us/ccscost-tool/
- CCSA, “Accelerating a europe-wide CO2 storage market,” CCSA, Tech. Rep., Dec. 2024.
- ENTSO. (2022). Ten-year network development plans (TYNDP) 2022: Scenario Report. https://2022.entsos-tyndp-scenarios.eu/
- ENTSO. (2024). Ten-year network development plans (TYNDP) 2024: Scenario Report. https://2024.entsos-tyndp-scenarios.eu/
- Jamali, A., Fleiger, K., Ruppert, J., Hoenig, V., & Anantharaman, R. (2018). Optimised operation of an oxyfuel cement plant Work package: WP 6-Oxyfuel modeling and optimisation - CEMCAP Project.
- Kim, S., & Léonard, G. (2025). CO_2 capture technologies and shortcut cost correlations for different inlet CO_2 concentrations and flow rates. Part 1. Chemical absorption. (Preprint available). International Journal of Greenhouse Gas Control. https://doi.org/10.2139/ssrn.4967576
- Lyons, S., Durusut, E., & Moore, I. (2018). Industrial Fuel Switching - Market Engagement Study.
- Rahimalimamaghani, A., Ramezani, R., Pacheco Tanaka, D. A., & Gallucci, F. (2023). Carbon molecular sieve membranes for selective CO_2/CH_4 and CO_2/N_2 separation: Experimental study, optimal process design, and economic analysis. Industrial & Engineering Chemistry Research, 62(45), 17323–17337. https://doi.org/10.1021/acs.iecr.3c01936
- Salman, M., Beguin, B., Nyssen, T., & Léonard, G. (2024). Techno-economic analysis of AMP/PZ solvent for CO2 capture in a biomass CHP plant: towards net negative emissions. Frontiers in Energy Research, 12. https://doi.org/10.3389/fenrg.2024.1325212
- Schorcht, F., Kourti, I., Scalet, B. M., Roudier, S., & Delgado Sancho, L. (2013). Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide. Publications Office.
- S. Roussanaly, N. Berghout, T. Fout, et al., “Towards improved cost evaluation of carbon capture and storage from industry,” International Journal of Greenhouse Gas Control, vol. 106, 2021.
- Vito. (2023). PATHS 2050 - Scenarios towards a carbon-neutral Belgium by 2050. https://perspective2050.energyville.be/
- Zühlsdorf, B. (2023). High-Temperature Heat Pumps: Task 1 – Technologies. Task Report (Annex 58). IEA Heat Pumping Technologies TCP. Danish Technological Institute. Report no. HPT-AN58-2.

economie

This research is supported via the **Energy Transition Fund** organized by the **FPS economy**.

TRILATE Project

TRILateral research for optimal Investments in
Adequate cross-border infrastructure for energy transition

Project Consortium

LIÈGE université
UNIVERSITEIT GENT
KU LEUVEN
vito
Energy Ville
EPFL
fluxys
elia

Thanks for your attention!

Muhammad Salman
Alexis Costa, Rafailia Mitraki, So-mang Kim,
Salar Fakhraddinfakhriazar, Brieuc Beguin,
Daniel Flórez-Orrego, Guy De Weireld,
François Maréchal,
Grégoire Léonard

Contact:
Email: m.salman@uliege.be
Tel: +32-465671822