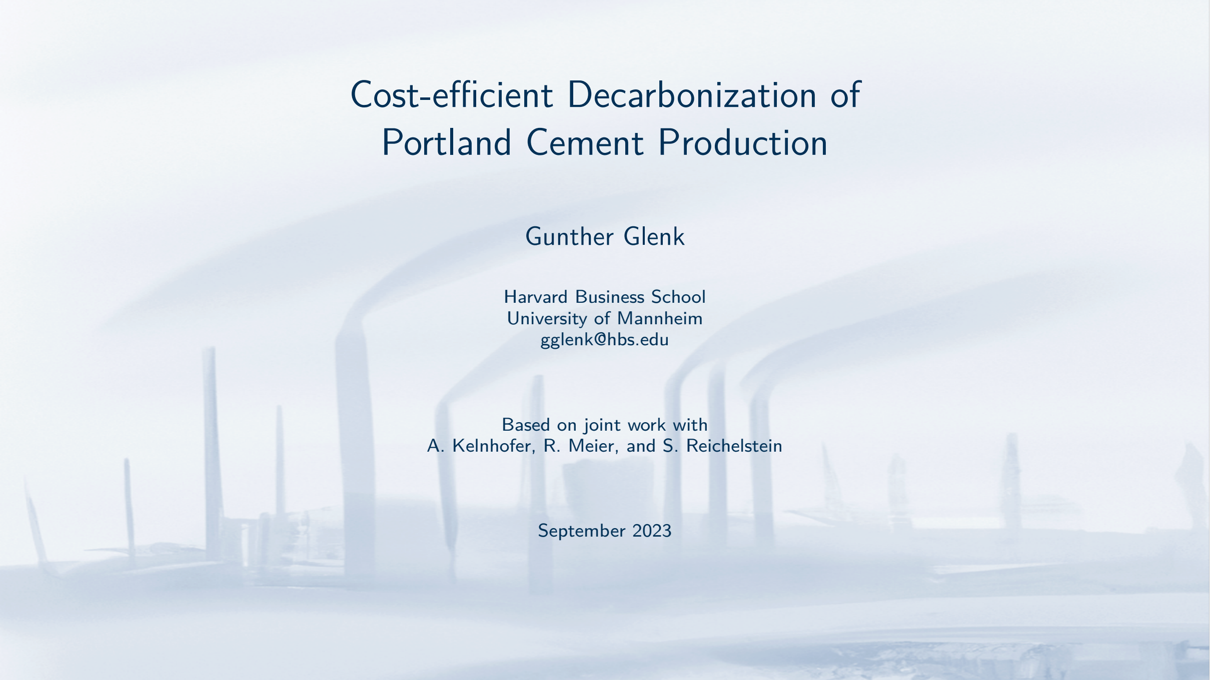

Cost-efficient Decarbonization of Portland Cement Production

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Based on joint work with
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The Decarbonization Challenge

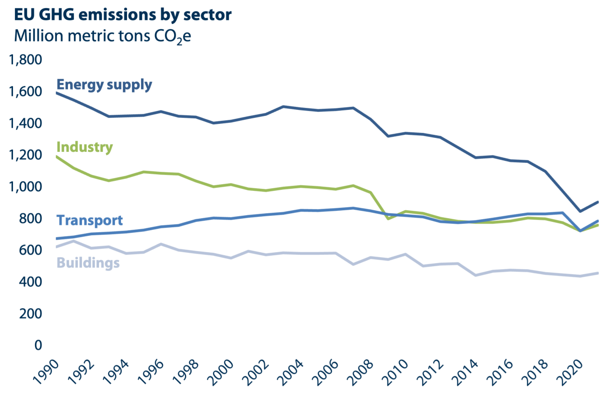
Emissions from industry are now almost on par with those from power generation

Hard-to-decarbonize industries[1]:

- Essential to a modern economy
- Inherent process emissions

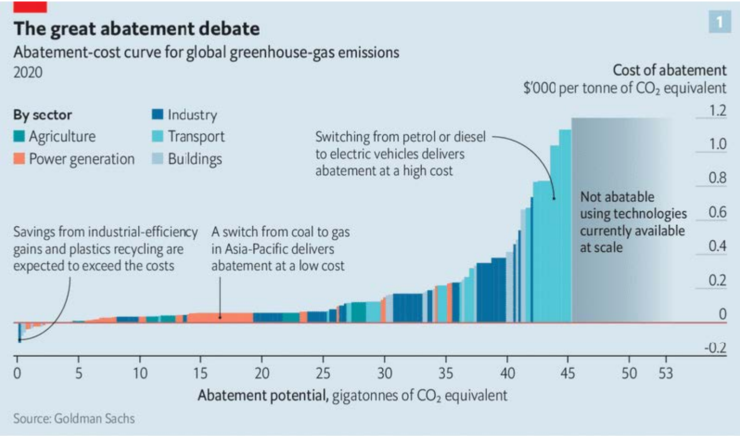
Global cement industry:

- ≈8% of global annual CO_2 emissions[2]
- Net-zero pledges by major manufacturers[3]



[1] Davis et al. (2018, *Science*), [2] Fennell et al. (2021, *Joule*), [3] PCA (2022), CEMBUREAU (2020)

Marginal Abatement Cost Curve



The Economist

- Popularized by McKinsey (2007), it shows the unit cost per CO_2 abated of individual levers
- Crucial assumption: separability of levers if implemented together at one production facility

This Talk...

Generic Economic Model

- Cost-efficient combination of levers to achieve a given emission reduction target
- Optimal abatement level under carbon pricing regulation

Decarbonization of Portland Cement Production

- At €81/tCO_2 (average of 2022), firms are incentivized to reduce direct emissions by one-third
- Optimal abatement is highly sensitive in the range of €80–140/tCO_2

Portland Cement Production

Limestone Extraction

- Quarrying
- Crushing and Grinding
- Mixing with gypsum, shale, clay, or sands

Clinker Production

- Pre-heating
- Pre-calcination
- Rotary Kiln

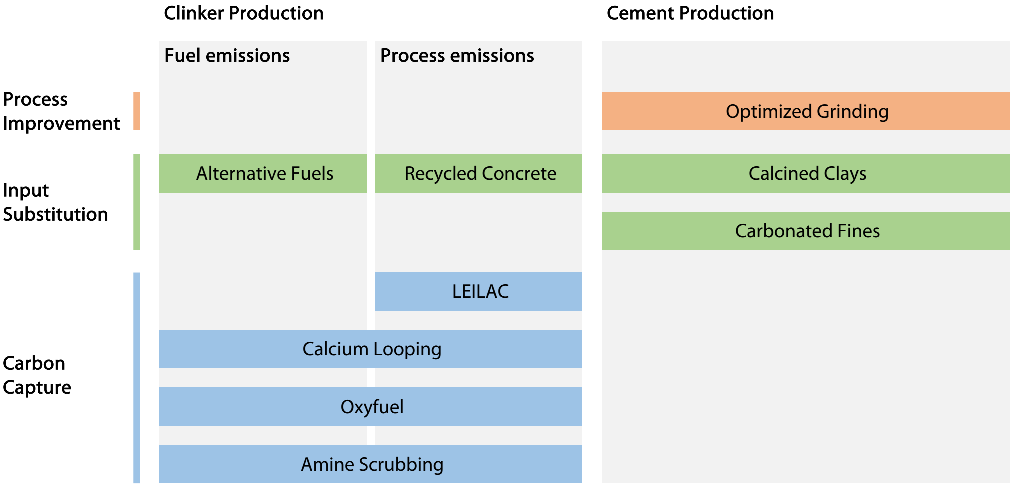
Cement Production

- Air Cooling
- Blending with supplementary cementitious materials
- Grinding

> 90% of all direct CO_2 emissions

- **≈ 60%** due to chemical processes: calcium carbonate ($CaCO_3$) $\longrightarrow$ calcium oxide (CaO) + CO_2
- **≈ 40%** due to fuel combustion: frequently coal combustion for heating the kiln to about 1,400°C

Abatement Levers for Portland Cement



Clinker Production

Cement Production

Fuel emissions

Process emissions

Process Improvement

Optimized Grinding

Input Substitution

Alternative Fuels

Recycled Concrete

Calcined Clays

Carbonated Fines

Carbon Capture

LEILAC

Calcium Looping

Oxyfuel

Amine Scrubbing

- 9 elementary levers yield at most $2^9 = 512$ technologically feasible combined levers
- Combined levers have a non-separable impact on cost and abatement → interaction effects!

Economic Model

- Reference plant that produces a given quantity of cementitious material
- Annual production results in E_0 tons of direct CO_2 emissions in the status quo
- The firm can implement a combination of m elementary levers denoted by $\vec{v} = (v_1, ..., v_m)$, where $v_i \in \{0, 1\}$ indicates whether lever i is implemented $\rightarrow$ $\vec{v}_0$ reflects the status quo
- Implementing $\vec{v}$ may require upfront investment and result in modified operating costs
- $DE(\vec{v})$ gives the total discounted expenditures (in €) incurred if $\vec{v}$ is implemented

Abatement Cost

- The firm chooses a target level E for future emissions and seeks to identify combined lever $\vec{v}$ that minimizes $DE(\vec{v})$ such that the plant's future annual emissions do not exceed E

- The abatement cost of reducing emissions from E_0 to E in a cost-efficient manner is thus:

$$AC(E) \equiv \min_{\vec{v} \in V_f(E)} \{DE(\vec{v})\} - DE(\vec{v}_0)\},$$

  where $V_f(E)$ is the set of technologically feasible $\vec{v}$ resulting in emissions not exceeding E

- $AC(E)$ reflects the break-even value that leaves the firm indifferent between the status quo and re-configuring its plant so that annual emissions will not exceed E

- By construction, $AC(E_0) = 0$ and $AC(\cdot)$ is a weakly decreasing step-function of E
  → let $E_n < \ldots < E_i < \ldots < E_1$ denote the stepping points, i.e., cost-efficient emission thresholds

Portland Cement Production in Europe

- Calibration to European reference plants for Portland cement production
- Status quo: 1.0m tons of clinker → 1.4m tons of cement + 0.8m tons of CO_2 per year
- New industry data[1] corroborated with expert interviews, technical reports, and journal articles
- Focus on direct emissions incurred at the production site (i.e., Scope 1 emissions)

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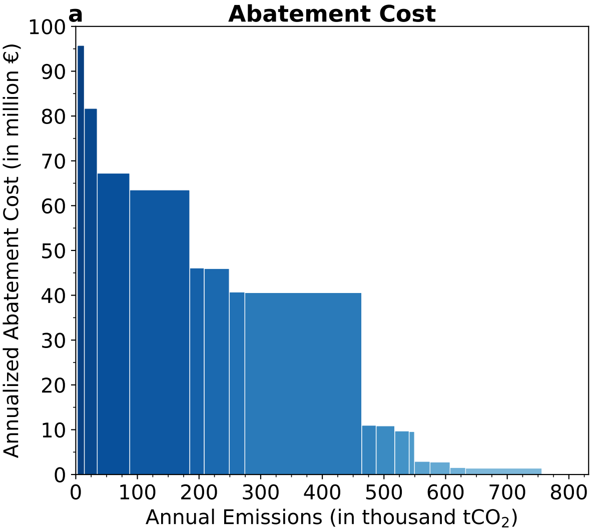
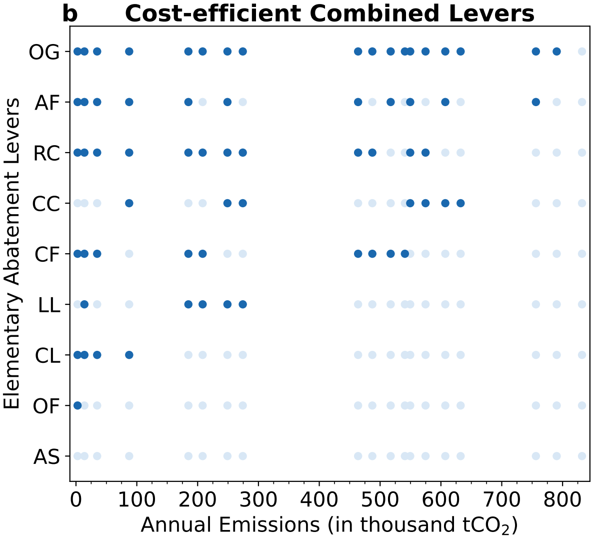
[1] ECRA (2022), ▷ Details

Cost-efficient Abatement: Cost



- 18 cost-efficient emission thresholds, where $E_{18} \approx 0.3\%$ of status quo emissions
- $AC(E_1) = AC(E_0) = 0$, because Optimized Grinding lowers emissions and expenditures
- $AC(\cdot)$ is non-convex (i.e., marginal cost is not increasing), because the joint cost and emission reduction impact is not separable across combined levers
- Abatement cost is significant relative to the overall revenue of a typical cement plant

Cost-efficient Abatement: Combined Levers



- At $E_2 = 756{,}184$ tCO_2, firms would adopt Optimized Grinding and Alternative Fuels
- At $E_{11} = 274{,}253$ tCO_2, firms would adopt LEILAC, Optimized Grinding, Recycled Concrete, and Calcined Clays
- For more ambitious targets, firms would install Calcium Looping alone or together with LEILAC

Optimal Abatement Under Carbon Pricing

Suppose a charge of €p per ton of CO_2:

- The total cost of reducing emissions from E_0 to E comprises the abatement cost and the avoided compliance cost associated with the status quo emissions:

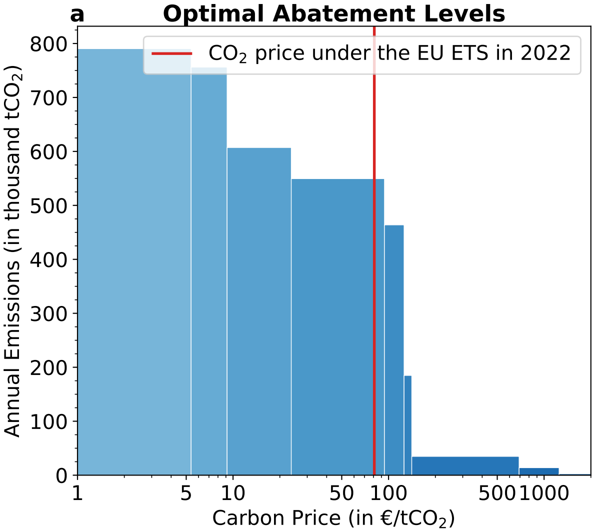
  $$TC(E, p) = AC(E) - p \cdot (E_0 - E) \cdot A(r, T),$$

  where $A(r, T)$ is the annuity factor of €1.0 over T years at cost of capital r

- For any p, firms identify the optimal emission level $E^*(p)$ that minimizes the associated total cost

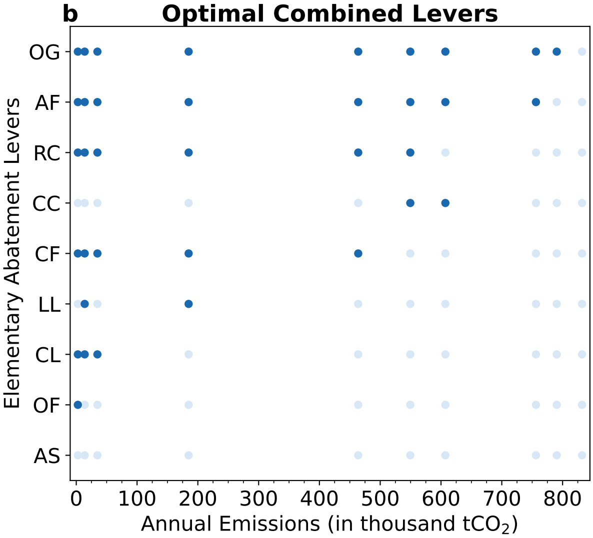
- $E^*(p)$ is one of the cost-efficient emission thresholds and hence a step function in p

Optimal Abatement Levels



- Optimal abatement response always selects 1 out of 9 different combined levers
- High price elasticity of the optimal abatement level for prices between €80–140/tCO_2
    - €81/tCO_2 → 34% reduction
    - €126/tCO_2 → 78% reduction
    - €141/tCO_2 → 96% reduction
- Near-complete decarbonization (99.7%) requires carbon prices $\geq$ €1,249 t/CO_2

Optimal Abatement Levers



- 34% reduction: Optimized Grinding, Alternative Fuels, Recycled Concrete, and Calcined Clays
- 78% reduction: LEILAC, Optimized Grinding, Alternative Fuels, Recycled Concrete, and Carbonated Fines
- 96% reduction: Calcium Looping instead of LEILAC
- 99.7% reduction also requires Oxyfuel

Sensitivity Analysis

- Availability restrictions for individual elementary levers
- Different costs for transporting and storing captured CO_2
- Enhanced operation of carbon capture technologies at higher cost
- Advances in the cost and capture rates of carbon capture technologies

→ Magnitudes of the abatement costs and optimal abatement levels are **consistent!**

▷ Details

Policy Implications

- Potential expansion of carbon pricing or subsidy mechanisms
- Affordability of low-carbon cement for economic development
- Carbon contracts for difference for accelerated decarbonization
- Need for carbon removal to achieve net-zero positions

▷ Details

Concluding Remarks

- Available levers offer cement producers substantial abatement potential at reasonable cost
- The 2022 average carbon price of €81/tCO_2 incentivizes firms to reduce emissions by 34%
- Incentives to abate emissions increase sharply ($\approx$ 96%) at a carbon price of €141/tCO_2
- Absent carbon prices above €500/tCO_2, residual emissions will likely amount to at least 4%
- Abatement cost concept can facilitate the arrangement of carbon contracts for difference
  → At €81/tCO_2, plants would need €14.0m per year to increase abatement from 34% to 78%

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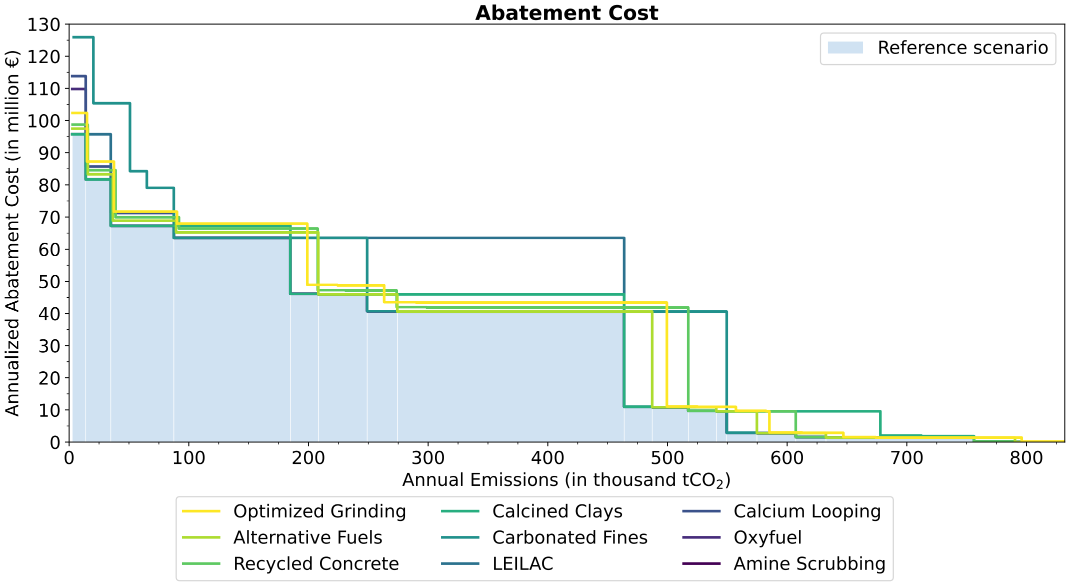
Appendix

Main Changes in Cost and Operational Parameters

in 2020€	**Abatement** %	**Investment** €	**Fixed Cost** €/year	**Variable Cost** €/ton of clinker
Process Improvement				
Optimized Grinding	5.0% clinker replacement	5,000,000	0	-0.03
Input Substitution				
Alternative Fuels	15.0% increase in biomass	5,000,000	0	-0.21
Recycled Concrete	16.0% limestone replacement	5,000,000	2,240,000	-0.69
Calcined Clays[1]	25.0% clinker replacement	45,454,546	3,750,000	-5.80
Carbonated Fines[2]	30.0% clinker replacement	75,000,000	4,035,326	16.55
Carbon Capture				
LEILAC	57.3% capture rate	150,937,500	0	7.50
Calcium Looping	92.5% capture rate	282,187,500	3,855,000	7.15
Oxyfuel	92.5% capture rate	203,437,500	595,000	22.91
Amine Scrubbing	92.5% capture rate	155,859,375	23,881,500	25.12

1: For an annual production volume of 165,000 tons; 2: For an annual production volume of 300,000 tons.

Availability Restrictions: Cost-efficient Abatement



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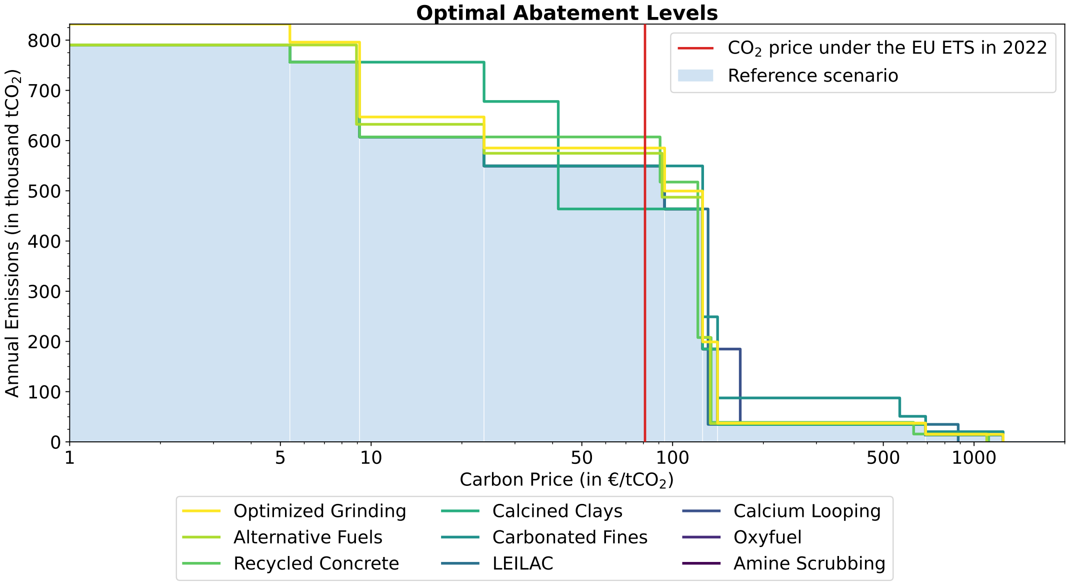
Availability Restrictions: Optimal Abatement



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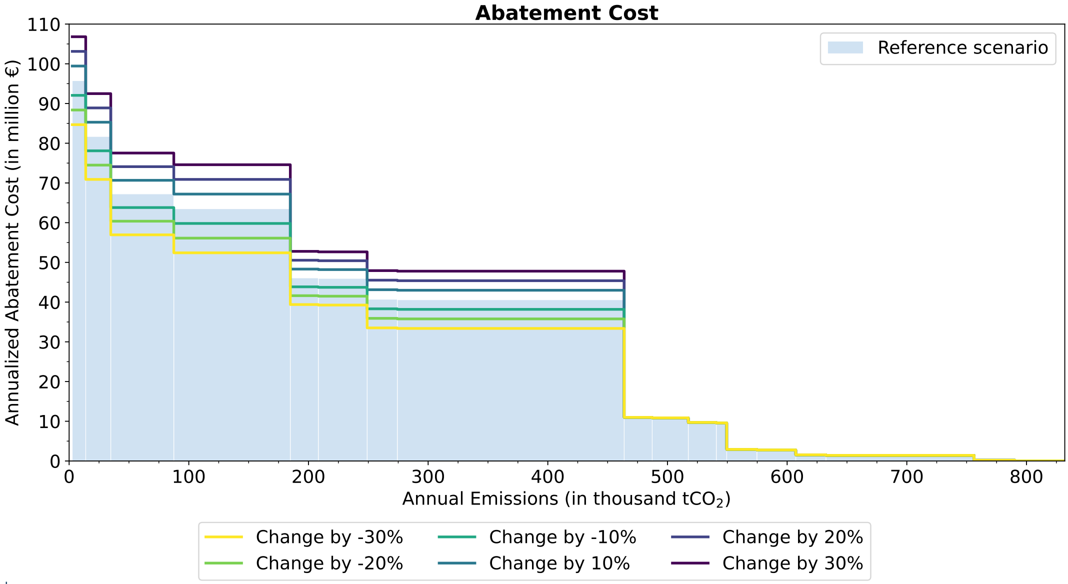
Transporting and Storing CO_2: Cost-efficient Abatement



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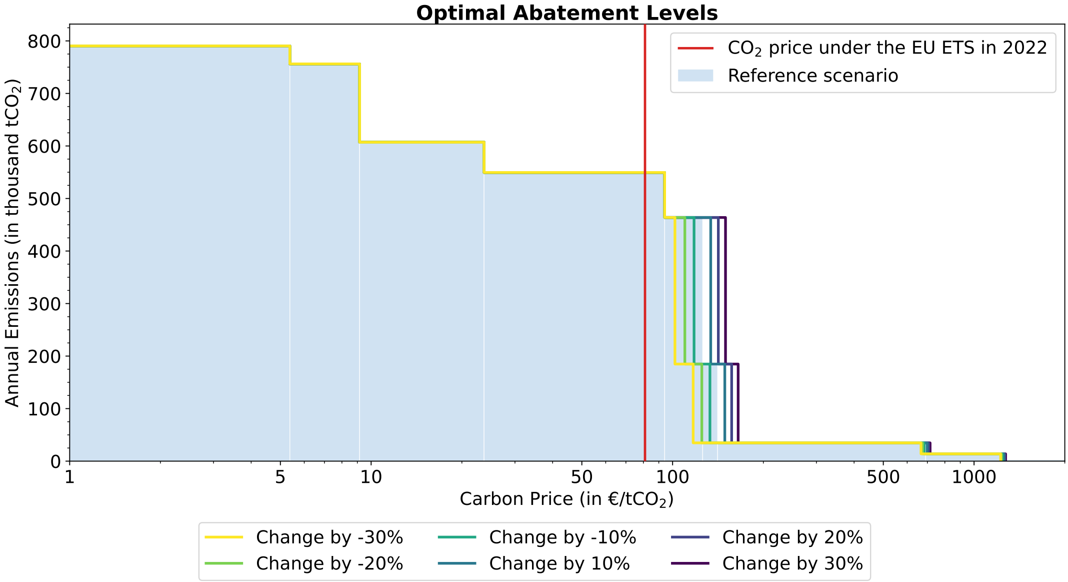
Transporting and Storing CO_2: Optimal Abatement



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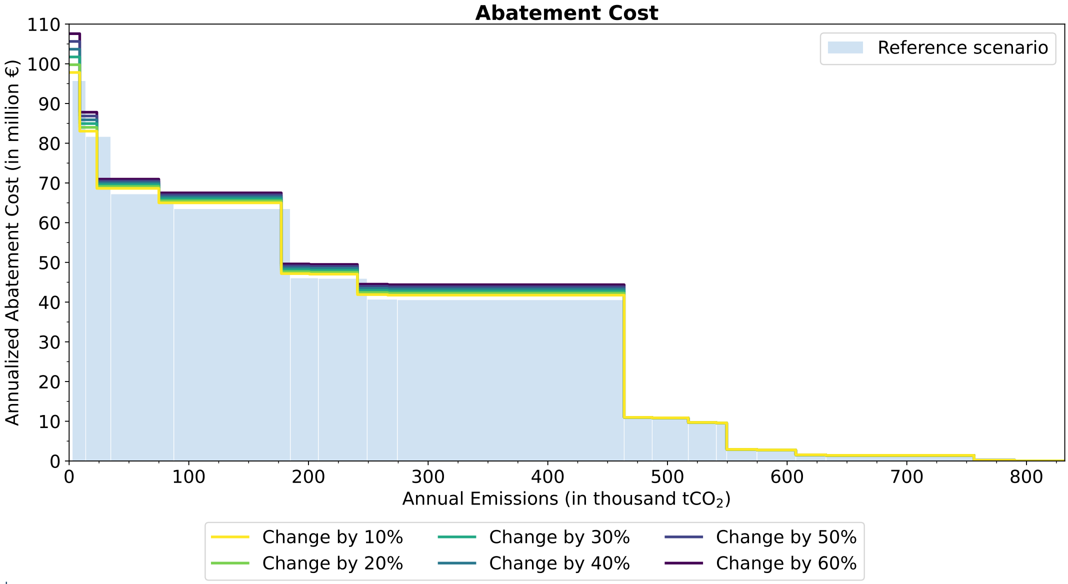
Deep Carbon Capture: Cost-efficient Abatement



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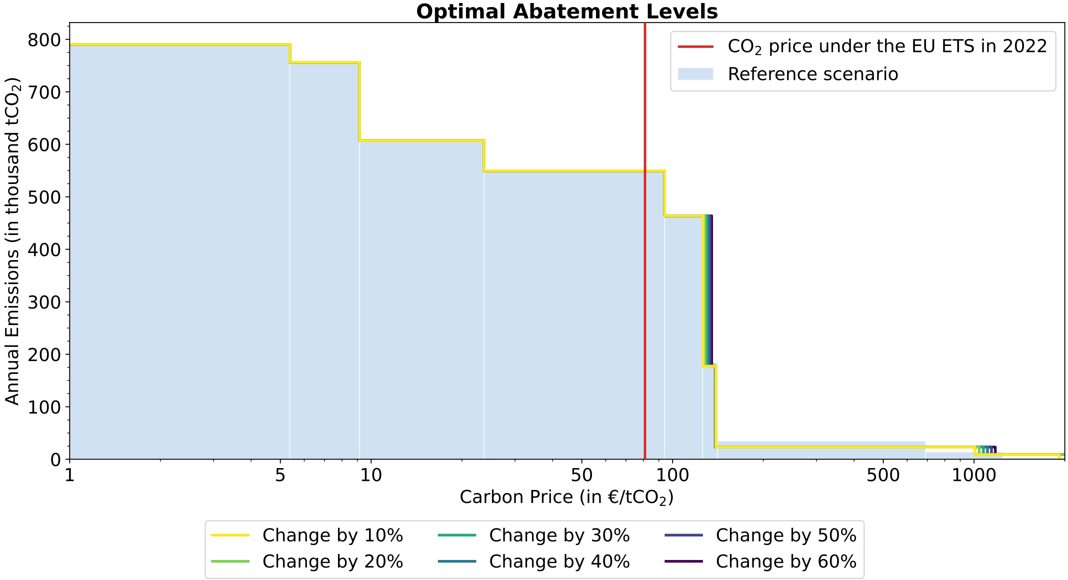
Deep Carbon Capture: Optimal Abatement



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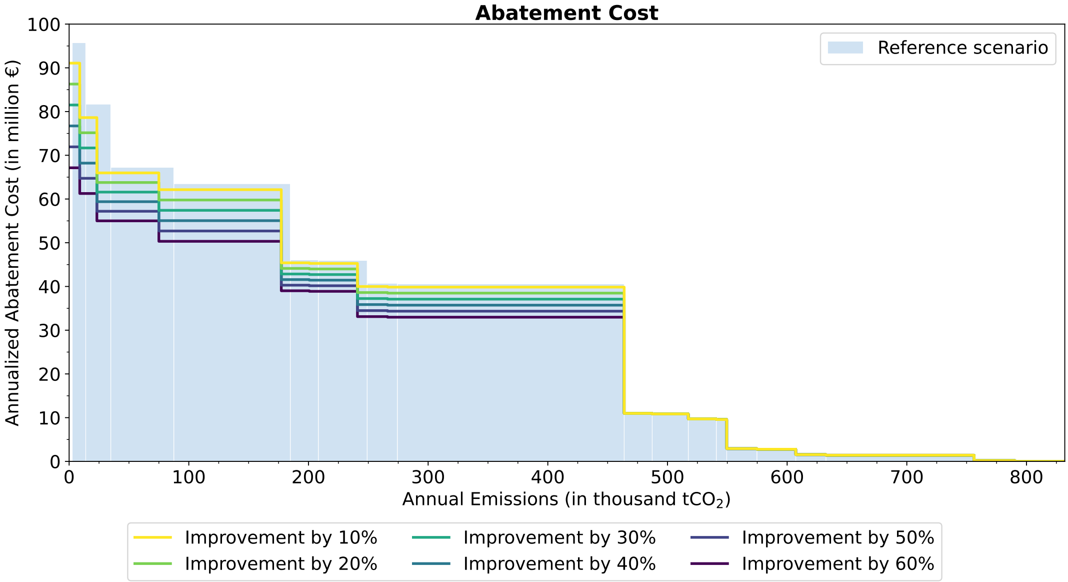
Carbon Capture Technologies: Cost-efficient Abatement



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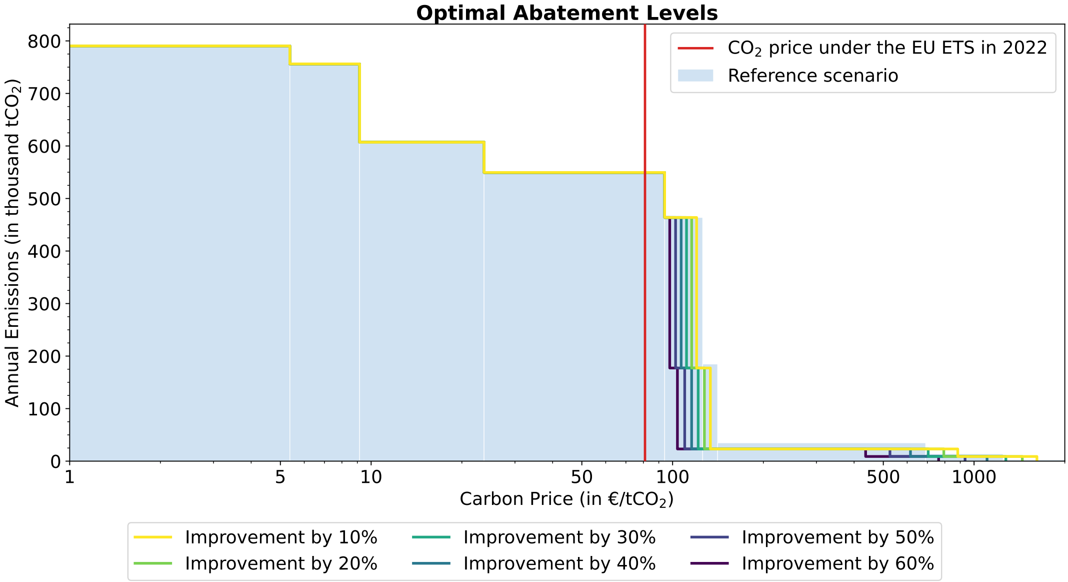
Carbon Capture Technologies: Optimal Abatement



Affordability of Low-Carbon Cement

- Earlier studies: comprehensive abatement would double the full cost of cement production[1]

- Without carbon pricing, $AC(\cdot)$ quantifies the change in production costs from decarbonization

- With carbon pricing, the increase in unit production cost resulting from an increase in the carbon price from p_1 to p_2 captures that firms respond by reducing emissions from $E^*(p_1)$ to $E^*(p_2)$:

$$\Delta = \big[[AC(E^*(p_2)) - AC(E^*(p_1))] \cdot A(r, T)^{-1} + p_2 \cdot E^*(p_2) - p_1 \cdot E^*(p_1)\big] \cdot q^{-1}$$

→ If $p_1 = €81/\text{tCO}_2$ and $p_2 = €126/\text{tCO}_2$, then $\Delta = €16/\text{tCO}_2$

[1] Fennell et al. (2022, *Nature*), ◁ Back

Carbon Contracts for Difference

- Governments seek to accelerate decarbonization by arranging carbon contracts for difference
- The annual minimum subsidy required for cement producers to reduce emissions to E^T, when the prevailing carbon price p only incentivizes $E^(p) > E^T$ is then:

$$S = [AC(E^T) - AC(E^*(p))] \cdot A(r, T)^{-1} - p \cdot (E^*(p) - E^T)$$

→ If $p = €81/tCO_2$ and $E^T = 184{,}824$ tCO_2, then $S = €14m$ per plant or $€37/tCO_2$ additionally abated