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Role of the cement industry in climate neutrality considering uncertainties in deployment of carbon capture technologies: A site-specific modeling approach

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Motivation & Context

- Many countries have set climate targets in response to global warming. Reaching them requires actions across all sectors. Industry as a major contributor is a big problem and not on track.
- Hard-to-abate industries rely on **long-lived, capital-intensive assets**, requiring **upfront investment**. Uncertainty related to future technologies (e.g., CCS) complicates decision-making.
- Cement production is **concentrated in a few plants**; Major changes made at facilities can have an impact on carbon emissions/energy demands at the national/regional scale.
- Assessments of pathways often rely on insights from energy system optimization models (ESOMs)
- Traditionally ESOMs usually treat industry as **homogeneous aggregated entities** with **continuous investment being available**. Although this can be reasonable assumption, it may not be so for small countries with a limited number of productions sites.

Research Questions

- Does a more realistic, site-specific representation of cement production investments within ESOMs change the conclusions about the timing and extent of mitigation activities in Finland?
- What role does the cement sector play in the decarbonization of the Finnish energy system, and how does this depend on technology availability and natural sinks?

Case study: Finnish cement industry (with two sites).

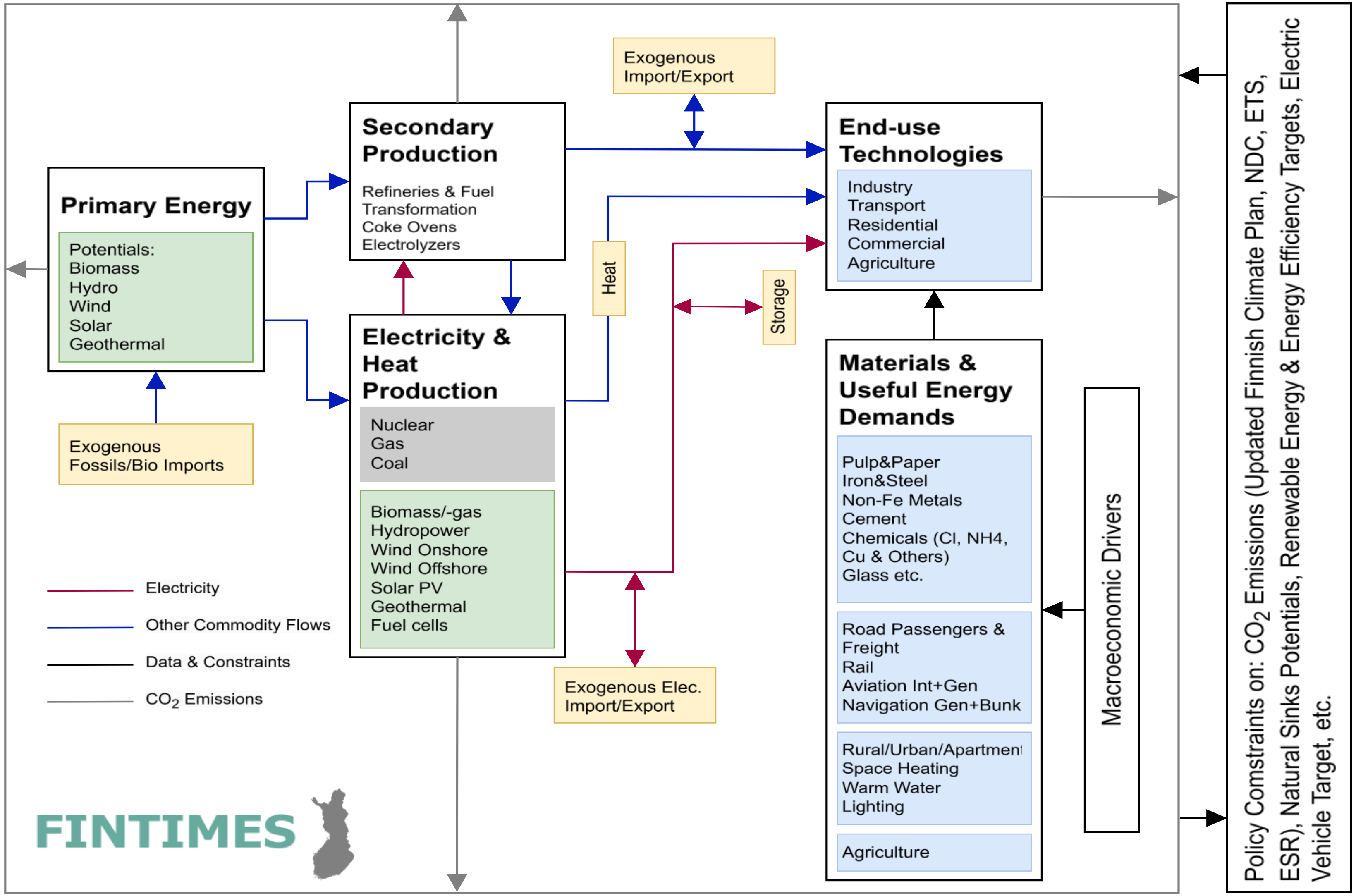
We developed a variant of FINTIMES, a bottom-up linear optimization model for Finland with site-specific details and compared with a general LP variant.

FINTIMES: A Finnish energy system model

- Model: FINTIMES (bottom-up, linear optimization) developed from JRC-EU-TIMES
- Scope: full energy system, 2020–2050 with five years period intervals

Updates

- Calibration of the power sector up to 2024
- Technoeconomic data update for hydrogen production, CCUS and electricity generation and finally the cement & steel



Aggregated vs. site-specific formulation

Feature	Aggregated LP	Site-specific MIP
Investment variable	Continuous	Discrete (binary)
Investment size	Fractional capacity allowed	Specific kilns/CCS sizes only
Retirement mechanism	Linear decay	Whole-unit retirement at once
Potential implications	Hedging against the later availability of a superior technology by small fractional investment on second-available technologies	Creates different commitment windows for each site therefore put each site with all or nothing type of investments

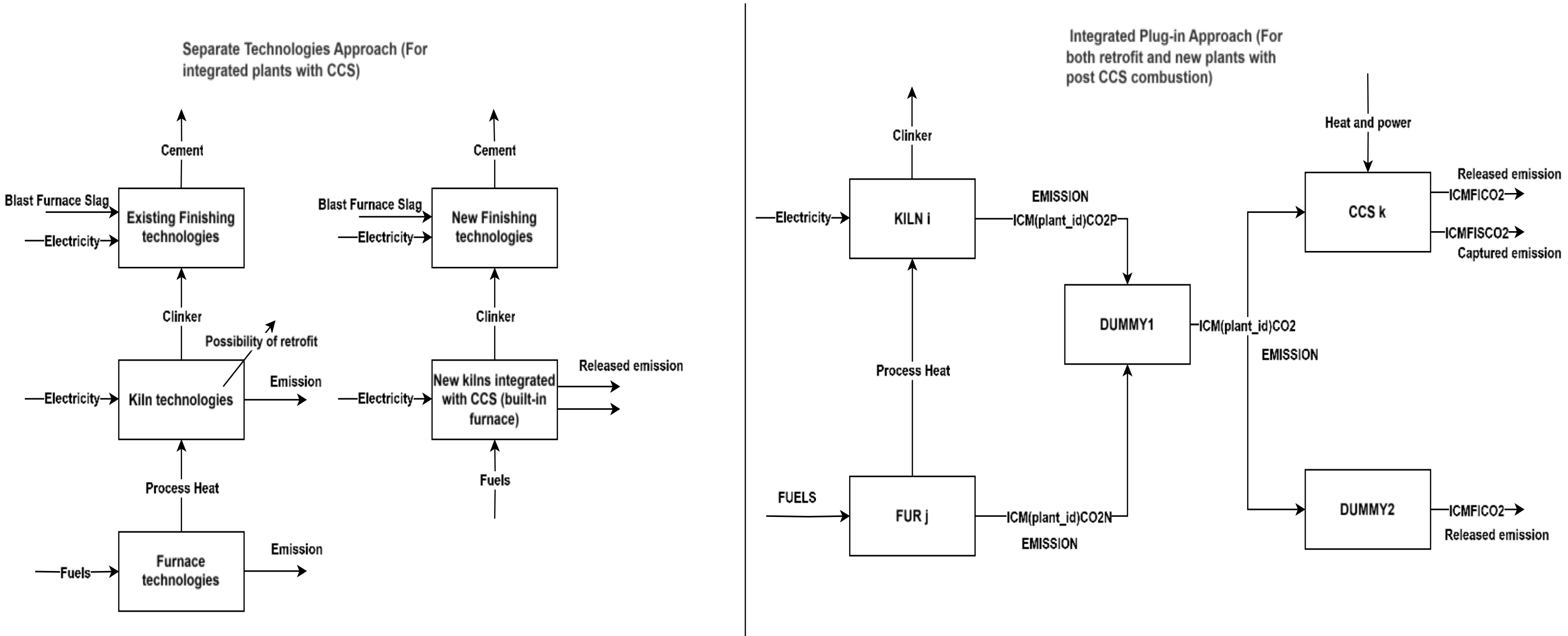
Site-specific modelling of cement

Each plant is represented with:

- Existing kiln vintages, plant-specific characteristics and remaining lifetimes (retirement tied to plant lifetimes).
- Retrofit and new-build options with/without CCS.

Discrete decisions:

- Whole kilns & CCS units / No fractional additions



- Model implementation of Finnish cement industry with two operating plants

Plant	Site label	Location	Establishment	Refurbishment year	Clinker production capacity (Mt clinker)
Parainen	PARA	Southwest Finland (Pargas)	1917	2000	1
Lappeenranta	LAPP	South Karelia (Lappeenranta)	1938	2007	0.6

Scenario Definition

Each dimension have two different pathways:

- Natural sinks:
  Available at baseline or unavailable from 2035
- CCS availability:
  Baseline TRLs or delayed by 5 years
- Modelling approach:
  Aggregated LP vs site-specific MIP

Scenario	Natural Carbon Sinks	CCS Availability Timeline	Approach for Modeling Cement	Model Used
BASE (LP)	Available (100% of baseline)	Follows baseline availability timeline (current TRLs)	Continuous	LP (Aggregated)
BASE (MIP)			Discrete	MIP (Site-specific)
DELAY5 (LP)	Available (100% of baseline)	TRL-based availability delayed 5 years	Continuous	LP (Aggregated)
DELAY5 (MIP)			Discrete	MIP (Site-specific)
NOSINKS (LP)	Not available	Follows baseline availability timeline (current TRLs)	Continuous	LP (Aggregated)
NOSINKS (MIP)			Discrete	MIP (Site-specific)
NOSINKS-DELAY5 (LP)	Not available	TRL-based availability delayed 5 years	Continuous	LP (Aggregated)
NOSINKS-DELAY5 (MIP)			Discrete	MIP (Site-specific)

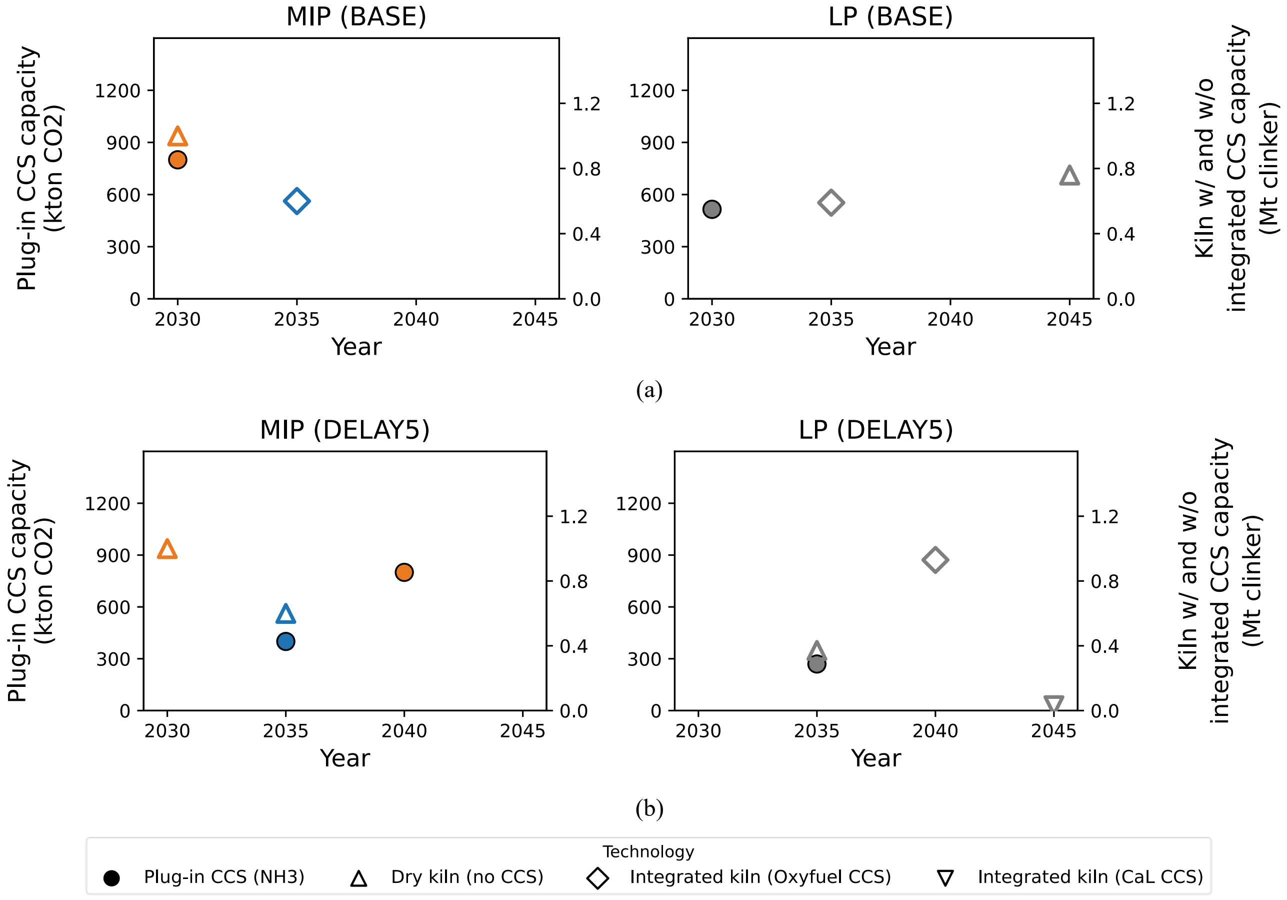
Cement technology deployment patterns: LP vs MIP

Aggregated (linear):

- Gradual CCS uptake (small chilled NH_3 capture then oxy-fuel which is the superior technology) in BASE
- In DELAY5, model hedges with small chilled NH_3 retrofit in 2035, oxy-fuel in 2040

Site-specific (mixed-integer):

- MIP creates commitment points: LAPP adopts oxy-fuel kiln at first availability, 2035, while PARA chooses plug-in option (BASE)
- With CCS delay, MIP chooses chilled NH_3 retrofits for both site (which is not the superior among
and sin
PARA



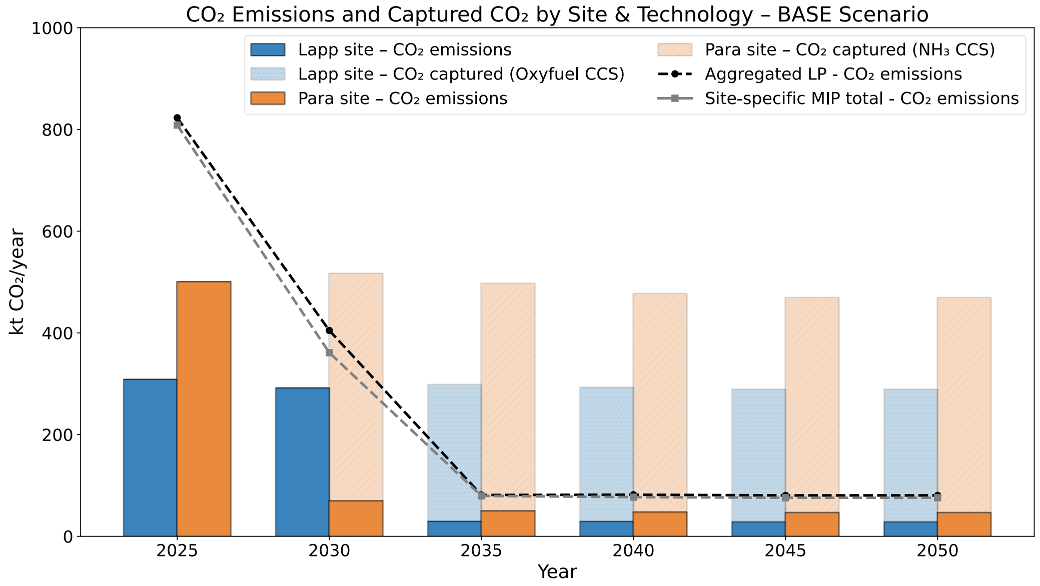
(a)

(b)

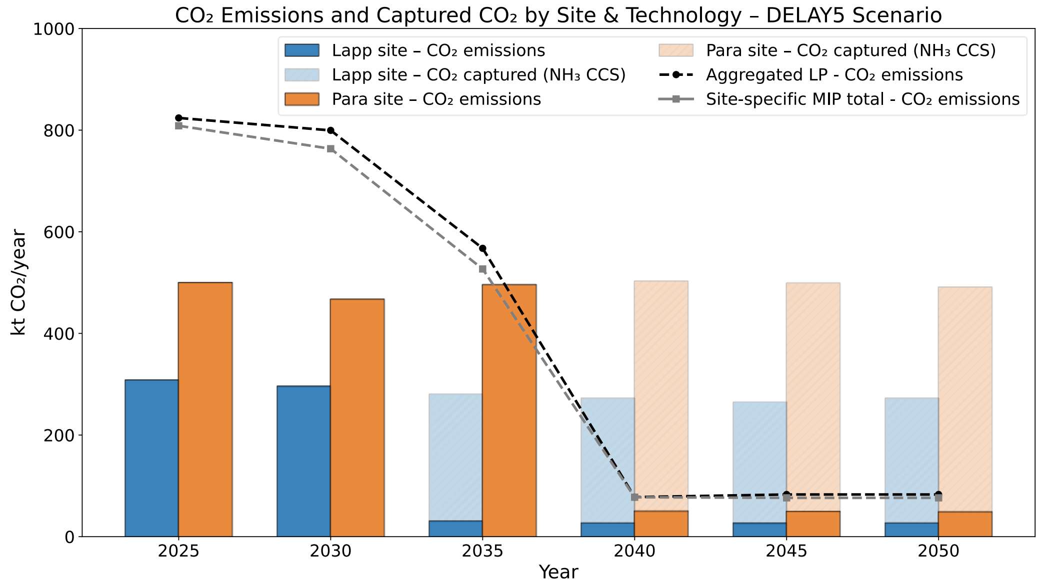
Discrete investment modelling prevents fractional investments, leading to a different pattern in technology deployment

Decarbonization of cement

- ○ Fuel switching and efficiency measures address only energy-related emissions, leaving process emissions from calcination untouched.
- ○ Process emissions from calcination remain unless CCS is deployed.
- ○ The pace of emission reduction slightly differ in each model variants.
- ○ There is a change in production rates in across site (not visible from this graph).



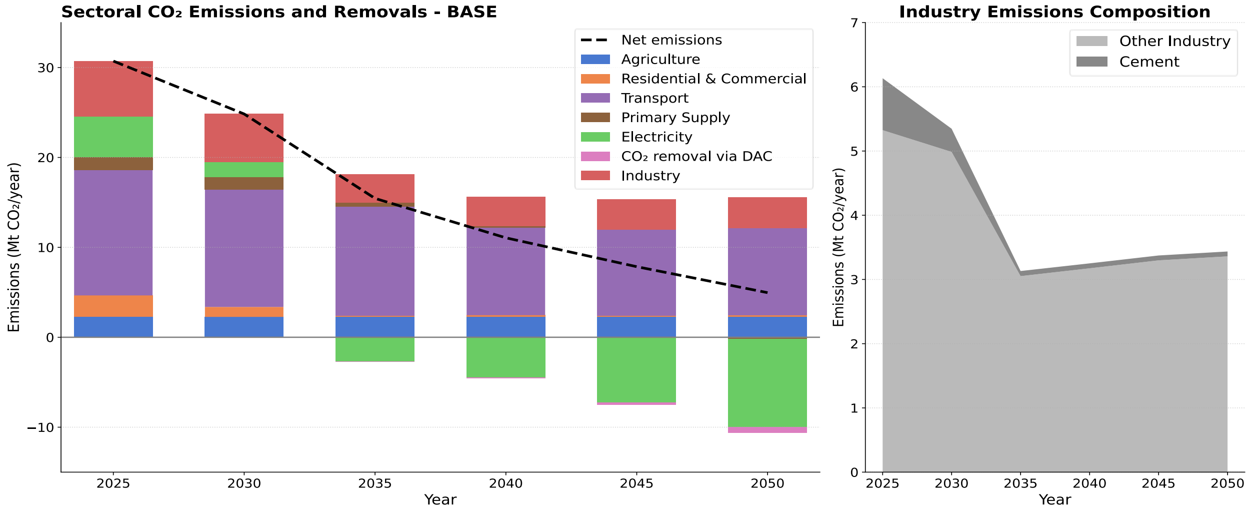
CO₂ Emissions and Captured CO₂ by Site & Technology – BASE Scenario



CO₂ Emissions and Captured CO₂ by Site & Technology – DELAY5 Scenario

Sectoral energy transition pathways

- ○ Delaying CCS keeps emissions higher in power & hard-to-abate sectors, creating a carbon lock-in effect.
- ○ The system compensates by:
  - Pushing other sectors (especially transport) to decarbonize faster
  - Increasing reliance on other measures such as (direct/indirect) electrification
- ○ Total discounted system cost rises further when CCS is delayed.



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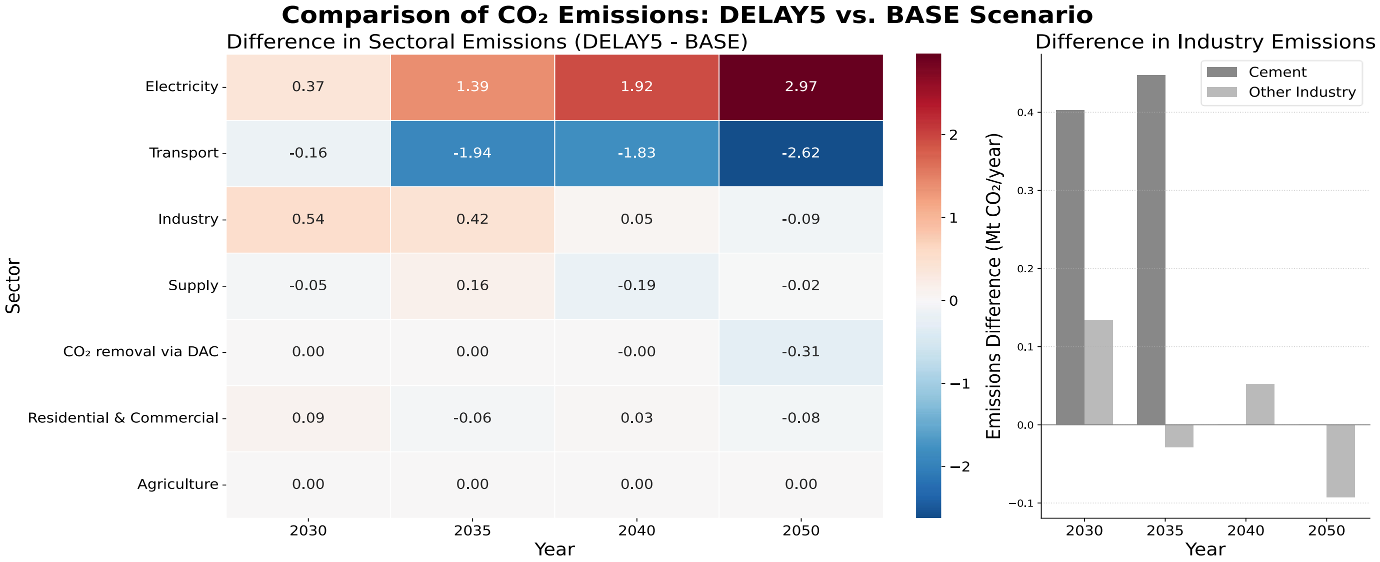

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Takeaways

- Site-specific modelling matters:
  - Prevents hedging & fractional investments
  - Allow the model to capture CCS investment patterns on site level
  - The approach is generalized to other hard-to-abate sectors
- Considering the combination of carbon sinks potentials and CCS availability is necessary in identifying when and which sectors can become a bottleneck for energy transitions.
- Delayed CCS shifts burden to transport and increases system cost.
- Decarbonizing (cement) industry is not an isolated challenge therefore the trade-offs with the rest of the system matter and should not be overlooked.

Limitations

- Perfect foresight
- Lack of spatial resolution
- Demand-side mitigation options not considered

Future work

- Extending site-specificity to other hard-to-abate sectors

Thank you for your attention!

Kiitos

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Read the full article here:

https://doi.org/10.1016/j.enconman.2025.120792

TRL Assumptions

Technology	CCS category	Capacity unit	Design capacity Para	Design capacity Lapp	TRL	Earliest start year
Dry process kiln (without CCS)	-	Mt clinker	1.0	0.6	9	2020
Oxyfuel kiln with CCS	Integrated	Mt clinker	1.0	0.6	7	2035
Calcium looping kiln with CCS	Integrated	Mt clinker	1.0	0.6	6-7	2035
MEA post-combustion CCS	Plug-in	Mt CO_2	0.8	0.48	8-9	2030
Chilled-ammonia CCS	Plug-in	Mt CO_2	0.8	0.48	8	2030
Membrane-assisted CCS	Plug-in	Mt CO_2	0.8	0.48	5	2040

Investment modelling formulations

Continuous/
STOCK

$$TOT\_CAP_{(p,t)} = \sum_{v \leq T \,\&\, (B_{(t)} - B_{(v)}) < L_p} VAR\_NCAP(v,p) + EXISTING\_CAP(t,p)$$

Lumpy/
PASTI

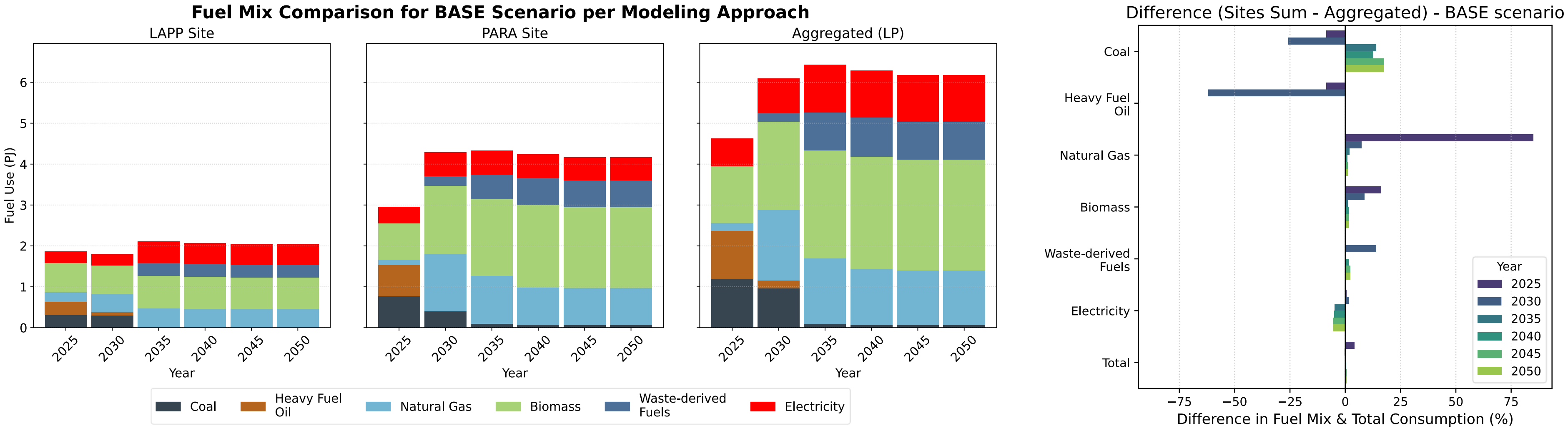
$$VAR\_NCAP_{(i,v,p)} = \sum_{u} NCAP_{DISC\,(i,p,u)} \cdot u_{(i,v,p,u)}, \qquad u_{(i,v,p,u)} \in \{0,1\}$$

Feasibility of Finnish climate targets across various natural sinks potential and CCS availability

Climate Target	**CCS Availability**	**SINKS available (100%)**	**80% Sinks**	**70% Sinks**	**60% Sinks**	**50% Sinks**	**40% Sinks**	**20% Sinks**	**NOSINKS**
2035 Carbon Neutrality target	Current TRLs	Feasible	Feasible	Feasible	Feasible	**Infeasible**	**Infeasible**	**Infeasible**	**Infeasible**
	TRLs shifted by 5 years	Feasible	Feasible	Feasible	**Infeasible**	**Infeasible**	**Infeasible**	**Infeasible**	**Infeasible**

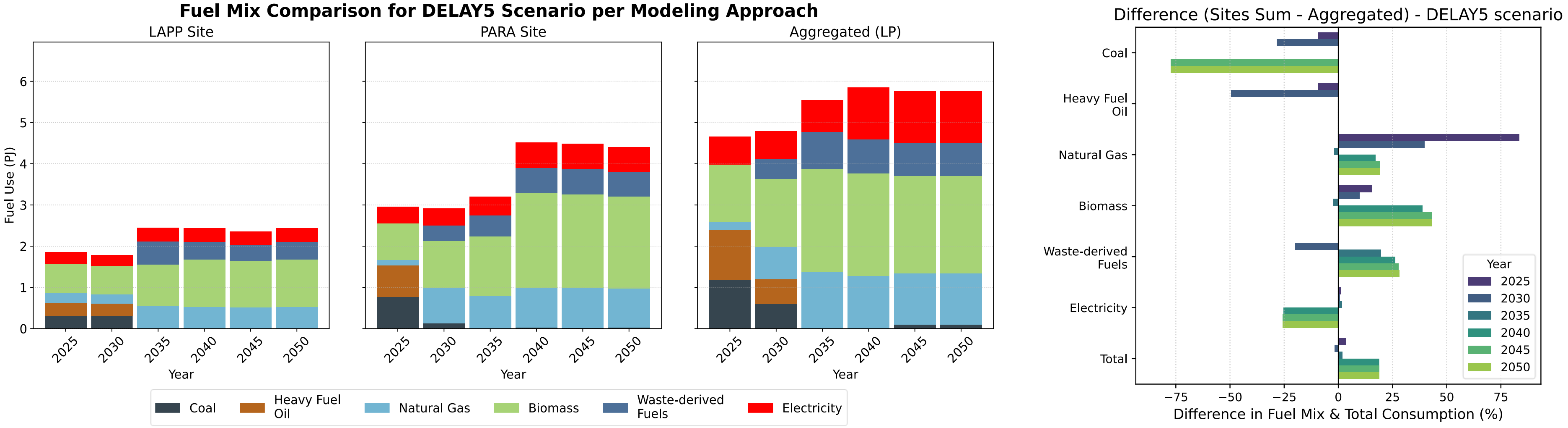
The 2035 target becomes infeasible if sink capacity falls below 60% of the projected baseline, especially if CCS is delayed

Fuel mix comparison


Fuel Mix Comparison for BASE Scenario per Modeling Approach

Difference (Sites Sum - Aggregated) - BASE scenario

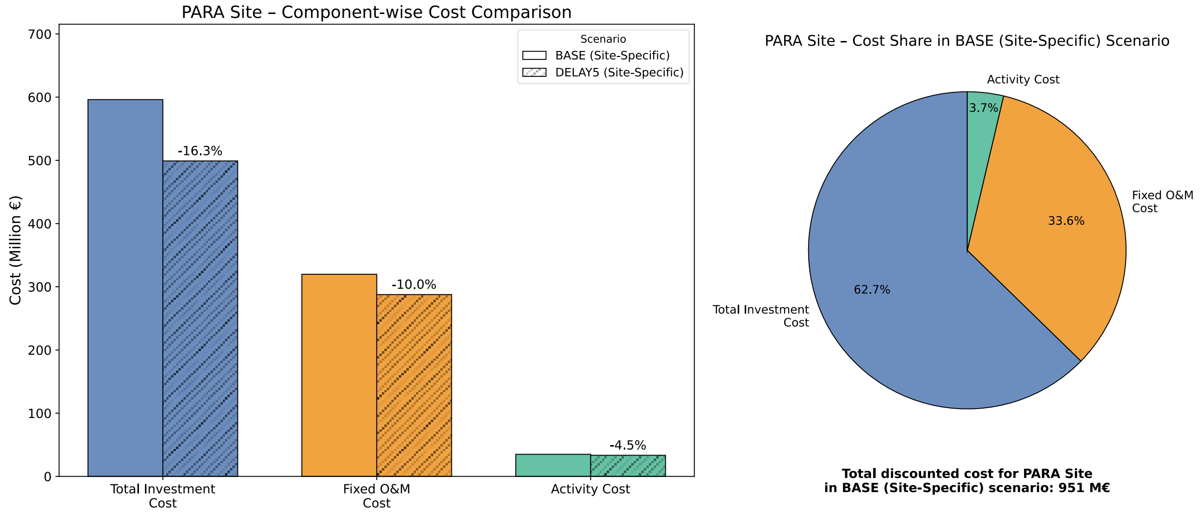
(a)


Fuel Mix Comparison for DELAY5 Scenario per Modeling Approach

Difference (Sites Sum - Aggregated) - DELAY5 scenario

(b)

Cost figures



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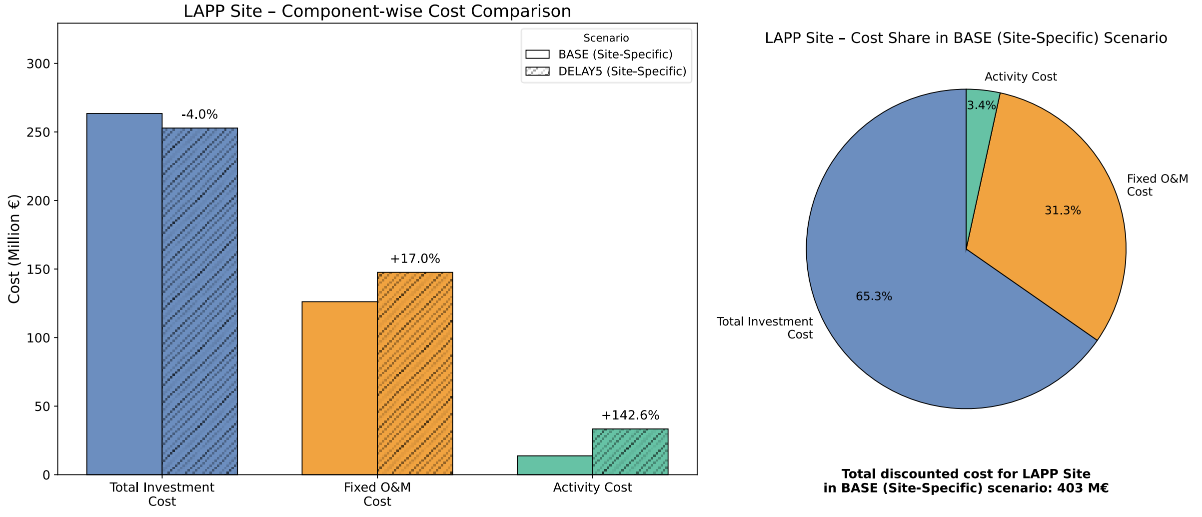

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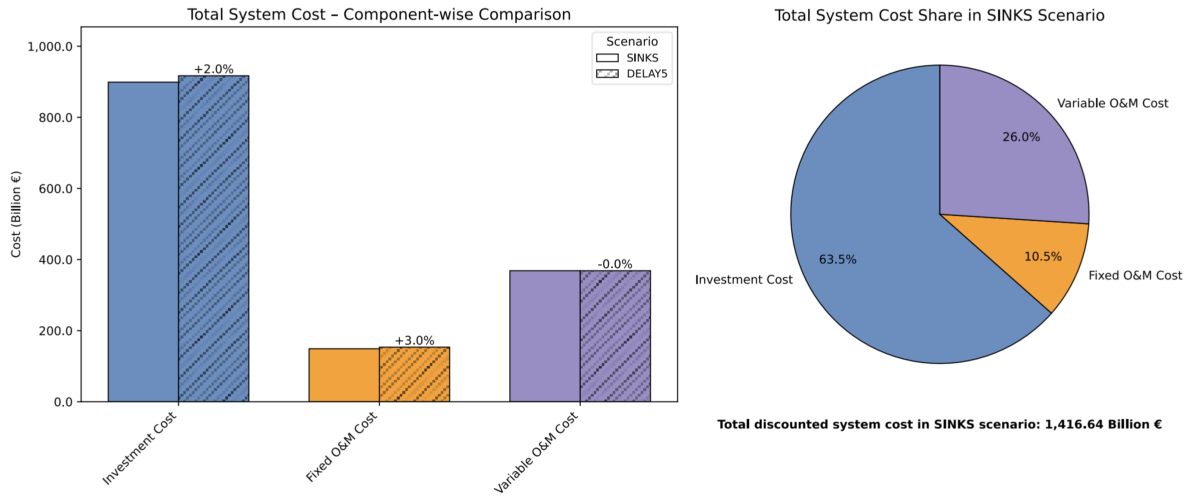
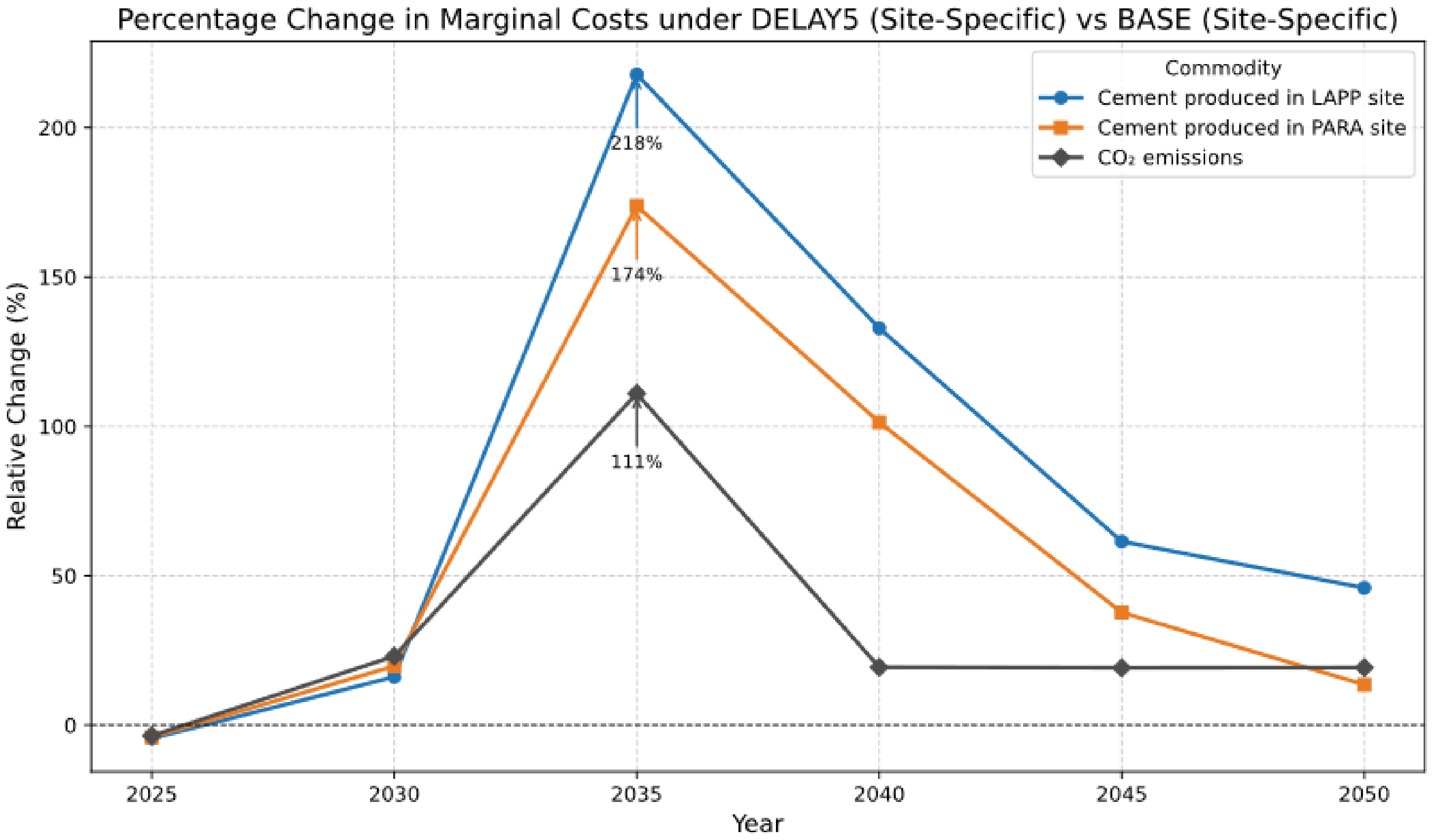
For LAPP: Increase in fixed operational and activity costs is due to the reliance on the less efficient, fuel-based CCS unit instead of the superior integrated kiln



Marginal costs across time under DELAY5 vs BASE.



The absolute cumulative investment values across two scenarios from the MIP variant for the entire modeling horizon.

Sector/mitigation route	Cumulative Investment in BASE (€ million)	Cumulative Investment in DELAY5 (€ million)
Carbon removal technologies (BECCS and DAC)	4971	2989
Storage systems	8571	8544
Building (residential and commercial)	32203.02	32815.6
Power sector excluding BECCS	25433.13	26134.69
Hydrogen	2632	2824
Industry sector	20,175	20065
Biorefinery	399	584
Transport sector	94634	98823