Direct Air Capture and interactions with the electricity market

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Presentation at INRAE conference, Paris, May 19th 2025

Introduction

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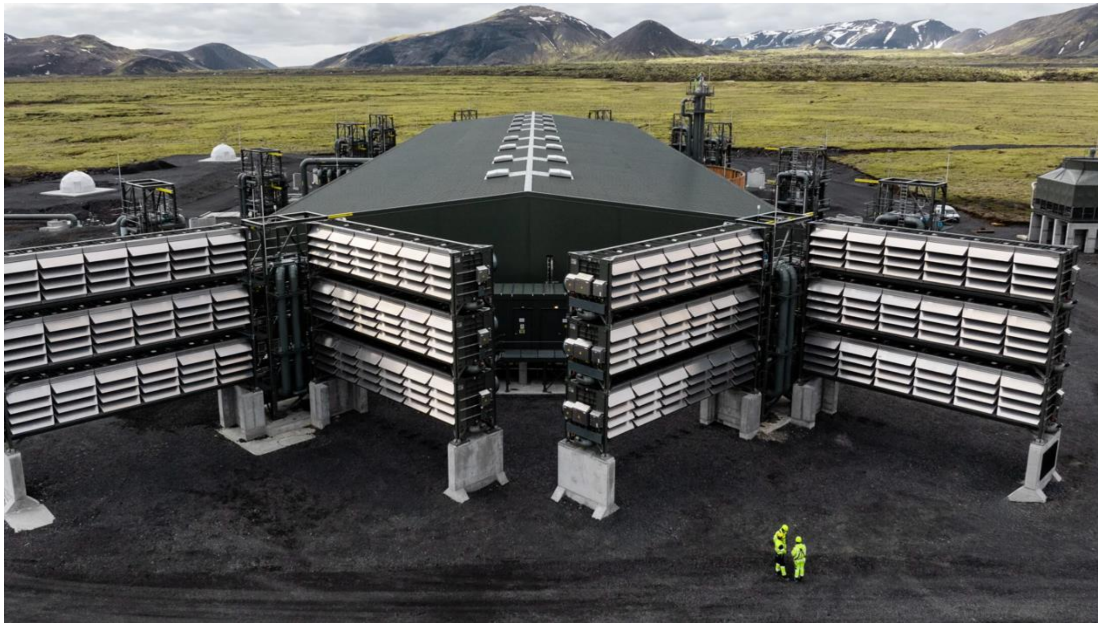
- Stabilizing global warming requires net zero CO_2 emissions
  - But: What about hard-to-abate emissions?

→ Carbon Dioxide Removals (CDR) needed («negative emissions»)
  - Planting trees; BioCCS
  - Direct Air Capture (DAC)
  - IPCC and IEA scenarios include extensive use of DAC in the future

- What is DAC?
  - Extracting CO_2 from the air
  - Storing it underground or below seabed



Climeworks
Mammoth DAC facility (Iceland)

Introduction

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- DAC is not a quick fix of the climate change problem
  - Challenge: CO_2 concentration in the air ca. 430 ppm → 0.043%
  - High costs (>> EU ETS price)
  - Very energy intensive (electricity and heat)
  - Where to store gigatons of CO_2?
- But: DAC is an immature technology
  - RD&D activities in different companies → costs may come down
  - Economies of scale? Or rising costs due to scarcity of energy and storage?
  - Different DAC technologies with different energy intensities
- How will DAC adoption interact with the electricity market?
  - Will DAC plants run continously or flexibly (depending on electricity price)?

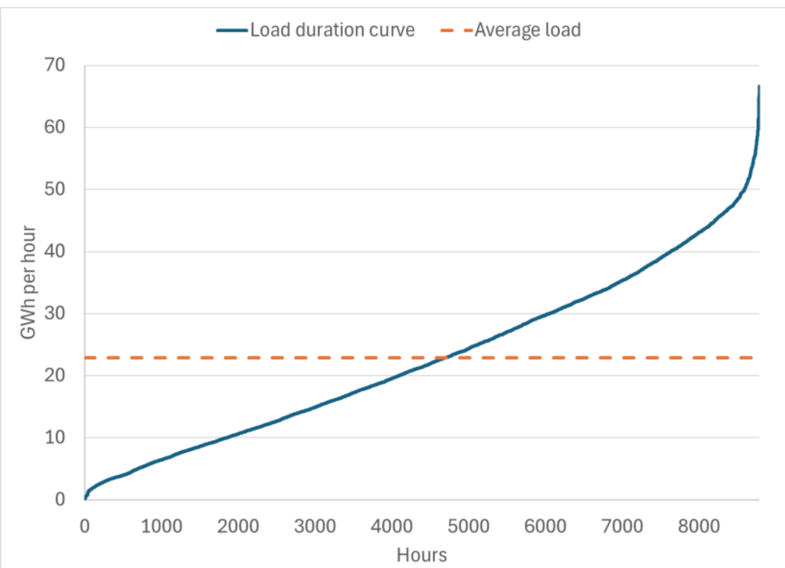
Introduction

- Future electricity market: Intermittent sources will dominate
  - Wind and solar

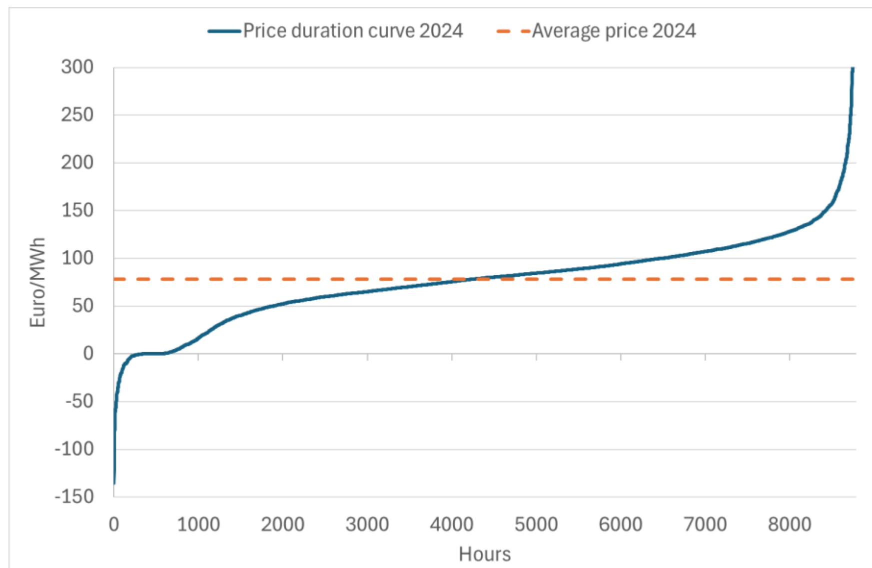
→ More volatile electricity prices

- Illustration: Germany 2024 (hourly data)

Load duration curve for wind and solar



Price duration curve



Research questions

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- **How will DAC adoption interact with the electricity market?**

- Will it aggravate or alleviate electricity price volatility and imbalances?
- How will changes in the electricity market affect the choice of DAC technology – and vice versa?
- Should the government support the most or the least energy-intensive DAC technologies (if any)?

DAC: Different technologies

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- Two main DAC configurations: Liquid or solid sorbents
  - Keith et al. (2018); Realmonte et al. (2019) Ozkan et al. (2022); Herzog (2022)
- Liquid DAC: high temperature, large-scale operations, equipment already technologically mature, energy intensive
- Solid DAC: low temperature, small-scale modular, less energy intensive, higher capital costs
- Our analysis: Two different DAC technologies «solid» and «liquid»
  - Possible outcome: Capital-intensive «Solid» runs continuously, while energy-intensive «liquid» only runs when electricity price is sufficiently low

Theoretical model

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- Partial equilibrium model with two phases t = 1,2
    - t = 1: High production of electricity (S); t = 2: Low production (σS, $\sigma < 1$)
- Price of electricity p_t
    - Relative price (volatility): $\hat{p} = \frac{p_2}{p_1} > 1$
- Unit capacity cost of electricity prodution β
- Profits for electricity producers: $\pi^S = p_1 S + p_2 \sigma S - \beta S$

→ Zero profit condition $p_1 + p_2 \sigma - \beta = 0$

- Negative relationship between the two prices

  (for given β and σ): $dp_1 = -\sigma dp_2$
- Demand (excl. DAC): $D(p_t)$, $D' < 0$
    - Assume isoelastic demand to derive reduced form expressions

Theoretical model

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- Add electricity demand from DAC (disregard heat)
- Assume two DAC technologies *j* with different unit capital costs (γ_j) and energy intensities (ε_j) – per unit CO_2 captured
  - $\gamma_1 > \gamma_2$
  - $\varepsilon_1 < \varepsilon_2$
- Electricity used to capture one ton of CO_2: $e_{j,t} = \varepsilon_j C_{j,t}$
  - $C_{j,t}$: CO_2 captured by technology *j* in phase *t*
- Electricity market equilibrium in phase *t*: $S_t = D(p_t) + \sum_j e_{j,t}$
- Cumulative capture of CO_2: $C = \sum_{j,t} C_{j,t}$
- Assume convex storage costs $u(C) \rightarrow u'(C) < 0$
  - DAC producer faces fixed unit storage cost *u* equal to equilibrium level of $u'(C)$
  - Reduced form expressions: Assume quadratic $u(C)$ function

Theoretical model

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- DAC producer's profit:

$$\pi^{DAC} = \sum_{j,t}\left[\tau - p_t\varepsilon_j - u\right]C_{j,t} - \sum_j \gamma_j K_j \qquad \text{s.t. } C_{j,t} \le K_j$$

  - τ: CO_2-price (= DAC subsidy)

→ First order conditions:

1. $\tau - p_t\varepsilon_j - u - \lambda_{j,t} \le 0 \qquad \left\{= 0 \text{ if } C_{j,t} > 0\right\}$

2. $-\gamma_j + \lambda_{j,1} + \lambda_{j,2} \le 0 \qquad \left\{= 0 \text{ if } K_j > 0\right\}$

  - $\lambda_{j,t}$: Shadow price on the capacity constraints

1. → Produce if net operating income is (weakly) positive

2. → Invest if net income ($\lambda_{j,1} + \lambda_{j,2}$) covers capacity cost ($\gamma_j$)

- Note: Capacity is fully used in phase 1 (low electricity price)

Theoretical analysis

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- Will adoption of DAC increase or decrease price volatility $\hat{p} = \dfrac{p_2}{p_1}$?
- We find: $$d\hat{p} < 0 \ \text{ iff } \ \frac{\sum_j \varepsilon_j dC_{j,2}}{\sum_j \varepsilon_j dC_{j,1}} < \sigma \qquad (\sigma = S_2 / S_1)$$
- In words:

  Prices become *more* volatile unless DAC utilization is sufficiently lower in the high-price phase 2 than in phase 1
- In other words:

  If DAC is mostly turned off during the high-price phase, prices become *less* volatile
- What if one technology runs continuously and one flexibly?

Theoretical analysis

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- Two possible main outcomes:
- **OUTCOME 1**: Investments in only *one* technology

  $C_{j,1} = K_j$ and $0 \le C_{j,2} \le K_j$

- **OUTCOME 2:** Investments in *both* technologies

  $C_{j,1} = K_j$

  - Three alternatives:

    2i) $C_{j,2} = 0$

    2ii) $C_{1,2} = K_1$ and $C_{2,2} = 0$

    2iii) $C_{j,2} = K_j$
- Alternative ii) most likely in our model (cf. also simulations)
- Here: Focus on Outcome 2ii)

$\hat{p}$

Theoretical analysis

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- We derive reduced form expressions and investigate how changes in important parameters affect price volatility, DAC investments etc

		Parameter				
		τ	γ_1	γ_2	ε_1	ε_2
Variable	u	+ (= 1)	-	-	-	-
	p_1	0	+	-	+	-
	p_2	0	-	+	-	+
	$\hat{p}$	0	-	+	-	+
	K_1	+	-	?*	-	?*
	K_2	+	?*	-	?*	-
	S	+	-	?	?	?

- Higher CO_2 price:
  - Increases investments in both DAC technologies
  - Price volatility unchanged

Theoretical analysis

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		Parameter				
		τ	γ_1	γ_2	ε_1	ε_2
Variable	u	+ (= 1)	-	-	-	-
	p_1	0	+	-	+	-
	p_2	0	-	+	-	+
	$\hat{p}$	0	-	+	-	+
	K_1	+	-	?*	-	?*
	K_2	+	?*	-	?*	-
	S	+	-	?	?	?

- Higher capital cost for technology *j* (γ_j) :
  - Price volatility *decreases* if *j* = 1 (*least* energy intensive), but *increases* if *j* = 2 (*most* energy intensive)
  - Investments drop for technology *j* – ambiguous for the other technology
- Higher energy intensity for technology *j* (ε_j) :
  - Similar results as for capital costs

Theoretical analysis

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Intuition behind the results:

- Lower (capital or energy) costs for the least energy-intensive DAC technology (which runs continously)

  → More use of this technology

  → More electricity demand in *both* phases

  - More *inflexible* electricity demand makes prices more volatile

- Lower (capital or energy) costs for the most energy-intensive DAC technology (which runs continously) → More use of this technology

  → More electricity demand *only in low-price* phase

  - More *flexible* electricity demand makes prices less volatile
  - Might even need *less* electricity capacity if capital costs decline for this technology

Numerical analysis - calibration

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- Parameterize the model based on various DAC data (γ_j and ε_j) and in the context of the German electricity market – annual data

Parameter	**Value**	**Unit**
Electricity intensity of capital-intensive DAC (ε_1)	0.25	MWh/tCO_2
Electricity intensity of energy-intensive DAC (ε_2)	1.535	MWh/tCO_2
Cost of capture capacity of capital-intensive DAC (γ_1)	380	$Euro/tCO_2$
Cost of capture capacity of energy-intensive DAC (γ_2)	152	$Euro/tCO_2$
Share of intermittent electricity supply in phase two (σ)	0.333	
CO_2 price (τ)	400	$Euro/tCO_2$
Cost of electricity capacity (β)	100	$Euro/MWh$
Electricity demand parameter ($\bar{D}$)	2373	$TWh/year$
Long-run price elasticity of electricity demand (α)	-0.5	
Initial marginal cost of storage (μ_0)	15	$Euro/tCO_2$
Marginal cost of storage coefficient (μ)	0.126	$Euro/(tCO_2)^2$

Numerical analysis - simulation

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- We simulate the model without and with DAC

Variable	Value	Unit
Without DAC:		
Electricity price in phase 1 (p_1)	25	Eur/MWh
Electricity price in phase 2 (p_2)	225	Eur/MWh
Price volatility ($\hat{p}$)	9	-
Electricity capacity per phase (S)	475	TWh
With DAC:		
Electricity price in phase 1 (p_1)	42	Eur/MWh
Electricity price in phase 2 (p_2)	173	Eur/MWh
Price volatility ($\hat{p}$)	4.1	-
Electricity capacity per phase (S)	935	TWh
Investments in capital-intensive DAC (K_1)	525	$MtCO_2$
Investments in energy-intensive DAC (K_2)	286	$MtCO_2$
Captured CO_2 ($C_{j,t}$)	1,336	$MtCO_2$
Electricity use for DAC in phase 1 ($e_{j,1}$)	570	TWh
Electricity use for DAC in phase 2 ($e_{j,2}$)	131	TWh
Marginal cost of storage (u)	183	$Euro/tCO_2$

<u>Without DAC:</u>

- High price volatility

<u>With DAC:</u>

- Outcome 2ii)
- Lower price volatility
- Highest investment in technology 1

Numerical analysis - simulation

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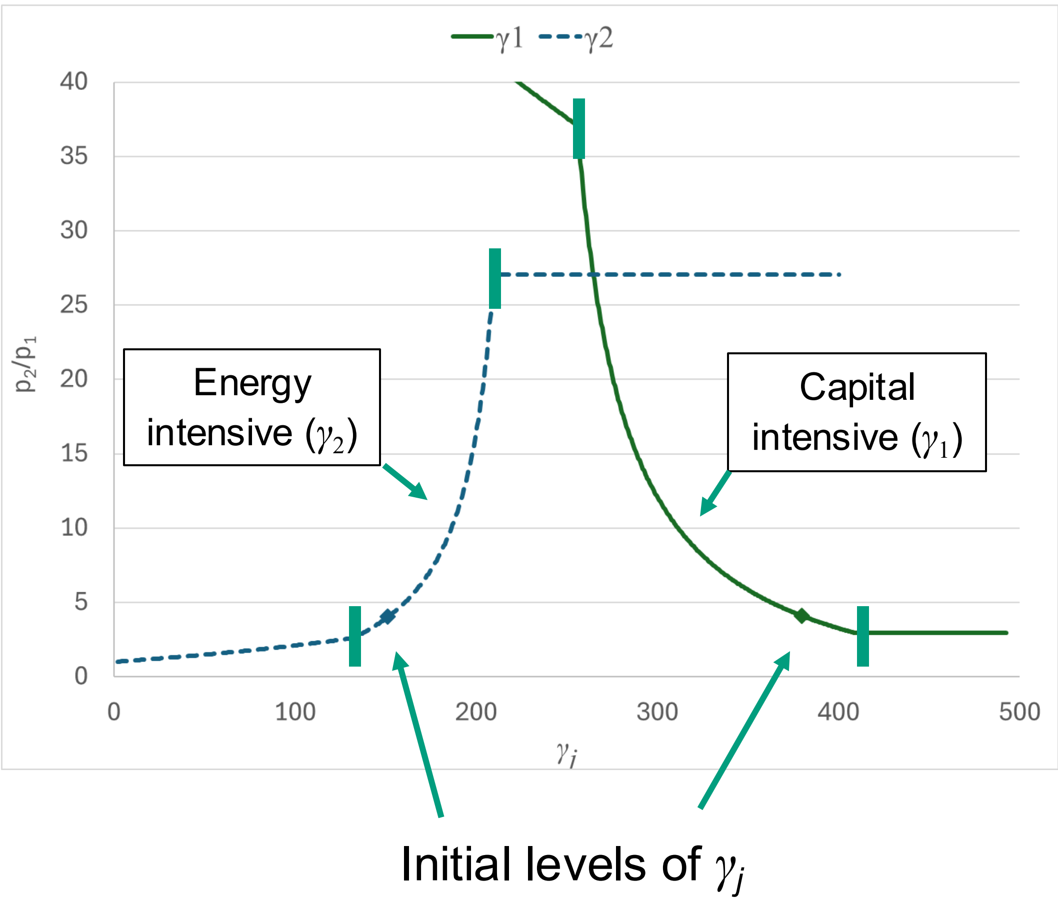
- What are the effects of changes in capital costs (γ_j)?



: Boundaries of Outcome 2

Results are in line with analytical results for Outcome 2

Similar pattern if technology *j* is alone in the market (Outcome 1)

Numerical analysis - simulation

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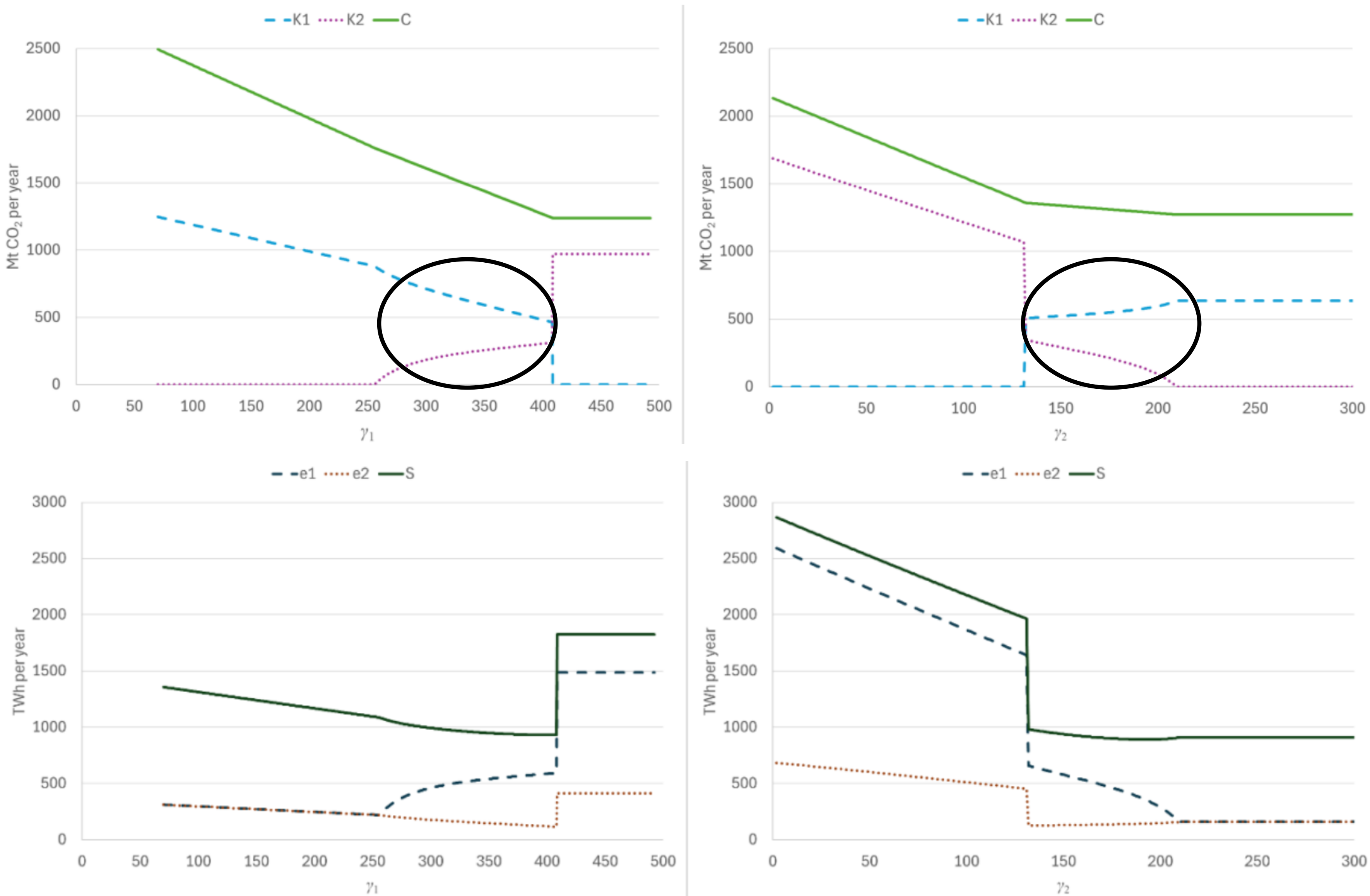
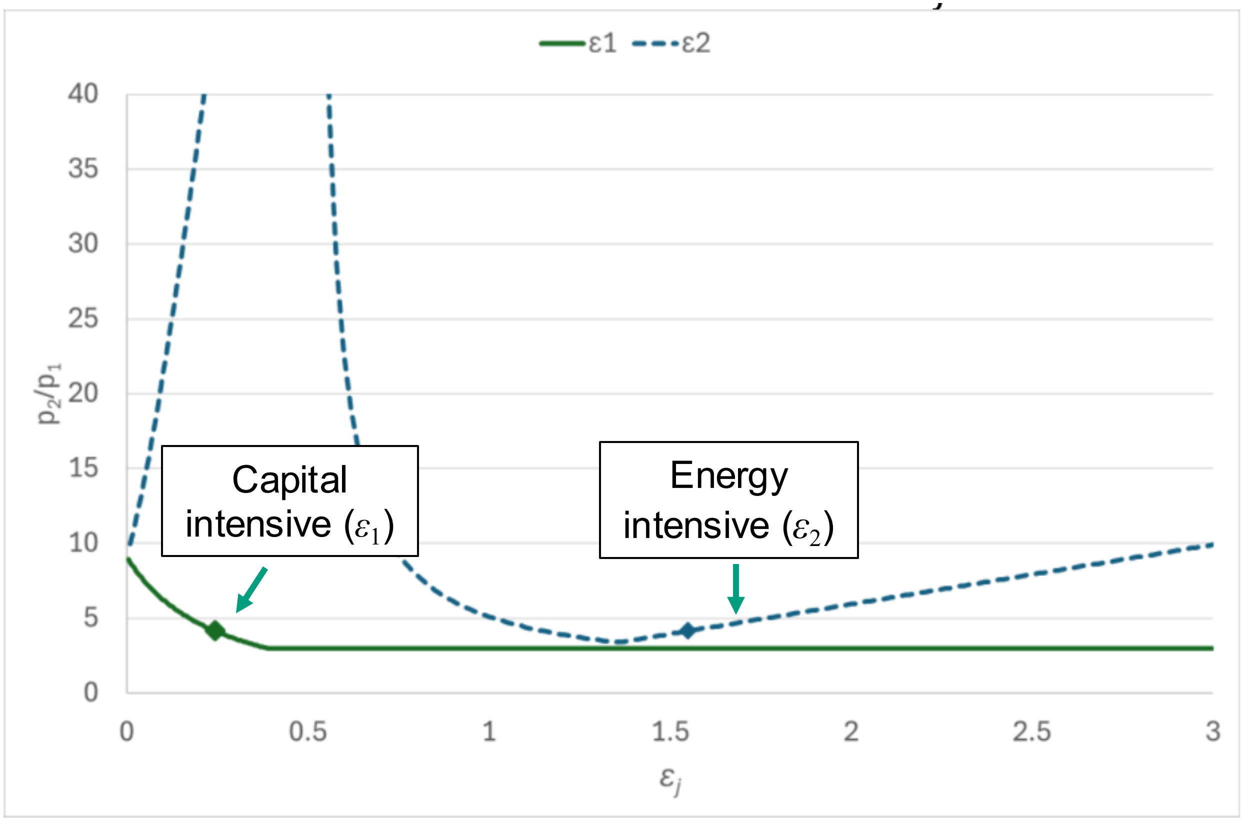


Numerical analysis - simulation

- What are the effects of changes in energy intensity (ε_j)?



Results are in line with analytical results for Outcome 2

If tech 2 is alone in the market (Outcome 1), further efficiency improvements have opposite effects

Changes in energy intensity have several effects on energy use

Numerical analysis - simulation

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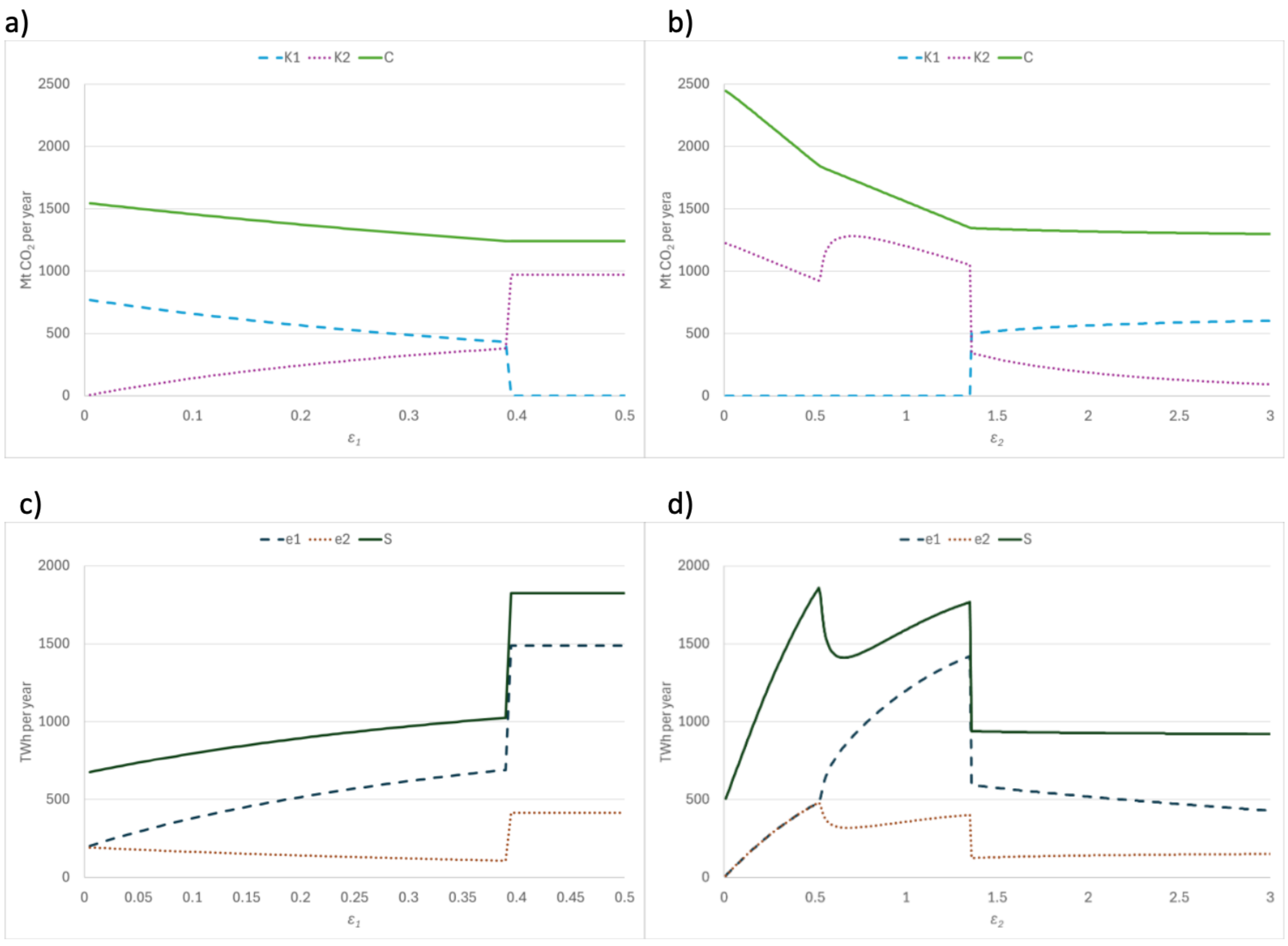

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Numerical analysis - simulation

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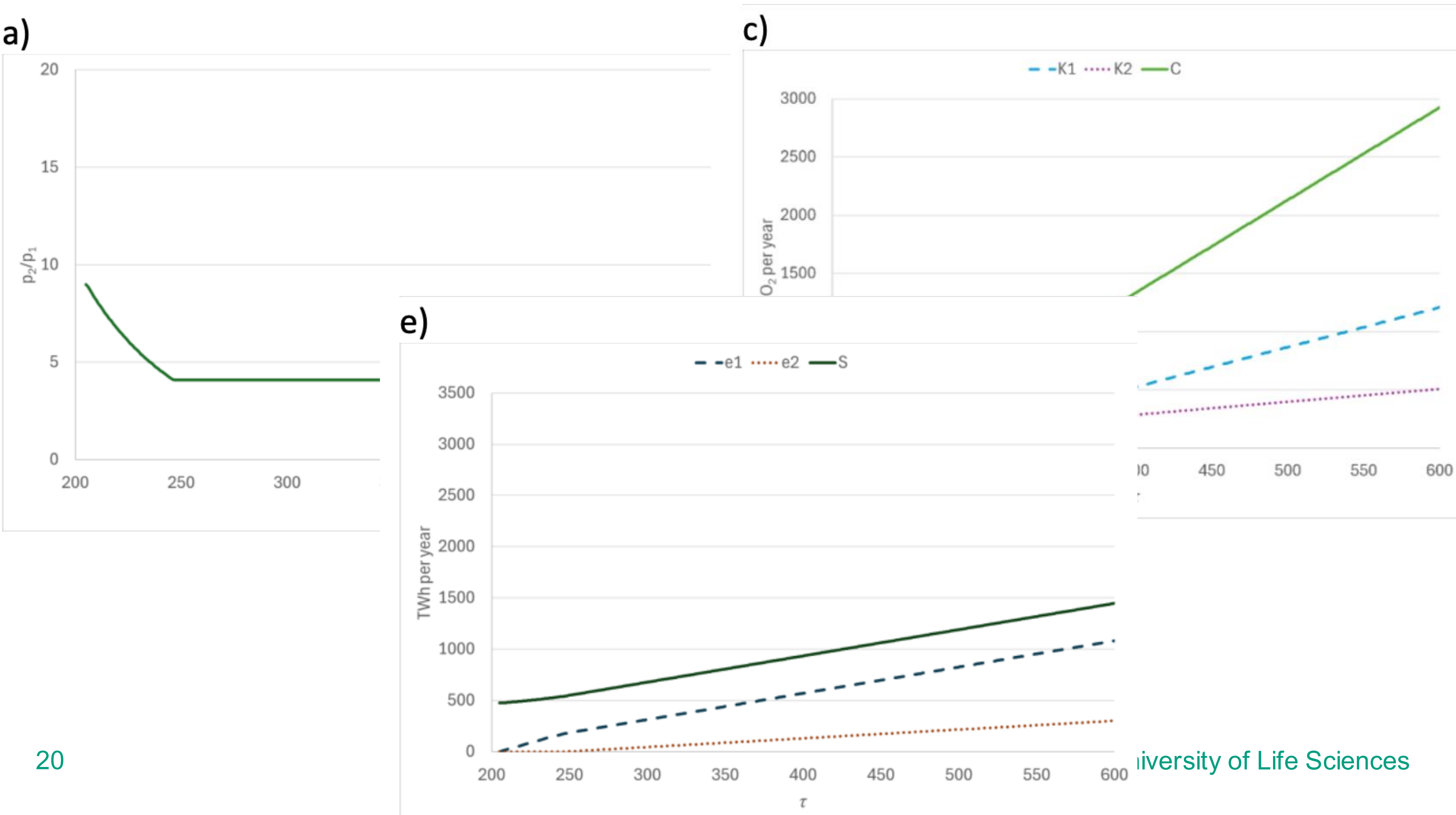
- What are the effects of changes in the CO_2 price?



Conclusions

- DAC can either increase or decrease electricity price volatility.
  - Depends on the choice of DAC technology
- Cost reductions for the most energy *efficient* DAC technology increase price volatility
  - More continuous electricity demand
- Cost reductions for the most energy *intensive* DAC technology decrease price volatility
  - Larger share of electricity demand is flexible and turned off in high-price phases
- Higher CO_2 prices increase deployment of the most energy efficient DAC technology to a larger degree than the most energy intensive
  - More profitable to run the DAC plant continuously