Unravelling CO_2 Value Chain Participation under Negative Emission Pricing and EU Industry Relocation

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CO_2 Value Chain: Carbon capture (CC), transport & storage (T&S)

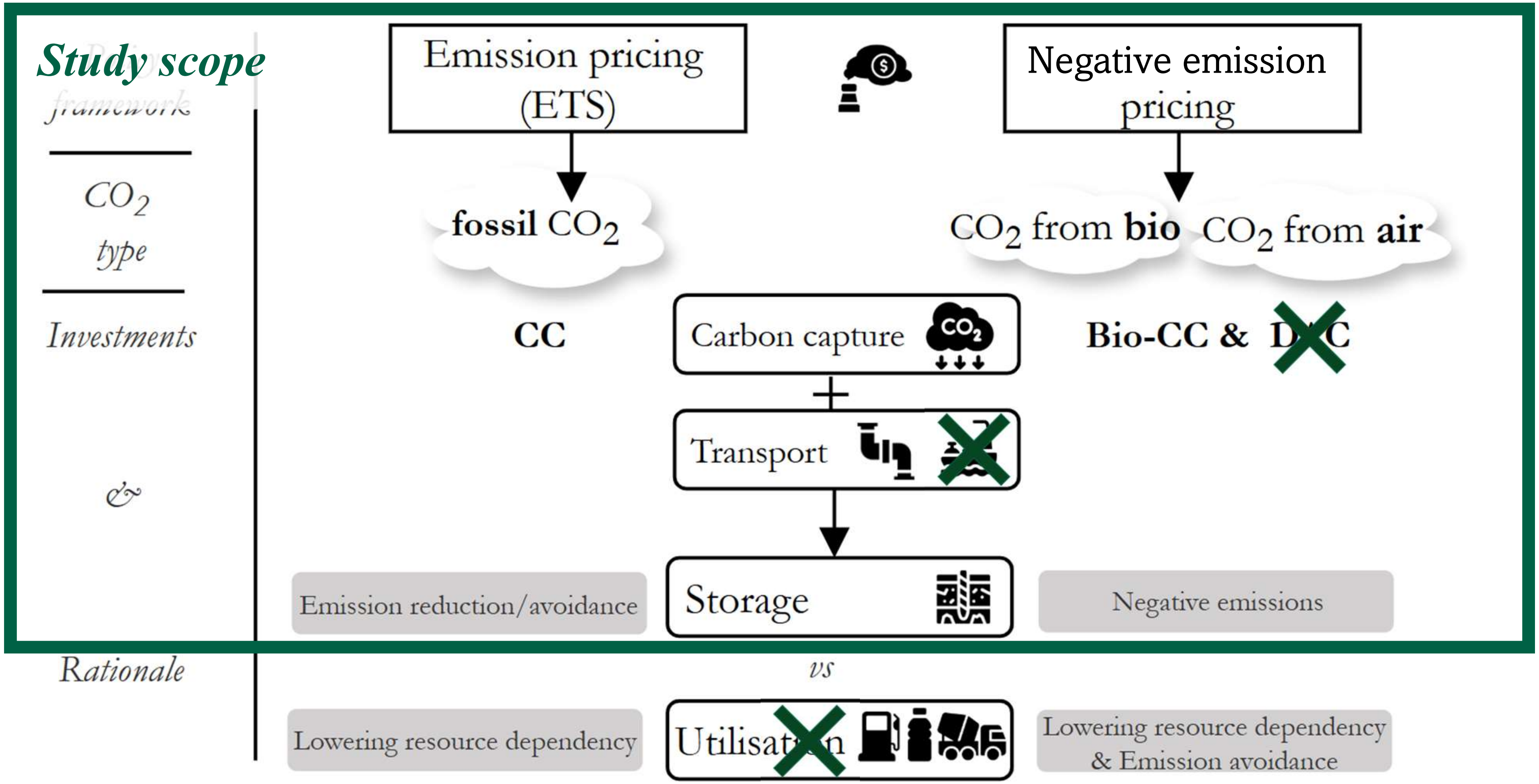

Fig. CO_2 value chain components

EU policy context: industry/ CCS side

- **1) EU industrial carbon management strategy** (2024): 450 $MtCO_2$ capture per year in 2050:
  - >60% Bio-CC/DAC
  - >60% storage
- **2) Clean Industrial Deal** (2025): decarbonisation aligned with economic competitiveness
- **3) EU ETS reform** (2026): how to reward carbon dioxide removals (CDR: Bio-CCS & DACS)?

F. Verbist, J. Meus, J. A. Moncada, P. Valkering, and E. Delarue, "Carbon removals meet Emission Trading System design: A precautionary path towards integration," Energy Economics, vol. 145, p. 108389, May 2025, doi: 10.1016/j.eneco.2025.108389.

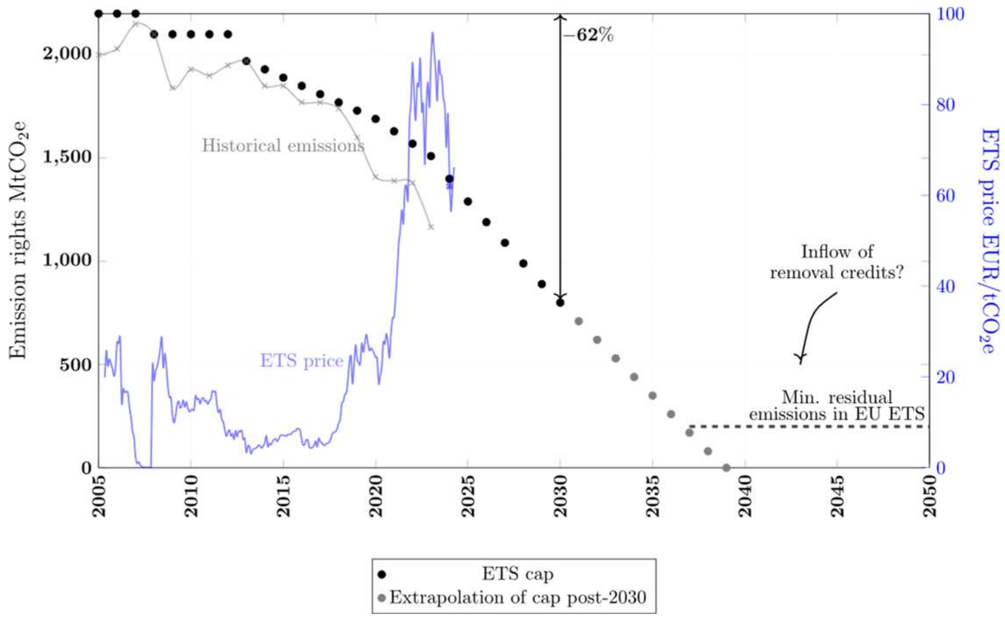

Fig. Current EU ETS designed up to 2030

Left y-axis: EU ETS cap, right y-axis: ETS price evolution

(source: Hoogesteyn A. & Verbist F. (2024))

Network externalities: T&S side

- **Economies of scale**
  - CAPEX driven
  - Natural monopolies
  - Club effect: critical mass
    - Low/ high adoption level
- **Complementary markets problem**
  - Chicken & egg: capture, transport, storage/utilization

→ Coordination failures

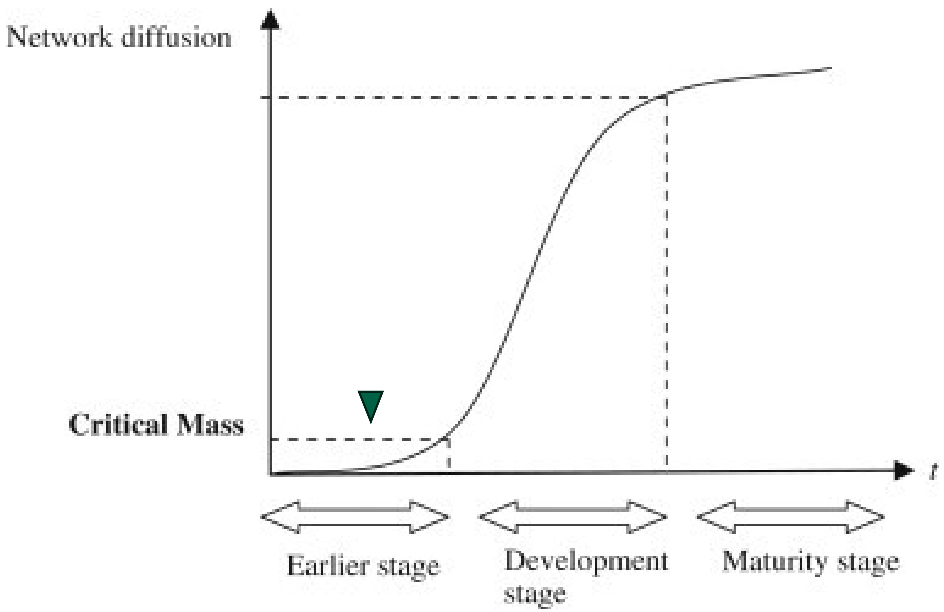

Fig. Club effect: low or high adoption equilibrium

Source: N. Bento, "Building and interconnecting hydrogen networks: Insights from the electricity and gas experience in Europe," Energy Policy, vol. 36, no. 8, pp. 3019–3028, Aug. 2008, doi: 10.1016/j.enpol.2008.04.007.

Research question: **"How do negative emission pricing & industry relocation affect the rollout of the CO_2 value chain?"**

- **Aim**: investigating economies of scale (EoS):
  - → Negative emission pricing: enhanced EoS
  - → Industry leakage: reduced EoS
- **Literature**: 2 strands:
  - (i) CO_2 network optimization models (MILP)
    - → optimizing T&S components
    - → exogenous carbon capture investments
  - (ii) Sector-coupled optimisation models (LP)
    - → Little/no spatially explicit details: focus on CC
    - → endogenous carbon capture investments
- **Contribution**:
  - Capturing entire value chain dynamics: modelling best of (i) & (ii)
  - EU policy-focus

Key insights:

1. The importance of industry clusters & spatially-explicit modelling
2. Scale effects under CDR pricing & industrial carbon leakage

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Modelling Scope & Inputs

- Spatial-explicit MILP
- **Emitters**: AIDRES database*:
  - 227 industry sites (BE-NL-NRW region)
  - 6 main industries: steel, cement, refineries, chemicals, glass & fertiliser
  - > 150 production routes
  - Database preselection algorithm:
    - Min. cost route (1)
    - Min. cost route without carbon capture (noCC)
- **Pipelines**: gas grid (SciGRID)
- **Storage** data (JRC)

*AIDRES, 'Advancing industrial decarbonization by assessing the future use of renewable energies in industrial processes': assessment and geo mapping of renewable energy demand for technological paths towards carbon neutrality of EU energy intensive industries : methodology and results in support to the EU industrial plants database," Publications Office of the European Union, 2023.

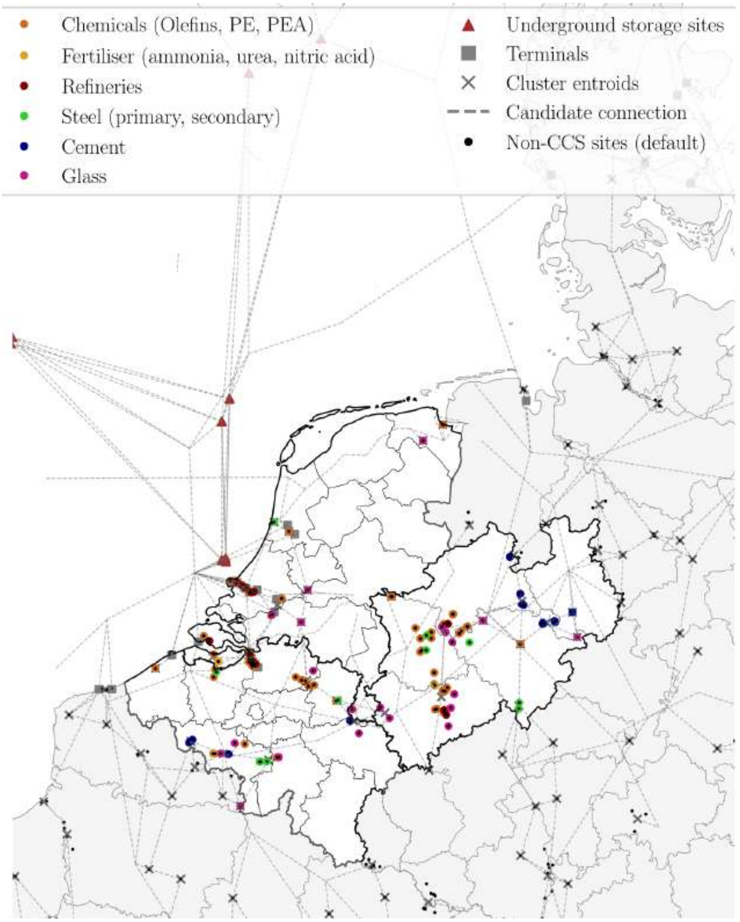

Fig. Modelled region

Modelling Scope & Inputs: cases

Tab. Case overview. Carbon prices (150 €/tCO_2) to bio-CCS are included as a revenue in the *CDR credit* cases. CDR = carbon dioxide removals

			Negative emission (CDR) pricing
Industry relocation		**CDR:** ETS on fossil CO_2 emissions, “-” ETS on bio-CCS	**No CDR:** ETS on fossil CO_2 emissions
	EU based: all 6 main industries (but reduced outputs for refineries & fertilizer)	**1. EU based – CDR**	**2. EU based – no CDR**
	EU exit: only glass & cement	**3. EU exit – CDR**	**4. EU exit – no CDR**

1) Industry clusters & spatially-explicit modelling

EU based-CDR credit case

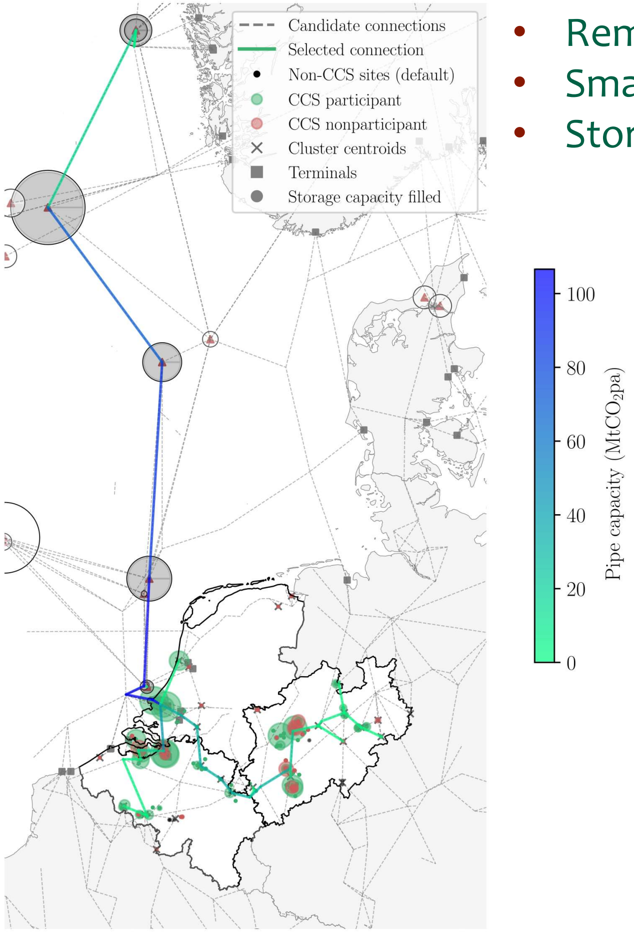

Fig. Endogenous assumption on carbon capture

- Remote emitters
- Small clusters
- Storage investment barrier

→ T&S costs x 1.6 →

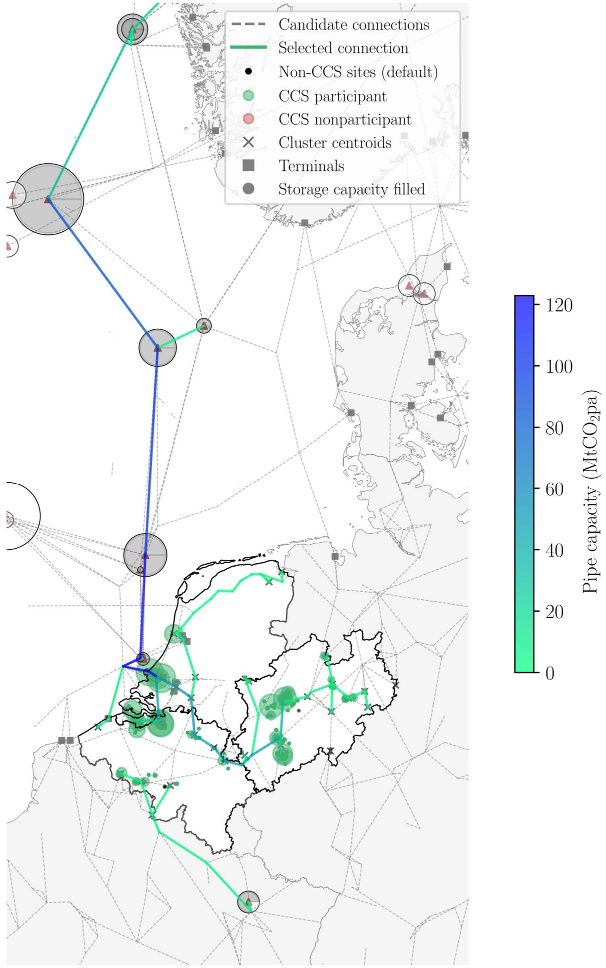

Fig. Exogenous assumption on carbon capture

2) Scale effects under CDR pricing & industrial carbon leakage

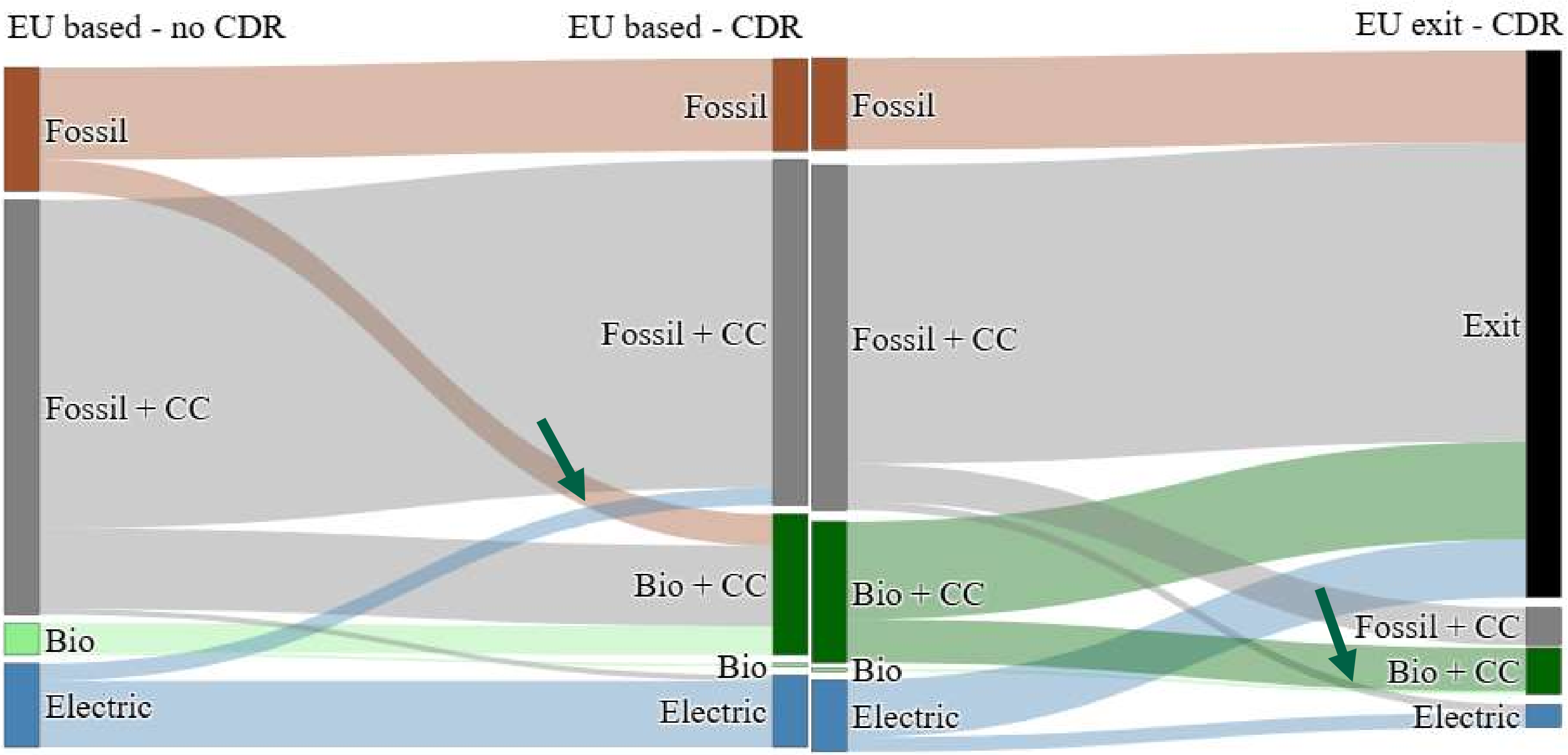

Fig. Sankey diagram indicating the production route selection and change between scenarios: from EU based – no CDR to EU based – CDR to EU exit - CDR

2) Scale effects under CDR pricing & industrial carbon leakage

Tab. Key results in numbers

Result (CC, T&S optimised)	**EU based No CDR**	**EU based CDR**	**EU exit CDR**	Unit
… optimized connections	144	171	26	-
… optimized capture vol.	37.0	106.60	9.36	$MtCO_2/tpa$
Average T&S costs	28.25	19.79	64.01	€/tCO_2
Biomass use	43.73	989.47	17.29	TWh/a

2) Scale effects under CDR pricing & industrial carbon leakage

EU exit cases

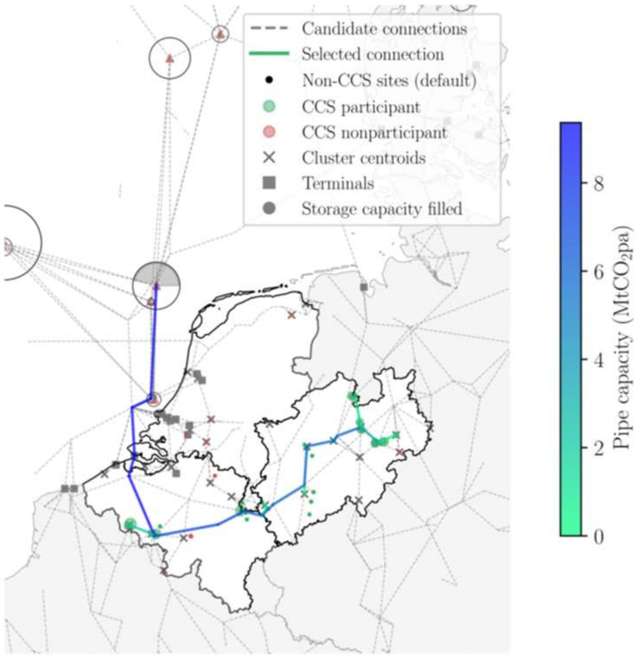

Fig. EU exit – CDR credits

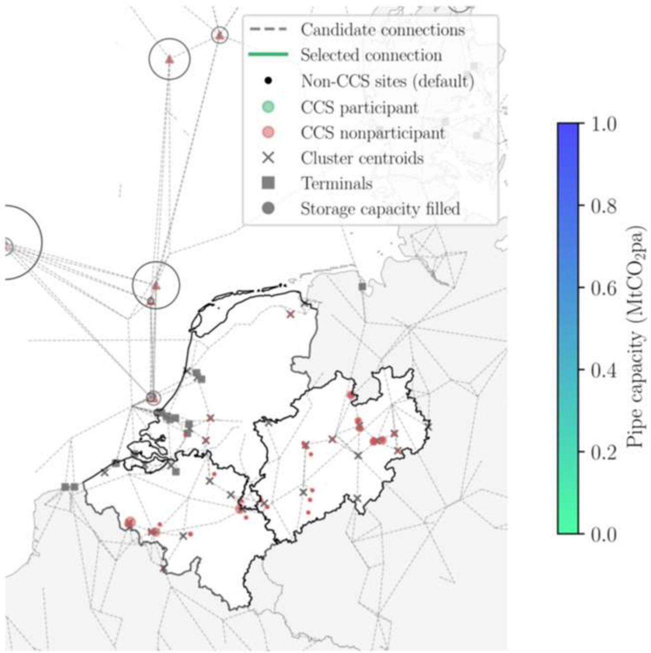

Fig. EU exit – no CDR credits

Conclusion

1. **Negative emission pricing**

   (CDR credit scenarios)

   - Enabler of economies of scale: intra-cluster facilitation, reduced costs
   - Effective planning needed: volume increase!
   - Storage limitations
   - Environmental concerns: high biomass reliance

2. **Industry relocation**

   - Reduced economies of scale, increased costs for remaining industries
   - CDR credits = enabler of value chain

Thank you! → Q&A

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Data input: Verbist, Flore (2025). Preprocessed input data files CC, T&S optimisation model. figshare. Dataset. https://doi.org/10.6084/m9.figshare.30122296.v1
Code: Github: https://github.com/FloreVerbist/CCTS_network_code.git
Paper: preprint soon on google scholar

Table 4 Indication of the first-best CC and no-CC routes derived from the AIDRES data preoptimisation step. Both the case with CDR credits and without CDR credits are shown. The colours indicate the feedstock source comprising: biomass (green), biomass waste (yellow), alternative fuel mixture (blue), fossil fuel source (brown) and electrification (transparent). When the CC route is more expensive than the no-CC route or is missing, an arrow is used ("→"). The used abbreviations are: *Afm = Alternative Fuel Mixture, BM = Biomass, BMW = Biomass Waste, CC = Carbon Capture, CEM2 = Portland Cement II (clinker-to-cement ratio of 70%), DEA = Diethanolamine Carbon Capture (ammonia production process), DRI = Direct Reduced Iron, EAF = Electric Arc Furnace, EL = Electrification, FT = Fischer–Tropsch Synthesis, LN = Naphtha Cracking, MEA = Mono-ethanolamine Carbon Capture, MEOH = Methanol Production, MVR = Mechanical Vapor Recompression, NG = Natural Gas, Oxy = Oxyfuel Combustion, REF = Conventional Crude Oil Refining, SMR = Steam Methane Reforming* [32].

Product names	**CDR credits**		**No CDR credits**	
	CC route (if cost optimal)	**No CC route**	**CC route** (if cost optimal)	**No CC route**
cement	CEM2-(BMW)MEA	CEM2-(BMW)	CEM2-(Afm)Oxy-MEA	CEM2-(BMW)
chemical-olefins	((BM)MeOH)O-MEA	(LN)O	(LN)O-MEA	(LN)O
chemical-PE	(NG)PE-MEA	(EL)PE	(NG)PE-MEA	(EL)PE
chemical-PEA	(NG)PEA-MEA	(EL)PEA	(NG)PEA-MEA	(EL)PEA
fertiliser-ammonia	(BM)NH3-DEA	(BM)NH3	(NG)NH3-MVR-DEA	(BM)NH3
fertiliser-nitric-acid	(BM)HNO3-DEA	(BM)HNO3	→	(BM)HNO3
fertiliser-urea	(BM)Urea-DEA	(BM)Urea	→	(BM)Urea
glass-container	(NG)-CC	(EL)	(NG)-CC	(EL)
glass-fibre	(EL)-CC	(EL)	(EL)-CC	(EL)
glass-float	(NG)-CC	(EL)	(NG)-CC	(EL)
refineries-light-liquid-fuel	(BM)FT-MEA	REF-SMR	REF-SMR-MEA	REF-SMR
steel-primary	(NG)DRI-EAF-MEA	(NG)DRI-EAF	(NG)DRI-EAF-MEA	(NG)DRI-EAF
steel-secondary	→	Scraps EAF	→	Scraps EAF

Infrastructure Economics: network externalities

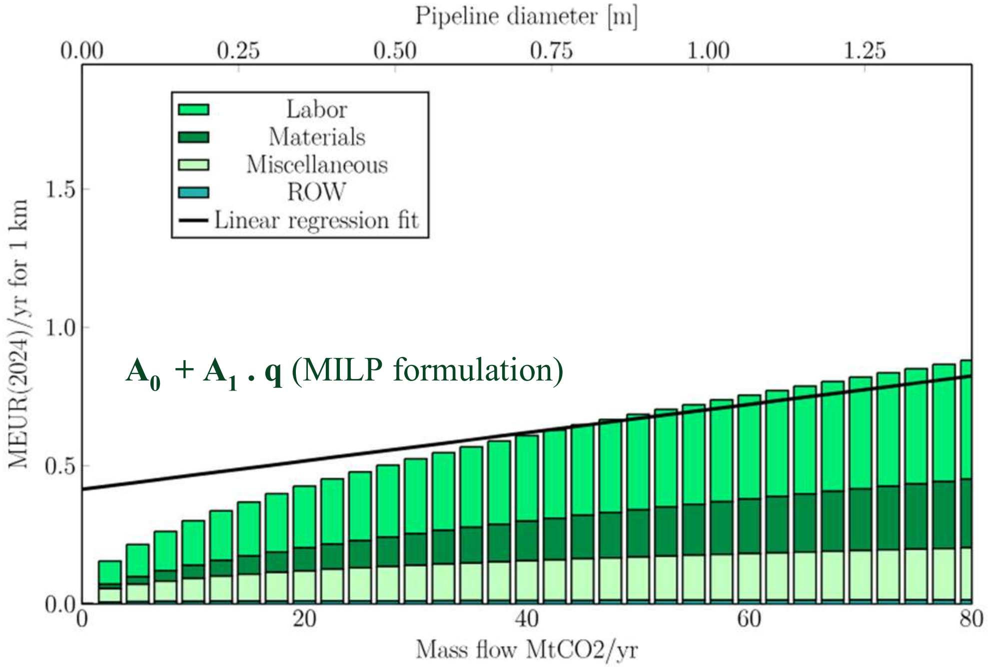

Fig. Pipeline construction costs in $MEUR_{2024}$/yr for 1 km of pipeline

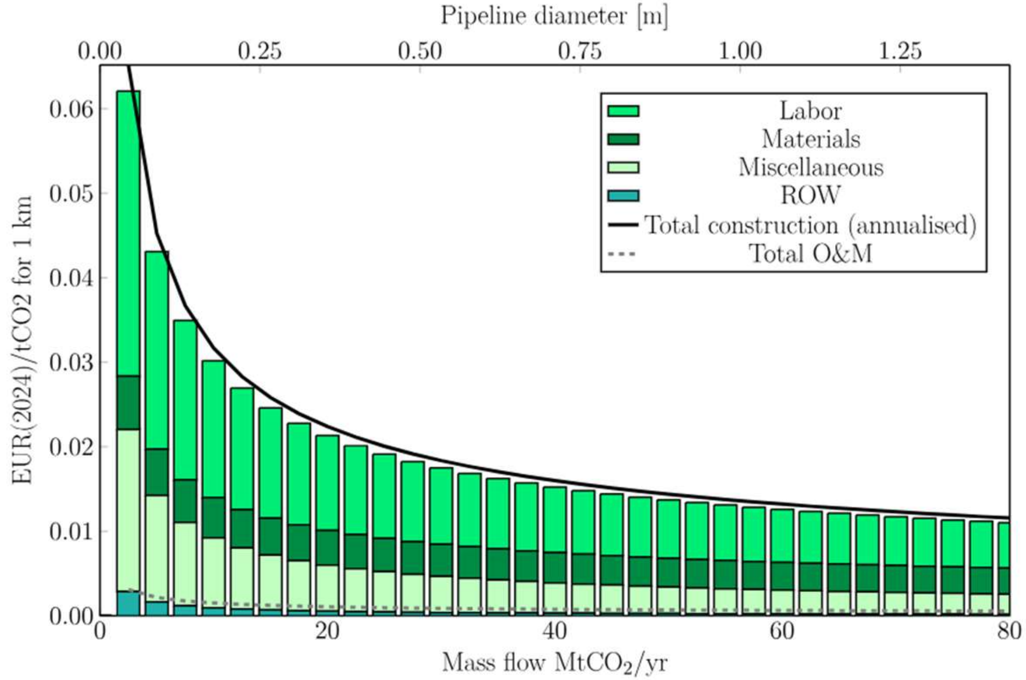

Fig. Pipeline construction costs in EUR_{2024}/tCO_2 for 1 km of pipeline

Economies of scale via lump-sum investment: the **average construction costs per tCO_2** transported **decrease** with larger capacities, small pipelines won't be constructed.

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Modelling Scope & Inputs: objective function (endogenous CC)

A) **Central planner's model**: system optimal (both i & ii), max. connectivity (ii)

$$\min_{u_e^{CC},\mathrm{q}_{p,pc},\mathrm{f}_{p,pc},\mathrm{z}_{p,pc},\mathrm{z}_s^{INL},\mathrm{z}_s^{OFF}} \overbrace{\sum_{e}^{\Omega_e} \left[\mathrm{u}_e^{CC}(\mathrm{CAPEX}_e^{CC} + \mathrm{OPEX}_e^{CC}) + (1-\mathrm{u}_e^{CC})(\mathrm{CAPEX}_e^{noCC} + \mathrm{OPEX}_e^{noCC})\right]}^{\text{(i) Production route resulting in the lowest total costs}}$$

$$+ \overbrace{\mathrm{c}^{T\&S}}^{\text{(ii) Transport \& storage costs}}$$

→ Could result in discriminatory pricing

B) *Next*: **Stackelberg model**: Carbon Network Operator (CNO) = profit maximizer.

$$\max_{u_e^{CC},\mathrm{z}_{p,pc},\mathrm{q}^{+}_{p,pc},\mathrm{q}^{-}_{p,pc},\mathrm{t}_e} \overbrace{r^{T\&S}}^{\text{Revenues from tariffs}} - \overbrace{c^{T\&S}}^{\text{T\&S costs}}$$

→ Depending on tariff structure: different outcomes, discriminatory/non-discriminatory

1) Industry clusters & spatially-explicit modelling

EU based-no CDR credit case

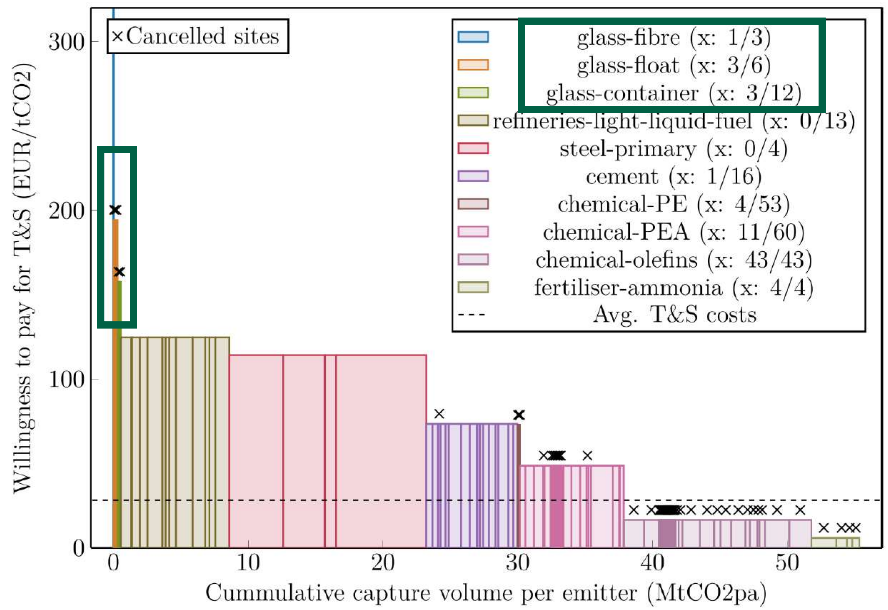
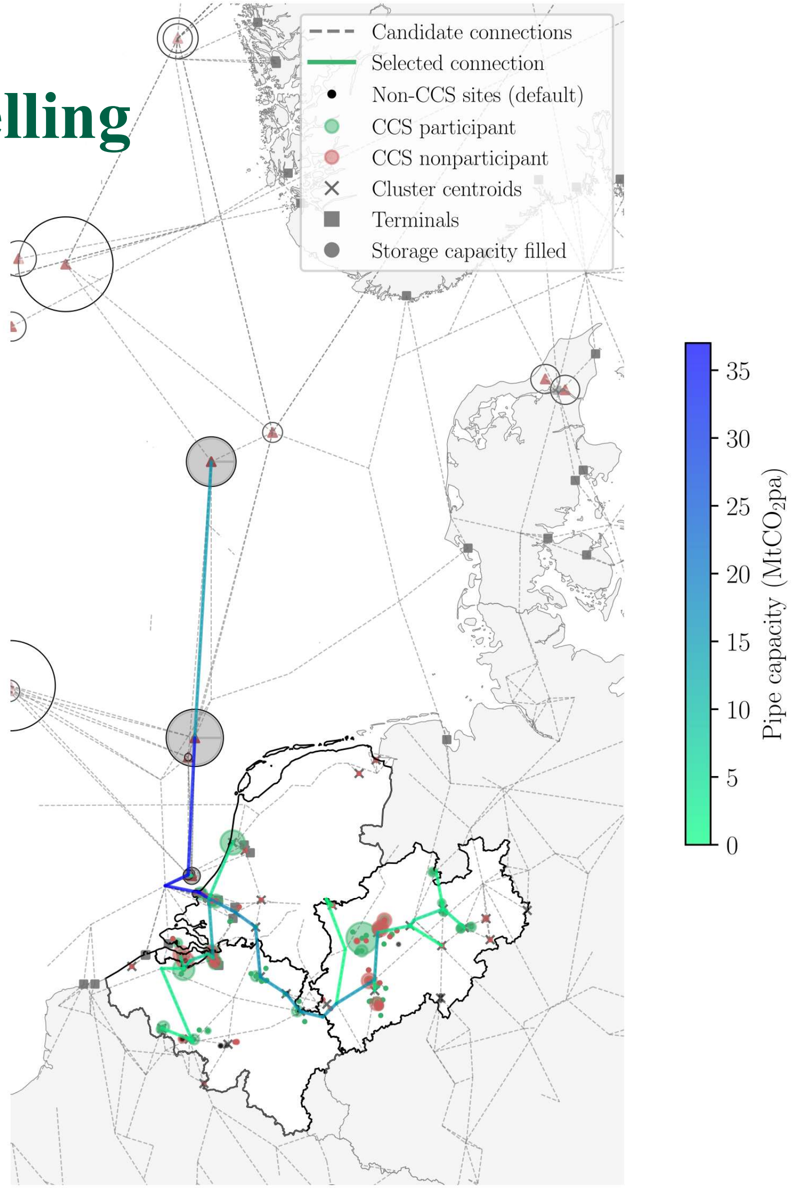


Fig. Indication of the willingness to pay for transport and storage connection in relation to the no carbon capture route for the *EU based-no CDR credit* case



1) Industry clusters & spatially-explicit modelling

EU based-CDR credit case

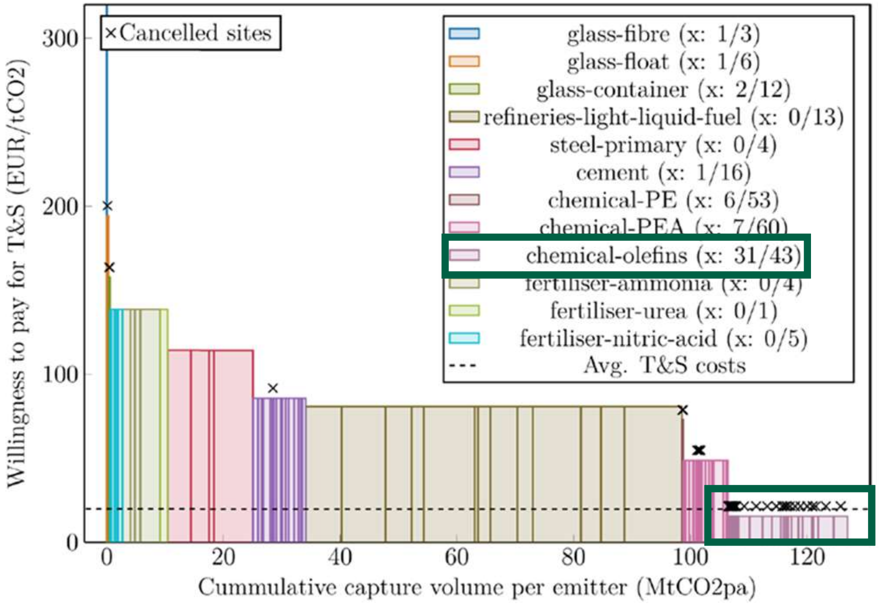


Fig. Indication of the willingness to pay for transport and storage connection in relation to the no carbon capture route for the *EU based-CDR credit* case