The Nexus of Green Steel and Carbon Transport

An Iterative Coupling Framework

Marcus Otti[1], Sebastian Zwickl-Bernhard[1,2]

[1]Energy Economics Group (EEG), TU Wien
[2]Norwegian University of Science and Technology

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Background

- Steel industry accounts for **7–8%** of global CO_2 emissions
- Two key decarbonization levers:
  - Fuel switching: BF-BOF → DRI-EAF (hydrogen, biomethane)
  - Increased secondary production and circular economy
- **Carbon capture** emerges as complementary strategy
  - Can reduce emissions by 40–60% when retrofitted in coal-based steel production
  - But: captured CO_2 must be transported and stored / utilized
- EU targets for carbon transport infrastructure **not on track**
- No established regulatory framework for cost allocation

Objective and Research Question

- Steel producers invest in capture only if transport infrastructure is available and the transport costs are viable
- Investments into a transport network become economically profitable if sufficient CO_2 volumes justify them

Is there an equilibrium of carbon transport costs and volume of CO_2 transported that enables the steel industry as a key player for future carbon networks?

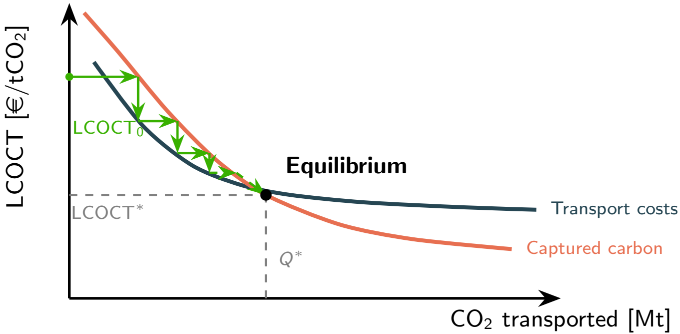
Framework Overview

Iterative coupling of two optimization models

Transformation Pathway Model ⟷ **Carbon Network Model**

optimizes technology investments

optimizes transport infrastructure



Transformation Pathway Model

Mixed Integer Linear Optimization Model (MILP) for calculating cost-optimal transformation pathways for the steel industry

Objective function:

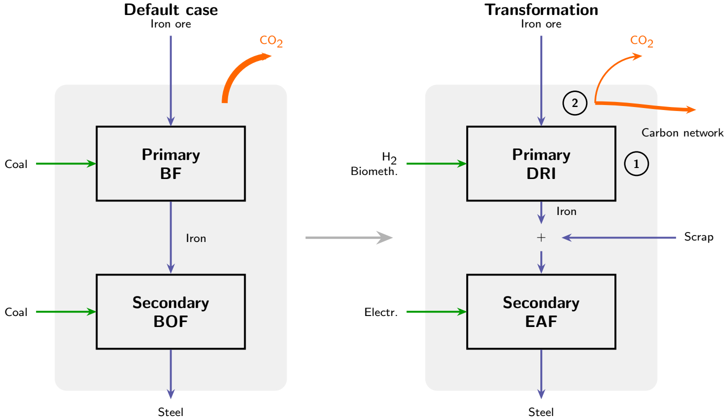
$$\min \sum_{y} \underbrace{c_y^{CAPEX}}_{\text{investments}} + \underbrace{c_y^{OPEX}}_{\text{operations}} + \underbrace{c_y^{residual}}_{\text{depreciation}}$$

OPEX includes:

- Energy carrier costs
- Carbon emission penalties (EU ETS)
- Material costs
- **Carbon transport costs**

Transformation Pathway Decisions

1. **Furnace investments** – Switch from BF/BOF to DRI/EAF
2. **Carbon capture**



Carbon Network Model

Two-stage stochastic MILP for CO_2 transport network design

Key innovation: Co-design of pipelines and boosting stations

Decisions:

- Pipeline routes and diameters
- Booster station placement
- Annual CO_2 flows
- Ship transport (offshore)

Constraints:

- Flow balance at nodes
- Pressure dynamics
- Storage capacity limits
- Commercial diameter selection

Output:

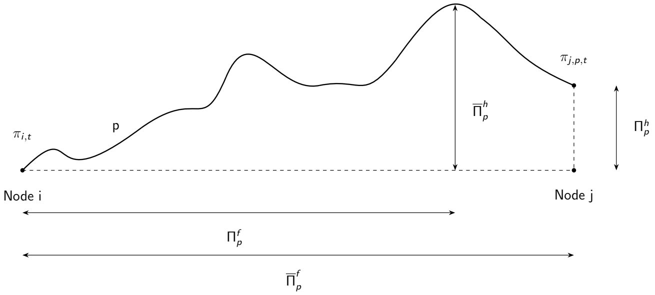
$$\text{Levelized Cost of Carbon Transport (LCOCT)} = \frac{\text{Total annualized costs}}{\text{Total transported } CO_2}$$

Carbon Network Model

Two-stage stochastic program:

$$\min \underbrace{c^{inv}(\mathbf{x})}_{\text{1st stage}} + \mathbb{E}_\xi \left[\underbrace{c^{op}(\mathbf{x}, \mathbf{q}, \xi)}_{\text{2nd stage}} \right]$$

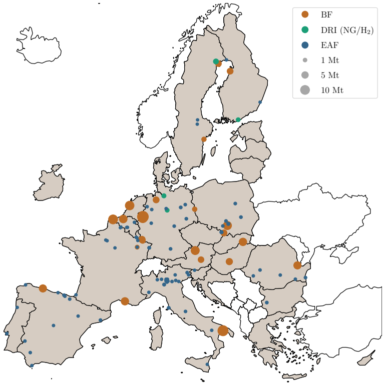
- **1st stage:** pipeline diameters $d_{ij} \in \mathcal{D}$, booster stations $z_k \in \{0, 1\}$
- **2nd stage:** flow allocation q_{ij} per scenario ξ



Pressure drop: elevation ($\overline{\Pi}^h$) and friction ($\overline{\Pi}^f$)

European Case Study

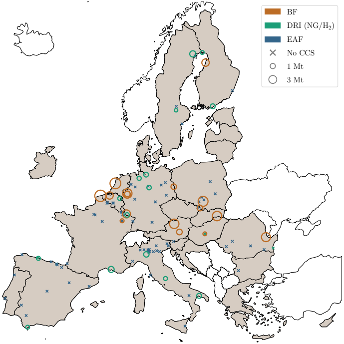
- Over 100 steel production sites across 18 EU countries
- Three furnace configurations: BF-BOF, DRI NG/H_2, EAF
- Carbon capture technologies
- Typical energy system parameters
- Biomethane and Hydrogen availability at the sites
- Regional electricity emission factors



Transformation Pathways (LCOCT = 20 e/tCO_2)

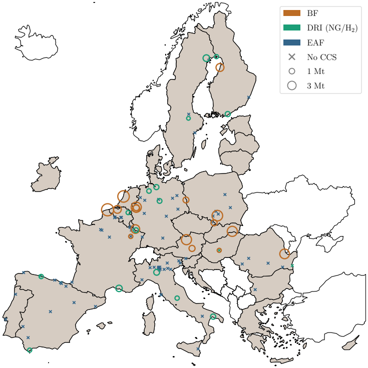
Key findings:

- Peak captured CO_2: **53.6 Mt** (2035)
- Declines to **35.8 Mt** (2045)
- Carbon capture predominantly on **blast furnaces**
- The capture declines as BFs are decommissioned
- 28/38 BF units retrofitted by 2035

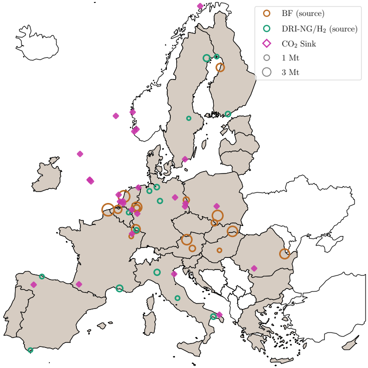


Captured CO_2 distribution (2035)

From Carbon Sources to Transport Infrastructure



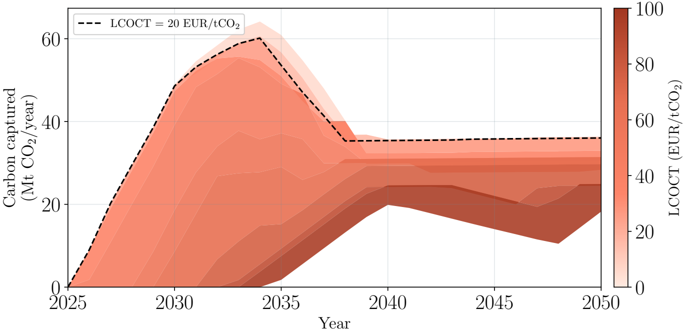
Carbon sources: captured CO_2 per site



Carbon network: sources, sinks, and transport

→ Given captured CO_2 volumes per site, the carbon network model determines **optimal transport infrastructure** connecting sources to storage sinks.

Sensitivity to Transport Costs



- Significant decline in captured volumes at LCOCT > 50 €/tCO_2
- Post-2040 stabilization: 15–35 Mt/year depending on transport cost

Conclusions and Outlook

Key contributions:

- Novel **iterative coupling framework** for steel transformation and carbon network design
- Explicit representation of equilibrium search between capture and transport

Preliminary insights:

- At 20 e/tCO_2, European steel sector can supply **35–54 Mt** captured CO_2
- Potential foundation for emerging carbon transport networks
- May only function as a bridging technology until other carbon sources emerge

Marcus Otti
otti@eeg.tuwien.ac.at

Energy Economics Group (EEG)
Technische Universität Wien

LinkedIn