THE NEXUS OF GREEN STEEL PRODUCTION AND CARBON TRANSPORT: A MODELING FRAMEWORK FOR EUROPE'S INDUSTRIAL TRANSFORMATION

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Motivation

The European steel industry faces a critical transformation as it seeks to decarbonize while remaining competitive in a global market characterized by structural overcapacity and volatile energy prices. With the EU accounting for only 7-8% of global production and sector emissions averaging 1.9 tonnes CO2 per tonne of crude steel, achieving climate neutrality by 2050 necessitates a fundamental shift from coal-powered blast furnace (BF) routes toward hydrogen- or gas-powered direct reduced iron (DRI) combined with electric arc furnaces (EAF). This transition faces challenges from different perspectives. Uncertainties in energy carrier availability and prices, particularly for green hydrogen, as well as constraints on quality and regional supply of materials like scrap, complicate long-term investment decisions. Carbon capture represents an alternative decarbonization pathway that could complement hydrogen-based routes, particularly for sites where existing assets have remaining lifetime value or where hydrogen infrastructure develops more slowly.

However, carbon capture introduces its own coordination challenge: the interdependence between capture investment decisions and the availability of transport infrastructure. The economic viability of carbon transport is a necessity for steel producers to invest in carbon capture technologies. Conversely, network operators will only invest in transport infrastructure if sufficient CO2 volumes justify the capital expenditure. This mutual dependency creates a coordination problem that cannot be resolved by optimizing either system in isolation. Current modeling approaches in the literature address steel transformation pathways and carbon network design separately, leaving a gap in understanding how these decisions interact and whether an economically viable equilibrium exists.

To address this question, we develop a novel bi-level optimization framework that iteratively couples steel-sector investment decisions with carbon-transport network design, while simultaneously accounting for energy and material consumption across the transformation pathway.

Methodology

The framework employs an iterative coupling of two distinct optimization models: (i) a steel transformation pathway model that determines cost-optimal technology investments and the resulting CO2 capture volumes, and (ii) a carbon network model that optimizes the design of transport infrastructure connecting steel production sites with carbon sinks.

The steel transformation model offers a comprehensive representation of both primary and secondary production routes across major EU sites. It explicitly links technology investment decisions to their energy and material consequences, capturing how furnace choices determine specific energy consumption across multiple carriers (coal, natural gas, hydrogen, electricity) and material inputs, including iron ore, scrap steel of varying quality grades, and intermediate products. The model covers technology choices among blast furnaces, natural gas DRI, hydrogen DRI, and EAF routes, as well as

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decisions on carbon capture deployment. The model accounts for regional differences in energy prices, hydrogen costs, and scrap availability.

The carbon network model determines cost-optimal pipeline routes, diameters, and booster station placements to transport captured CO2 from steel sites to storage locations. It accounts for pressure dynamics in dense-phase CO2 transport and returns the Levelized Cost of Carbon Transport (LCOCT) as a function of transported volume.

The iterative coupling identifies the equilibrium between LCOCT and the volume of captured CO2. Starting from an initial cost estimate, the steel model determines capture volumes, which are passed to the network model to calculate the resulting transport cost. This process iterates until convergence, revealing whether a mutually consistent configuration exists where both the steel sector's willingness to capture and the network's cost structure are compatible.

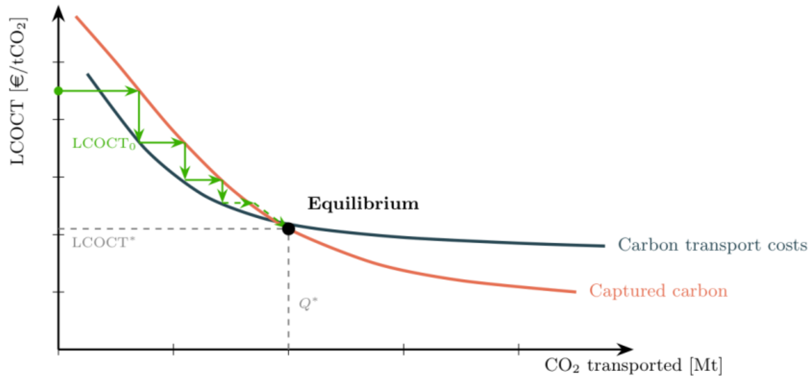

Figure 1: Iterative equilibrium search between steel sector capture and carbon network.

Expected results

The analysis will reveal the conditions under which carbon capture becomes economically viable for the European steel industry. By identifying the equilibrium between capture decisions and transport costs, the study will quantify the critical CO2 volume required for network viability. Results will show how technology choices at steel sites respond to transport cost assumptions.

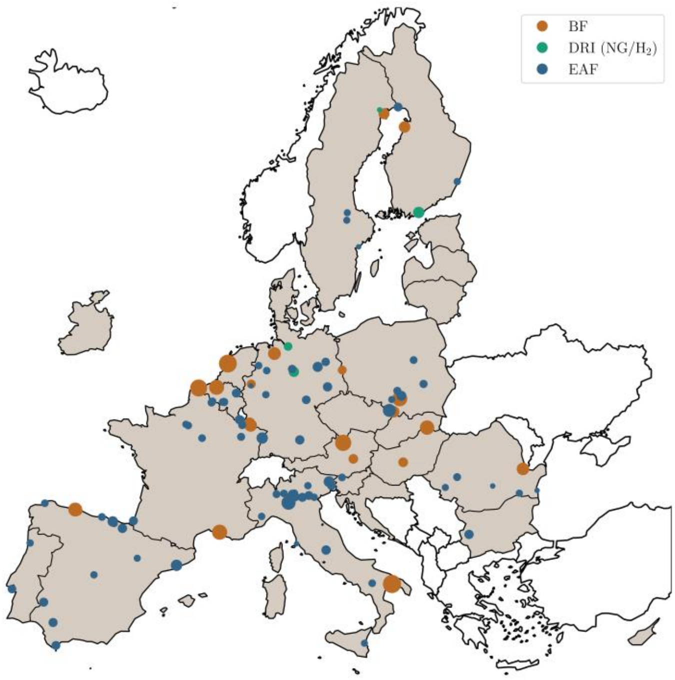

Figure 2: Analyzed steel production sites across the EU in 2025