Identifying Deployment Tipping Points between CCS and CDR for Small- and Medium-Scale Industrial Emitters

Introduction

Carbon capture and storage (CCS) is widely recognised as a key solution for mitigating carbon dioxide (CO_2) emissions from hard-to-abate industrial sectors (IEA, 2019). To date, deployment has primarily focused on large facilities benefiting from economies of scale and integration within industrial clusters connected to shared transport and storage infrastructure (IEAGHG, 2024; Rattle et al., 2024). However, a significant share of industrial emissions originates from small- and medium-scale emitters spanning a wide range of sectors, including food and drink production, ceramics, glass manufacturing, and smaller chemical industries (Rattle et al., 2024).

Compared with large clustered installations, these facilities are characterised by lower emission scales and typically low-to-medium CO_2 concentrations in flue gas streams, resulting in more capital- and energy-intensive capture processes (Pérez-Calvo and Mazzotti, 2022; Zanobetti et al., 2025). In addition, their geographically dispersed distribution increases transport requirements and limits opportunities for infrastructure sharing (Aldersgate Group, 2025). Together, these characteristics contribute to higher full-chain CCS costs and introduce substantial uncertainty regarding the economic feasibility of point-source capture for smaller emitters.

Under such conditions, carbon dioxide removal (CDR) technologies are increasingly considered as complementary options for compensating emissions that are technically or economically challenging to capture at source (Edelenbosch et al., 2024). While growing attention has been devoted to both CCS hub development and large-scale CDR deployment, limited quantitative evidence exists regarding the conditions under which point-source CCS remains preferable to removal-based solutions once full-chain logistics and infrastructure constraints are explicitly accounted for.

To address this gap, this work presents a quantitative, spatially explicit techno-economic assessment comparing point-source CCS and CDR options for small and medium industrial emitters. The analysis focuses on the United Kingdom and Italy, selected to represent contrasting industrial contexts and levels of CO_2 transport and storage infrastructure development. By integrating techno-economic models of CO_2 capture, transport, and geological storage, the assessment identifies tipping points defining the conditions under which point-source CCS becomes less cost-competitive than CDR solutions.

Method

A spatially explicit techno-economic optimisation framework was developed to compare point-source CCS and CDR pathways for small- and medium-scale industrial emitters. The analysis considers geographically distributed emission sources in the United Kingdom and Italy, representing two countries with contrasting industrial structures, geography, and CCS infrastructure development.

Industrial facilities are represented using emitter archetypes defined by annual CO_2 emission scale and inlet CO_2 concentration in flue gas streams, allowing heterogeneous emission sources to be consistently incorporated within a unified modelling framework.

The model explicitly represents full-chain CCS costs, including CO_2 capture, transport, and geological storage. Capture costs are parameterised as functions of emission scale and flue-gas CO_2 concentration using literature-based techno-economic correlations that account for sector-specific flue gas characteristics and economies of scale. CO_2 transport costs are modelled using a network-flow formulation incorporating alternative transport modes, including pipeline and non-pipeline options, while accounting for transport distance, infrastructure availability, and capacity constraints. Geological storage costs are represented through regionally consistent assumptions reflecting storage accessibility and deployment conditions in the investigated countries.

CDR options, including bioenergy with CCS (BECCS), direct air capture with storage (DACCS), biochar, and reforestation/afforestation, are included as benchmark alternatives with regionally constrained capacities and levelised removal costs consistent with UK and Italian deployment contexts.

The integrated modelling of emission sources, CCS infrastructure, and CDR deployment options is formulated as a mixed-integer linear programming (MILP) optimisation problem that minimises total system cost subject to mass balance, infrastructure capacity, and technology deployment constraints. This formulation enables identification of the cost-optimal allocation of emissions between CCS and CDR pathways for individual emitters or regions while optimising CO_2 transport flows and infrastructure utilisation.

Full-Chain CCS Cost Analysis and Comparison with CDR Options

Industrial emitters were classified into representative archetypes based on emission scale and flue-gas CO_2 concentration. Figure 1 presents the modelled CO_2 capture cost contours across this parameter space, with selected emitters from the United Kingdom and Italian case studies located according to their corresponding archetypes.

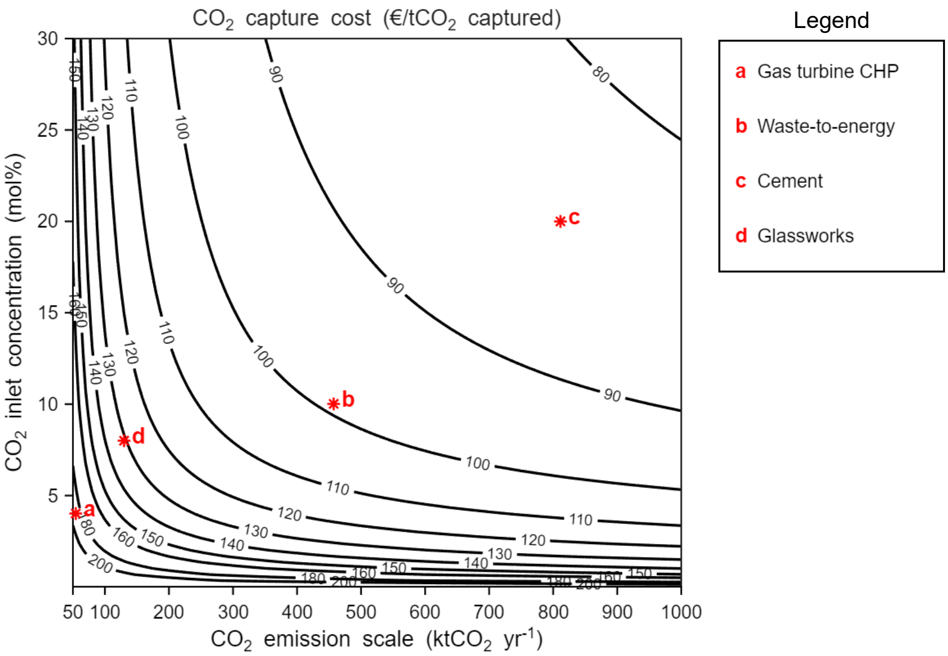

Figure 1 *Modelled CO_2 capture cost (€/tCO_2 captured) as a function of emission scale and inlet CO_2 concentration. Selected UK and Italian emitters are overlaid and positioned according to their characteristic operating conditions (archetype classification).*

CO_2 capture costs decrease with increasing emission scale and inlet CO_2 concentration, highlighting the combined influence of economies of scale and flue-gas composition on capture performance. The positioning of the selected emitters illustrates how different industrial sectors occupy distinct regions of the cost space. Emitters with low CO_2 concentrations and smaller emission scales, such as natural gas-fired combined heat and power (CHP) plants and glassworks, fall within higher-cost regions, whereas larger and more concentrated sources, such as cement production, shift towards lower-cost regimes, with waste-to-energy facilities occupying intermediate conditions.

An analogous modelling approach was developed for CO_2 transport and storage, with costs expressed as functions of transported CO_2 flow rate and transport distance for alternative transport modes, including pipeline and non-pipeline solutions. The optimisation framework determined the cost-optimal transport configuration for each emitter or region, subject to infrastructure capacity constraints.

CDR costs were represented using literature-based levelised removal cost estimates for technologies at current or near-commercial deployment stages (e.g. Fuss, 2022), consistent with existing carbon removal credit frameworks.

The findings indicate that CCS competitiveness for small- and medium-scale emitters emerges from the combined effect of emission scale and infrastructure accessibility, rather than plant-level capture performance alone. Differences between the United Kingdom and Italy result in region-specific deployment tipping points across emitter archetypes.

Conclusions

This work presents a spatially explicit techno-economic assessment comparing point-source carbon capture and storage (CCS) and carbon dioxide removal (CDR) options for small- and medium-scale industrial emitters. The analysis reveals significant variability in mitigation costs across industrial archetypes driven by emission scale and flue-gas CO_2 concentration. Combined with differences in access to transport and storage infrastructure, these factors influence CCS competitiveness, with geographically dispersed or low-volume sources increasingly favouring CDR alternatives.

Identified tipping points between CCS deployment and reliance on carbon dioxide removal solutions highlight the critical role of shared transport and storage infrastructure in enabling decarbonisation of dispersed emitters beyond industrial clusters.

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