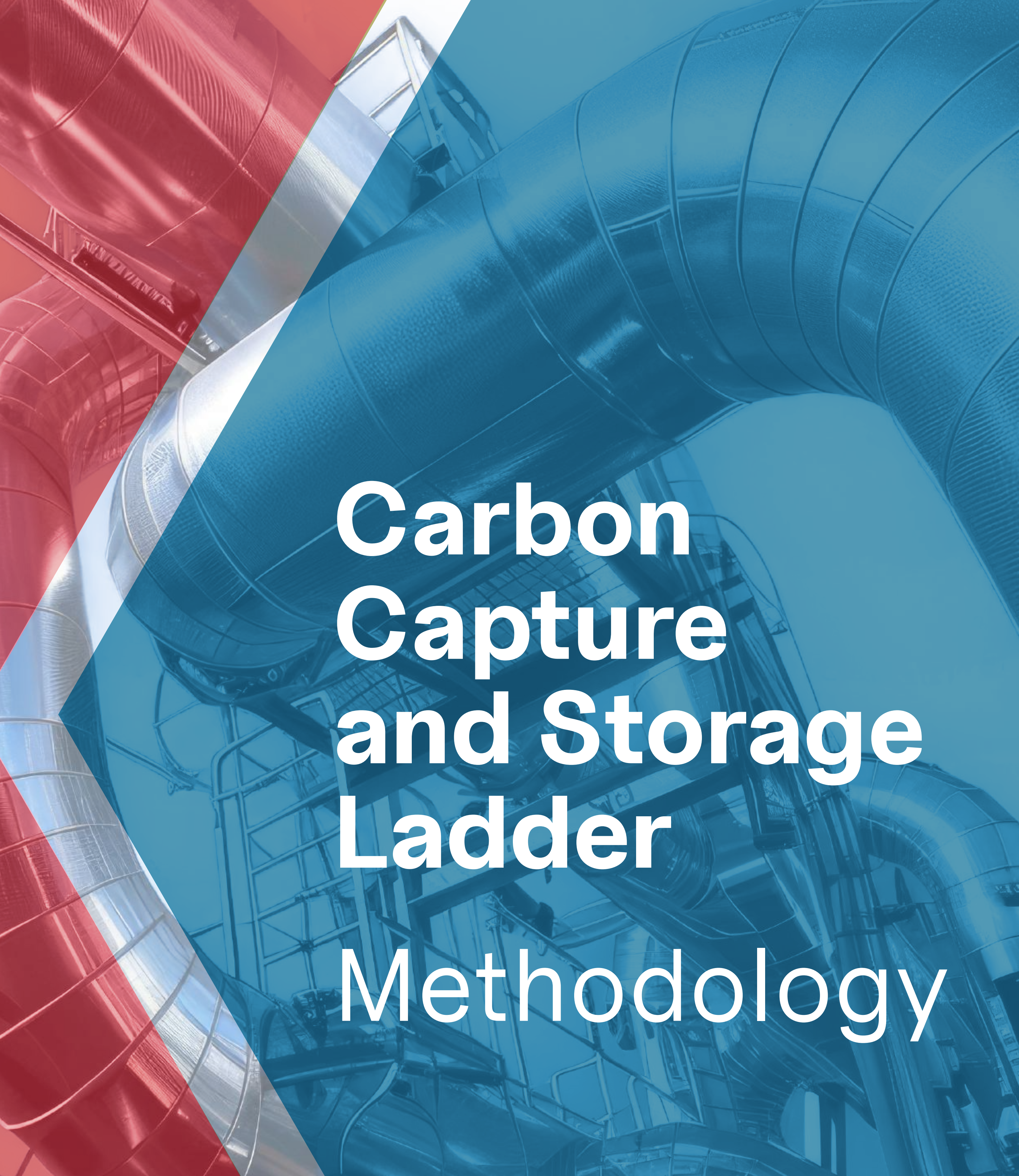

Carbon Capture and Storage Ladder

Methodology

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Update

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This methodological note describes how we assess the climate value of carbon capture and storage (CCS) applications in Europe as part of the updated 2025 CCS Ladder. While CCS technologies are traditionally assessed through a narrow emissions-reduction-to-investment lens, we argue that determining CCS's climate credentials in the context of deep decarbonisation requires a more comprehensive approach. CCS must be evaluated not only on its technical abatement potential but also on the availability of alternative mitigation options, the broader system impacts of deployment, and the feasibility of scaling CCS across different industrial contexts.

The 2025 update builds on the original 2023 methodology but slightly adapts the assessment logic, following extensive stakeholder feedback. CCS applications are evaluated across three criteria, each scored on a 1–5 scale for both 2030 and 2050. To reflect its central importance in determining whether CCS should be prioritised, the criterion on competition from alternative mitigation levers is double weighted in the overall scoring. Together, we believe these elements form a transparent and structured framework for comparing CCS use cases and understanding where CCS can deliver the highest climate value.

Criteria for assessing climate value

Rationale and underlying principles

We propose assessing the climate value of CCS applications across three criteria. These criteria are intended to capture the core factors that influence whether CCS deployment can make a meaningful contribution to Europe's deep decarbonisation objectives. They reflect a balance between the technical mitigation potential of CCS, its relevance within wider system transformation, and the practical feasibility of deploying CCS at scale.

This framework is grounded in the recognition that CCS is not without environmental and systemic impacts. Deploying CCS requires substantial CO_2 transport and storage infrastructure, increases energy use, and - where fossil fuels remain part of the value chain - can extend upstream and downstream environmental impacts associated with extraction and combustion. In this context, assessing the climate value of CCS requires examining not only how much CCS can reduce emissions, but also whether alternative mitigation options might achieve the same goal more effectively or with fewer trade-offs.

Accordingly, the three criteria are designed to help identify where CCS is likely to offer the greatest climate value - namely, in applications where:

- alternative decarbonisation or defossilisation options are limited or insufficient
- CCS can deliver substantial plant-level and life-cycle emissions reductions, and
- deployment is technically, economically and logistically feasible at a meaningful scale.

Taken together, the criteria provide a structured and transparent approach for comparing CCS applications and understanding how CCS can contribute within a broader net-zero strategy.

Criterion 1 - Competition from alternative mitigation levers

This criterion evaluates whether credible, scalable low-carbon alternatives exist that can produce the same good or material in a climate-neutral way, without relying on CCS. Where such alternatives are viable, mature, or likely to be deployable at scale within relevant timeframes, the climate value of CCS is correspondingly lower.

In assessing this dimension, we consider:

1. Technological alternatives

- The maturity (e.g. TRL), scalability and likely cost of alternative production routes compared to CCS-based pathways.
- The availability at scale and cost of required resources enabling these alternatives, such as clean electricity, renewable hydrogen or sustainable feedstocks.
- Whether these alternatives can address both energy-related and process-related emissions. Where a significant share of emissions is related to the decomposition of materials (e.g. lime production), technological alternatives may be limited or unavailable, sustaining the case for CCS.

2. System-level mitigation levers

Opportunities to reduce or avoid the need for the underlying process through broader structural or material changes, such as:

- improvements in circularity and material efficiency (re-use, recycling, waste sorting),
- substitution towards lower-carbon materials or products, and
- reductions in material throughput or overall demand through design changes or behavioural shifts.

2025 update - what is new?

Compared with the 2023 version, this criterion now more explicitly incorporates circularity, substitution and demand-side measures, alongside technological alternatives. Because this dimension fundamentally shapes where CCS is needed - and where not- it is double-weighted in the overall scoring.

Criterion 2 – Mitigation potential

This criterion assesses to what extent CCS deployment can reduce greenhouse gas emissions for a given application. It distinguishes applications where CCS can deliver deep, durable emission reductions from those where technical limits or life-cycle emissions constrain its overall climate value.

We assess three elements:

1. Plant-level mitigation potential

This captures how effectively CCS can reduce emissions at the installation level, considering the share of on-site emissions that CCS can feasibly capture.

2. Life-cycle mitigation potential

CCS may substantially reduce on-site emissions while still leaving significant upstream or downstream emissions untouched. We therefore assess what share of life-cycle emissions can be assessed through CCS. We thus assess upstream (e.g. fugitive emissions related to mining, extraction or transport of fossil fuels) or downstream (e.g. consumption of refined petroleum products)that are not addressed through deploying CCS.

3. Total mitigation potential of sub-sector

This reflects the broader potential relevance of the application for European climate goals:

- the total volume of emissions associated with the application across Europe,
- how this volume evolves to 2030 and 2050, and
- the proportion of these emissions that CCS could realistically mitigate.

2025 update – what is new?

The updated methodology more clearly differentiates the three components of mitigation potential: plant-level, life-cycle and system-wide. This allows scoring to better capture cases where CCS is technically effective at the plant but yields limited climate value once upstream or downstream emissions are accounted for.

Criterion 3 – Feasibility of carbon capture deployment

This criterion considers how practical it is to deploy and scale CCS in each application. Feasibility reflects both the physical characteristics of CO_2 sources and the broader system conditions that influence whether CCS infrastructure can be accessed effectively.

We assess three elements:

1. Emission source characteristics

These influence the technical and economic performance of CCS technologies:

- Size of point sources: larger, continuous CO_2 streams generally support lower capture costs and more efficient operation.
- CO_2 concentration: high-concentration (and fewer) streams typically enable higher capture rates and lower energy penalties, whereas dilute or variable streams increase complexity and cost.

2. Spatial distribution of emitters

The geographic configuration of facilities strongly shapes CCS feasibility: Clustered emitters can benefit from shared transport infrastructure, lowering overall costs, while highly dispersed sites face greater logistical and financial barriers, especially in early deployment phases. If big emitters there anyway, small can ride piggyback; if only small emitters no pipeline, aka too high transport costs (truck….), so only chance to get CCS rolling is to coordinate with other point sources sufficiently near by to get above pipeline-threshold. Further discussion on this, see [Annex]

Feasibility generally is expected to improve by 2050 as transport and storage networks expand and become more accessible.

3. Economic and regulatory constraints

Feasibility is also shaped by wider system conditions, including:

- rising carbon prices on residual emissions, which is especially relevant for applications where achieving high capture rates is challenging; and
- the energy penalties and diminishing returns associated with achieving very high capture rates
- relevant policy signals, such as existing phase-out pathways or commitments (such as for coal-based power in most European countries).

2025 update – what is new?

The updated methodology more explicitly incorporates regulatory and economic pressures alongside technical considerations. This ensures feasibility reflects not only what is technically possible,

but what is likely to be viable in the evolving policy and market environment toward 2030 and 2050.

Scoring and operationalisation

This section outlines how the three criteria are applied in practice to assess the climate value of CCS applications. The scoring framework is designed to be transparent, comparable across sectors, and sufficiently flexible to reflect evolving conditions between 2030 and 2050.

Selection of applications

We evaluate a set of 26 CCS applications that together illustrate the range of processes where CCS could play a role in European industrial decarbonisation. The list is designed to be representative rather than exhaustive, capturing the most relevant production routes and emission sources across energy-intensive industries, waste management and parts of the energy system.

Compared with the 2023 version of the Ladder, several changes have been made:

Applications removed

We have dropped applications that either fall outside the scope of this iteration or no longer offer meaningful differentiation within the framework:

- Dedicated bio-applications, including biomass power and biofuel production (See Box 1 on page 6 of the briefing for our reasoning);
- Hisarna steelmaking, as pilots have been discontinued;
- Direct Air Capture, as we firmly concentrate on process- and fossil-based CCS;
- Ammonia, which is now evaluated together with hydrogen via SMR, to avoid duplication.

Greater differentiation within existing applications

Where relevant, we have introduced more granular sub-categories to capture material differences in emissions profiles, technological realities and CCS applicability:

- Waste incineration – now assessed through three sub-categories: Incineration of mixed municipal waste; hazardous waste; and wastewater sludge;
- Gas-fired power – now broken down into three sub-categories: Gas-fired, mid-merit power plant (CCGT); gas-fired, daily peaker power plant (OCGT); and gas-fired seasonal/stress-test power plants.
- Cement clinker kilns – we now distinguish between wet kilns and dry kilns, due to significant differences in energy use and emissions performance.

New additions

The updated Ladder also includes a few new applications:

- Steam generation – assessed through two sub-categories: Steam/CHP networks (e.g. for industrial clusters); and standalone industrial steam boilers (e.g. for food & drink production)
- Fossil gas extraction and processing, recognising that emissions from upstream natural gas operations represent a sizable source of emissions and that most carbon capture deployment to date has occurred on this application (though mainly in the United States and paired with enhanced hydrocarbon recovery).

Table 1. Details and general parameters of applications covered in the 2025 CCS Ladder

Subsector	Application	Input	Process	Product
Aluminium	Aluminium smelter	Bauxite and electricity (electrolysis) and fossil fuels (refining)	Bayer high-temperature high-pressure	Alumina
Cement	Cement - electrified clinker kiln	Limestone and electricity	Decalcification and sintering	Cement clinker
Cement	Cement - dry clinker kiln	Limestone and coal/biomass & substitutefuels	Decalcification and sintering	Cement clinker
Cement	Cement - wet clinker kiln	Limestone and coal/biomass & substitute fuels	Decalcification and sintering	Cement clinker
Ceramics	Ceramics kiln	Raw materials and fossil/ biomass input	Ceramics kiln	Ceramics
Chemicals	Chemicals - steam cracking	Naphta, ethane, other fossil-based feed-stocks	Steam cracking	High Value Chemicals (HVCs)
Fossil fuels	Fossil-gas extraction & processing	Fossil reservoirs	Extraction & pro-cessing	Crude oil and/or fossil gas
Fossil fuels / refineries	Refining - fluid cata-lytic cracking (FCC)	High-weight fraction of crude oil	Fluid catalytic cracking	Gasoline, HVCs, other petroleum products
Glass	Glass furnace	Raw materials and mainly natural gas	Furnace + flat glass deposit	Glass
Hydrogen	Hydrogen - ATR	Natural gas	Autothermal re-forming (ATR)	Hydrogen
Hydrogen	Hydrogen - SMR (e.g. Ammonia)	Natural gas	Steam methane reforming (SMR)	Hydrogen
Hydrogen	Hydrogen - coal gas-ification	Coal	Coal gasification	Hydrogen
Lime	Lime kiln	Limestone and coal/biomass fuels	Decalcification	Lime
Paper	Paper kraft mill	Mix of biomass, electricity, gas and coal	Kraft pulp mil	Paper
Power	Gas-fired, mid-merit power plant (CCGT)	Fossil gas	Combined cycle gas turbine	Base load to grid bal-ancing power (daily/ hourly)
Power	Gas-fired, daily peak-er power plant (OCGT)	Fossil gas	Open cycle gas turbine	Grid balancing power (daily/hourly)
Power	Gas-fired seasonal / stress-test power plants	Fossil gas	(likely) open cycle gas turbine	Grid balancing power (daily in specific sea-son)
Power	Coal-fired power plant	Coal & substitute fuels	Various coal com-bustion technolo-gies	Base load power

Steam	Steam/CHP networks (industrial clusters, incl. district heating)	Coal and/or fossil gas, partly substitute fuels and industrial side products	Incineration, partly cogeneration	Different heat levels of steam
Steam	Standalone industrial steam boilers (e.g. for food & drink or down-stream metals)	Coal and/or fossil gas, partly substitute fuels and industrial side products	Incineration	Different heat levels of steam
Steel	Steel - BF-BOF	Iron ore, scrap, lime and cok-ing coal	Blast furnace and basic oxygen furnace	Steel
Steel	Steel - DRI+EAF (fossil gas)	Iron ore, scrap, fossil gas	Direct reduced iron and electric arc furnace	Steel
Waste Pro-cessing	Waste-to-chemicals / chemical recycling	Plastic waste	Pyrolysis or gasifi-cation, collection of side product	Syngas or pyrolysis oil
Waste Pro-cessing	Waste incineration - hazardous waste	Hazardous waste / industrial side products	Incineration	Electricity / heat / steam
Waste Pro-cessing	Waste incineration - mixed municipal waste	Mixed municipal waste	Incineration	Electricity / heat
Waste Pro-cessing	Waste incineration - wastewater sludge	Wastewater sludge	Sludge mono-incin-eration	Electricity / heat

Notes:

- If installations can run on different fuels – for example, coal, substitute fuels or biomass in the case of cement kilns – we assumed that the general fuel mix would likely change over time alongside Europe's decarbonisation trajectory. That is, coal use being phased down while alternative (renewable) energies are scaled up and made more widely available.
- Likewise, electrified installations are assumed to be powered by (nearly) 100% renewable electricity by 2050 for the purpose of this exercise.

Scoring approach

Each application is assessed against the three criteria using a 1–5 scale, where:

- 1 = weak competition of alternatives; low mitigation potential or low feasibility
- 5 = strong competition of alternatives; low mitigation potential or low feasibility.

Scores are based on a combination of quantitative indicators and qualitative assessment. The scor-ing process draws on internal analysis, published studies, and targeted stakeholder feedback.

Weighting

To reflect its central importance in determining where CCS is genuinely needed, the criterion on competition from alternative mitigation levers is given double weight. The criteria on mitigation po-tential and feasibility are each weighed once. Weighted scores are combined into a single numerical result for each application for both 2030 and 2050, translated into an A - F ranking. [1]

1 Category 'F' represents the bottom of the scale, incorporating processes with aggregate scores less than two while the 'A' category represents the top of the scale with processes that have aggregate scores of more than four. The intermediate categories B - E span increments of 0.5 on the aggregate score scale.

Time horizon: 2030 and 2050

To capture how the role and climate value of CCS could evolve over time as Europe's decarbonisation pathway advances, each application is assessed for two timeframes:

- 2030 – where limited availability of clean alternatives such as renewable hydrogen, relatively constrained CO_2 transport and storage infrastructure, and early-stage deployment of many alternative mitigation levers influence the relative value of CCS.
- 2050 – a climate-neutrality context in which large-scale electrification, expanded renewable and hydrogen capacity, deeper circularity and substitution practices, and a more extensive CO_2 network are expected to be in place.

Scoring the same applications at two points in time allows us to capture that the role and value of CCS will be dynamic and dependent on the trajectory and delivery of alternative mitigation levers.

Boundaries and assumptions

The assessment is scoped to Europe, with a primary focus on the EU and neighbouring countries. To ensure comparability across applications, we assume that captured CO_2. would be permanently stored as the climate benefits of using CO_2 are highly case-specific. We also assess applications according to the average fuel or feedstock mix used, while recognising that this varies considerably across applications.

Annex

The relevance of clusters for the feasibility of CCS

When multiple CO_2 sources are located close to each other, questions emerge how to potentially rate them in an aggregate manner for infrastructural considerations.

In our CCS ladder framework, applications that are geographically and organizationally clustered – particularly in coastal or industrial regions – tend to receive higher feasibility scores. This reflects the assumption that clustering, by bundling CO_2 streams from multiple plants, can lower transport costs, increase efficiency, and create business opportunities for applications that would otherwise struggle to implement CCS independently. While clusters offer some advantages, this section highlights the conditions, dilemmas, and trade-offs that complicate this perspective.

Clusters can be understood as concentrations of emission sources, capture facilities, and transport infrastructure within a defined region. They represent nodes of energetic and material intensity, combining fossil process and energy-related emissions with biogenic flows and, increasingly, renewable energy inputs. Pooling infrastructure within clusters can reduce both capital and operational costs, avoid redundant investments, and enable synergies such as heat integration or coupling CCS with emerging technologies, including low-carbon hydrogen. Industrial clusters – typically concentrated in chemical, steel, or refining sectors – benefit from high emission densities and existing infrastructure linkages. In these contexts, clustering can reduce transport costs while forming nuclei for innovation, knowledge exchange, and governance experimentation, effectively serving as testbeds for multi-stakeholder collaboration.

Conditions and Trade-offs

The effectiveness of clusters is conditional. Efficiency gains and cost reductions represent their primary potential benefits, but high emission density is a prerequisite. Dispersed hard-to-abate sectors – such as lime, cement, or, in most cases, waste – rarely benefit from clustering. Proximity to pipeline corridors further lowers transport costs and regulatory burden, while access to renewable energy enhances efficiency by powering capture processes or integrating low-carbon hydrogen. Realizing these advantages also depends on technological compatibility among participating actors.

Economically, clustering allows for cost pooling, reducing individual capital requirements. Although studies indicate modest transport cost reductions, clustering alone is rarely sufficient to make otherwise uneconomical CCS projects viable.[2] When evaluating the option to cluster for example post-combustion amine-based carbon capture from two sources at a project level, two main factors are decisive: the volume of flue gas (flowrate) and the distance between sources. Clustering becomes less attractive if flowrates are very high or sources are far apart, because economies of scale are limited and piping costs increase substantially. Studies indicate that combining flows at the desorber usually brings only minimal cost savings and is rarely decisive. By contrast, clustering at the absorber can raise costs overall, although in certain cases it can generate significant investment savings.[3] Cost reductions will therefore be site specific, while at the same time, interdependencies increase: withdrawal of a key participant can jeopardize the cluster's overall business case.

Clusters also raise governance and socio-economic challenges. Aggregation of multiple actors increases transaction costs and coordination complexity. Uneven benefits from cluster-based funding schemes may favor specific industries or regions, potentially constraining broader CCS acceptance. Mixed CO_2 streams complicate accounting, and without clear policy guidance, clusters may prioritize cost-efficient applications over genuinely hard-to-abate sectors, risking technological lock-in and misaligned climate outcomes. Structural changes – such as industrial relocation or decline – can further lead to underused or stranded infrastructure. Socially, anchoring CCS in existing industrial hubs may preserve employment and regional identity but can also slow transformative decarbonization if declining sectors are artificially sustained.

2 See among others Wang et al., 2025, Unveiling cost reduction potential of carbon capture and storage clusters in China under multiple uncertainties

3 See Subraveti et al., 2025, CO_2 capture from multiple sources: To be, or not to be clustered, that is the question

Assessing the climate value of cluster-based approaches requires strategic mapping of emission sources, transparent accounting frameworks, and incentive structures that reward demonstrable efficiency improvements. This is partially beyond the scope of the CCS ladder. While integration with renewable energy, hydrogen development, and CCU applications is desirable, the permanence of CO_2 reductions must remain the overarching priority. Clusters should be regarded as conditional instruments within a broader decarbonization strategy – most effective where emission densities, infrastructure availability, and renewable integration align to support long-term viability and genuine mitigation of hard-to-abate emissions.