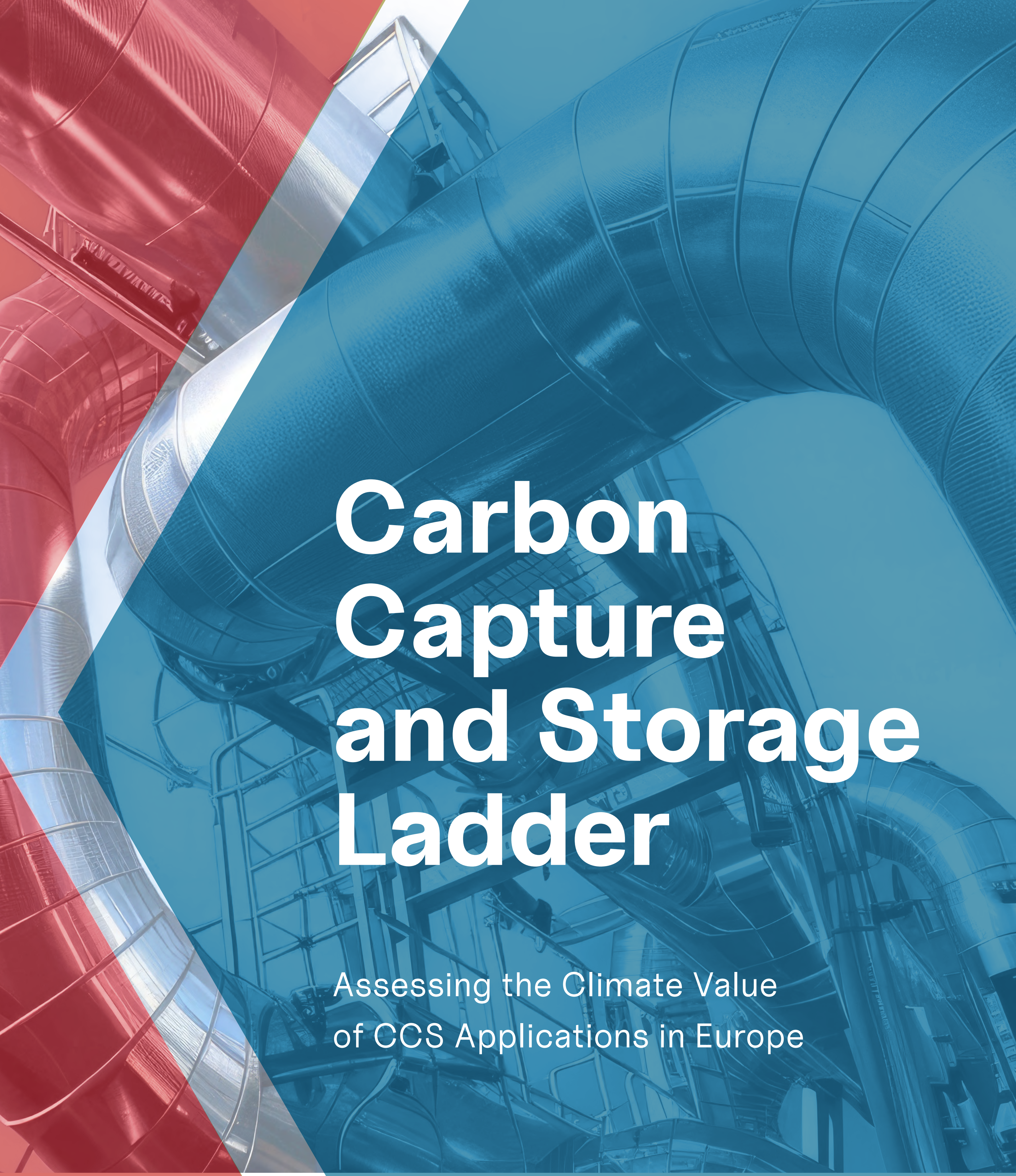

Carbon Capture and Storage Ladder

Assessing the Climate Value of CCS Applications in Europe

2026
Update

February 2026

E3G

BELLONA

Authors

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About E3G

E3G is an independent think tank working to deliver a safe climate for all. We drive systemic action on climate by identifying barriers and constructing coalitions to advance the solutions needed. We create spaces for honest dialogue, and help guide governments, businesses and the public on how to deliver change at the pace the planet demands.

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About Bellona

Bellona is a non-profit climate and environmental protection organisation who works on three fundamental challenges of our time: climate change, environmental pollution and the destruction of ecosystems. It advocates for democratic and just societies with free access to information – because only these can develop and implement the most effective responses to our challenges.

Bellona takes a systemic approach to identifying, developing and promoting sustainable solutions. It works in a science-based and solution-oriented manner with all relevant stakeholders – because developing effective solutions requires an enormous joint effort from science, industry, finance, civil society, the public sector and political decision-makers.

Bellona Deutschland, based in Berlin, focuses on climate action in industry.

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Acknowledgements

This work and its recommendations were tested with business, policy and civil society stakeholders across Europe, including through workshops. We are grateful to all those who shared their time, insights and feedback.

In particular, we would like to thank Aymeric Amand (ZEP), Dominic Hogg, Janek Vakh (Zero Waste Europe), Joren Verschaeve (ECOS) and Leon de Graaf (Sustainable Public Affairs) for their substantive feedback, and Behnam Lot, Louis Hennequin, Mats Rongved, Marco Sirotti, Mark Preston Aragones, Milan Loose, Tom Mikunda, Olav Øye and Fabian Liss (Bellona) and Laith Whitwham and Rheanna Johnston (E3G) for time and input, as well as Amrei Milch and Arnbjørn Mortensen (Bellona) and Daniele Gibney and Nesta Smith (E3G) for their communications support.

We also thank Green Ink for design and copy-editing support.

Table of Contents

Introduction

When E3G and Bellona published the first Carbon Capture and Storage (CCS) Ladder in 2023,[1] our objective was to bring nuance to a debate that is often polarised. In many circles, CCS is treated as a single technology or silver bullet with clear opponents and proponents, with little structured thinking on where it adds genuine climate value and where it risks delaying deeper transformation. The 2023 CCS Ladder proposed a transparent, multi-criteria assessment framework to evaluate the *climate value* of CCS across different industrial sectors and processes in Europe.[2]

That first edition was always meant to be a starting point. It invited feedback, discussion, and iteration as the policy, technological, and political landscape evolved. Since its release, the 2023 CCS Ladder has been taken up and adapted in other contexts – from the United States[3] to China[4] – illustrating the growing need for systematic decision-support frameworks for CCS deployment across sectors. Moreover, just three years on, both the context and the questions facing European decarbonisation have already changed.

This update builds on that foundation. It deepens the analysis, integrates further stakeholder feedback, and reflects the shifting realities of decarbonisation. Above all, it reaffirms the need for strategic thinking about where CCS can provide real and durable value for the climate, and where it cannot.

A rapidly changing context: progress and turbulence since 2023

Policy and deployment: Europe's first operational industrial carbon capture and storage project

Europe's CCS policy landscape is evolving rapidly. The European Industrial Carbon Management Strategy[5] published in 2024 foresaw the need to capture up to 50 million tonnes (Mt) carbon dioxide (CO_2) annually by 2030 and 450 Mt annually by 2050, of which roughly half is to be permanently stored to achieve Europe's climate neutrality goal.[6]

Indeed, the Net Zero Industry Act[7] has made carbon storage a defining feature of Europe's new industrial architecture, introducing an obligation for oil and gas producers to make at least 50 Mt of annual CO_2 storage injection capacity available by 2030. Meanwhile, the European Commission has launched work on a CO_2 markets and infrastructure package[8] that will shape future frameworks for access, transparency, and cross-border trade in CO_2.

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[1] E3G & Bellona, 2023, Carbon Capture and Storage Ladder

[2] Like the 2023 CCS Ladder, this update focuses on Europe, acknowledging that regional contexts vary and may lead to somewhat different transition pathways, opportunities, and challenges.

[3] Kleinman Center for Energy Policy, 2024, U.S. CCS Ladder for Industrial Decarbonisation

[4] GIZ, 2023, Facilitating China's Industrial Transformation with CCU/S – Sino-German Energy Transition Project (EnTrans)

[5] European Commission, 2024, Towards an ambitious Industrial Carbon Management for the EU

[6] According to the European Commission's Industrial Carbon Management Strategy, around 90% of the 2030 capture volumes would come from industrial process and fossil-combustion emissions and would be almost entirely destined for permanent storage. By 2050, over half of captured CO_2 is expected to originate from biogenic sources and direct air capture, with around 50% of total captured volumes used in synthetic fuels, chemicals, or materials rather than permanently stored. Our CCS Ladder primarily evaluates applications involving process and fossil-based emissions, assuming permanent geological storage.

[7] European Union, 13 June 2024, Regulation establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem

[8] European Commission, 6 October 2026, Commission launches public consultation CO_2 markets and infrastructure

At the same time, Europe's pipeline of capture projects has grown steadily. Dozens of new industrial CCS projects are now announced or in development, spanning cement, lime, chemicals, and waste management.[9] A major milestone was reached in 2025 when Europe's first full-scale industrial CCS facility began operating.[10]

The regulatory environment has also tightened. The EU delegated act on low-carbon hydrogen[11] now sets an emissions performance threshold for "blue" hydrogen, effectively defining what type of CCS-linked hydrogen production qualifies as low-carbon. Combined with successive rounds of the Innovation Fund[12] channelling growing support to sectors such as lime and cement, these policy measures are beginning to shape Europe's CCS landscape.

Technology trends: momentum versus delays

Technology costs are shifting fast. The prices of renewables – particularly solar – continue to fall,[13] while battery storage is scaling rapidly and becoming cheaper.[14] Together, these trends are accelerating fossil fuel phase-out from the power sector and strengthening the case for electrification.

Electrification potential is also expanding quickly. Recent analyses suggest that 90% of industrial process heat could be electrified by 2035[15] and that electricity could meet nearly two thirds of Europe's final energy demand by 2050.[16] Electrification consistently outperforms other options on cost, scalability and energy efficiency, especially in the mid- to long-term.

However, high electricity prices remain a major obstacle. In recent years, the energy crisis once again exposed Europe's vulnerability to volatile fossil fuel imports; however, it also highlighted the challenge of moving away from fossil fuels under current cost structures – many industries shut production rather than replacing fossil fuels with clean alternatives.[17] Thus, despite its potential, electricity use in industry has remained plateaued, hindered by high taxes, non-competitive power prices and grid bottlenecks.

Meanwhile, green hydrogen is facing a more difficult reality. Dozens of projects across Europe have been delayed or cancelled amid rising costs and uncertain offtake.[18] This has knock-on effects for the transition of many industries, including the steel sector, where several flagship projects – which would use green hydrogen to produce iron – have been discontinued or postponed.[19]

At the same time, both the cost of carbon capture and the cost and availability of CO_2 transport and storage remain highly uncertain. Until a critical mass of projects are operational, real-world costs will be difficult to estimate with confidence – much as recent experience with green hydrogen has shown. System costs for transport and storage may ease with scale but are not expected to fall by an order of magnitude.

Taken together, these developments both intensify and reshape the competition between CCS and some of its key decarbonisation competitors – highlighting that CCS's role in Europe's transition will remain dynamic, evolving with the pace and success of these parallel decarbonisation routes, as well as its own ability to deliver.

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[9] IOGP, 2025, Interactive Map of CCUS projects in Europe – accessed on 19 November 2025

[10] Heidelberg Materials, 17 June 2025, Brevik CCS – World's first CO_2-capture facility in the cement industry

[11] European Parliament Think Tank, 2025, Delegated act for low-carbon hydrogen

[12] European Commission, 2025, Innovation Fund projects - accessed on 15 November 2025

[13] IRENA, 2025, Renewable Power Generation Costs in 2024

[14] Solar Power Europe, 2025, European Market Outlook for Battery Storage 2025-2029

[15] Agora Industry, 2024, Direct electrification of industrial process heat

[16] European Commission, 2024, Staff working document impact assessment accompanying the communication: Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society

[17] European Central Bank, 2023, How have higher energy prices affected industrial production and imports?

[18] Westwood Global Energy Group, 17 December 2024, Over a fifth of all European Hydrogen projects stalled or cancelled

[19] GMK Center, 8 October 2025, Major pause in EU steel industry decarbonization projects

Political context: climate action under pressure

Across the world, political conditions for ambitious climate action have become more challenging. Trump's re-election in the United States has rolled back key climate legislation. In Europe, the political space to pursue decarbonisation to meet climate objectives alone is narrowing. The debate on the EU's 2040 climate target revealed deep divisions over the perceived trade-offs between competitiveness, industrial transition and social acceptance – a reminder that consensus on long-term climate ambition can no longer be taken for granted.

Policymakers are currently increasingly preoccupied with competitiveness, affordability, security and defence, while public finances are under significant strain. National budgets and EU funding instruments face tightening constraints, leaving less room for new spending. This has sharpened demands that every Euro of climate expenditure deliver measurable results – often framed as the need to achieve the highest emission reduction per Euro spent.[20] Yet, an exclusive focus on the cheapest short-term abatement can lead to corner-cutting and technological lock-in, favouring incremental rather than transformational solutions.

At the same time, the discourse of "technology neutrality" has become dominant in Brussels and many European countries. While intended to signal openness to multiple pathways, in practice it has often narrowed the policy conversation – discouraging informed prioritisation between technologies and sectors and blurring the distinction between near-term pragmatism and long-term strategy.

Carbon capture and storage prioritisation: why it matters

The political space for strategically planning, prioritising and implementing decarbonisation solutions has narrowed, yet prioritising interventions remains essential to guide cost-effective investment. Financial and infrastructure constraints limit simultaneous pursuit of every decarbonisation pathway – choices must be made about where each option can deliver the most value. We believe CCS is one technology whose inclusion in such prioritisation is necessary. Notwithstanding the reasonable perspective that CCS can significantly reduce CO_2 emissions in certain industries and processes, its climate value varies. CCS is unable to address upstream emissions and other environmental impacts from continued combustion activities or downstream emissions related to the use and disposal of a product, and uncertainty remains about whether and how quickly large-scale deployment can deliver. The CCS Ladder is designed to support policymakers in prioritising CO_2 decisions by providing a structured, comparative assessment of where CCS can deliver most climate value.

As with many nascent decarbonisation technologies, CCS also displays the characteristics of a scarce good. In the near term, practical CO_2 storage injection capacity and supporting infrastructure will be limited, and decision-makers face real trade-offs about where to develop this capacity, and where to direct public funding and regulatory attention. In the long run, this scarcity could be resolved: Europe has ample theoretical storage potential, and the necessary infrastructure can be built. But by the time these limitations are overcome, other technologies – from green hydrogen to electrification – are likely to have advanced further, reducing the need for fossil-based CCS altogether.

Although innovation is developing potentially game-changing technologies across most sectors that could obviate process- and fossil-based CCS over time, for most nascent technologies it is still too early to know which will be viable or arrive in time to meet Europe's climate targets.[21] In parallel, the need for CO_2 removal (CDR) technologies like bio-based CCS (BioCCS) and direct air capture (DACCS) to balance residual emissions and ultimately achieve net-negative emissions will increase,[22] so infrastructure development for transport and injection capacity is clearly needed in both the foreseeable and longer future.

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[20] European Commission, 2025, The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation

[21] For instance, fusion power may one day be transformative but remains speculative and unlikely to deliver before the EU has committed reaching climate neutrality. The same is likely to be true for multiple electrochemical production routes for various basic materials like iron, cement and some chemicals.

[22] European Commission, 2024, Towards an ambitious Industrial Carbon Management for the EU

The challenge is therefore one of timing. We are not operating in the long term but within the narrow window defined by the remaining carbon budget to achieve global temperature goals. The climate clock is ticking, and Europe has committed to reaching climate neutrality within the next 25 years. Policy must steer this judgement carefully: supporting process- and fossil-based CCS where it acts as a necessary solution or bridge to climate neutrality, while avoiding active support where it risks locking in low-value, uncompetitive pathways.

The 2026 update: purpose and scope

This update builds on the 2023 CCS Ladder, maintaining its central purpose: to provide a comparative, merit-order assessment of where CCS can deliver the most climate value across applications. The approach remains at a meta-level – ranking application groups, not individual projects – to inform strategic prioritisation rather than site-specific feasibility.

The 2026 update does not prescribe policy priorities but provides a structured basis for evaluating trade-offs and informing prioritisation decisions.

BOX 1. How to read the carbon capture and storage ladders

The CCS ladders are a decision-support framework designed to assess where CCS can deliver *climate value* across industrial sectors and processes. They are intended to inform strategic prioritisation and policy discussions as a resource to policymakers and stakeholders, supporting early decisions on how to allocate initially limited transport and storage infrastructure, including CO_2 injection capacity, as well as scarce public resources.

The CCS ladders are **not** meant to:

- **Be conclusive** – value propositions vary, and the underlying assumptions will evolve over time.
- **Denounce the use of CCS anywhere** – from a pure climate perspective, capturing and permanently storing CO_2 is always preferable to emitting it.
- **Judge whether CCS should or should not be applied on a project-by-project basis** – they *assess broad application groups not individual projects or installations*.
- **Serve as a direct funding guide** – climate value does not automatically justify financial support.

Additionally, the CCS Ladders do not assess or assume the qualitative integrity of individual CCS projects.[23]

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[23] Determining whether a project is "high-quality" depends on multiple factors – including storage permanence, achievable capture rates, upstream emissions, indirect emissions, and operational performance – and there are currently no established standards across applications. However, the EU has recently set criteria for low-carbon hydrogen produced with CCS. What is also emerging is a clearer view of what will be required for projects using CCS to count as "abated" in a more long-term net-zero context, including over 95% capture rates, permanent storage, and very low upstream fugitive emissions (see, for example, Bataille, C. et al., 2025, Defining 'abated' fossil fuel and industrial process emissions). These criteria are primarily relevant for the long term: projects commissioned in the 2020s will not necessarily meet such standards from day one. But CCS applications that cannot credibly reach these benchmarks over time are unlikely to remain compatible with Europe's climate-neutrality objectives.

Compared to the first edition, this update:

- **Integrates new evidence and stakeholder feedback** gathered since 2023.
- **Updates the methodology and scoring framework**, applying three criteria instead of four and assigning double weighting to the "Competition from Alternatives" criterion[24] (See methodology for full overview of criteria and weighting). The criteria have also been refined:
    - *Competition from alternatives* now more explicitly considers circularity, substitution and demand-reduction potential;
    - *Mitigation potential* continues to capture both plant-level and system-level potential of CCS to deliver emission cuts; and
    - *Feasibility* now includes regulatory and economic pressures such as carbon pricing on residual emissions and costs linked to achieving high capture rates.
- **Re-assesses the full list of applications**, deleting some, adding new ones and introducing more granular sub-categories where differentiation within a sector is meaningful (see Table 1 for full list). Notably, dedicated bio-based applications have been excluded from this update to reflect their distinct methodological and sustainability considerations.

BOX 2. Why bio-based applications are not included in this update

The 2023 CCS Ladder included only a few bio-based applications, omitting, for example, biomass fermentation processes. In practice, "bio-CCS" spans many pathways that convert biomass into heat, power, hydrogen and intermediary biorefinery products (bioethanol, lignin-derived chemicals or cellulose pulps).

While it is valuable and necessary to consider where CCS on bio-based applications could provide the greatest climate value, the core value proposition of bio-CCS differs from conventional CCS: the potential of bio-CCS for negative emissions. Realising that potential depends on robust life-cycle assessments of biomass supply chains and clear sustainability criteria at the project level – factors that cannot be captured within our system scoring framework.

Including bio-based applications would force simplifying assumptions that distort results: either assuming all biomass is sustainable (inflating scoring for "competition from alternatives" and "mitigation potential") or penalising all bio-based applications to signal clear system limits to the availability of sustainable biomass (risking undervaluation where sustainability can be demonstrated). Neither approach yields a fair comparison.

This is why our update excludes any dedicated bio-based applications. Applications that use a general fuel mix (which may include some biomass) remain, but any system-level potential for negative emissions is not assessed. This exclusion should not be read as a dismissal of their potential climate value. However, a credible appraisal of such applications requires a separate analytical framework incorporating sustainable biomass availability. **We encourage others to undertake that exercise.**

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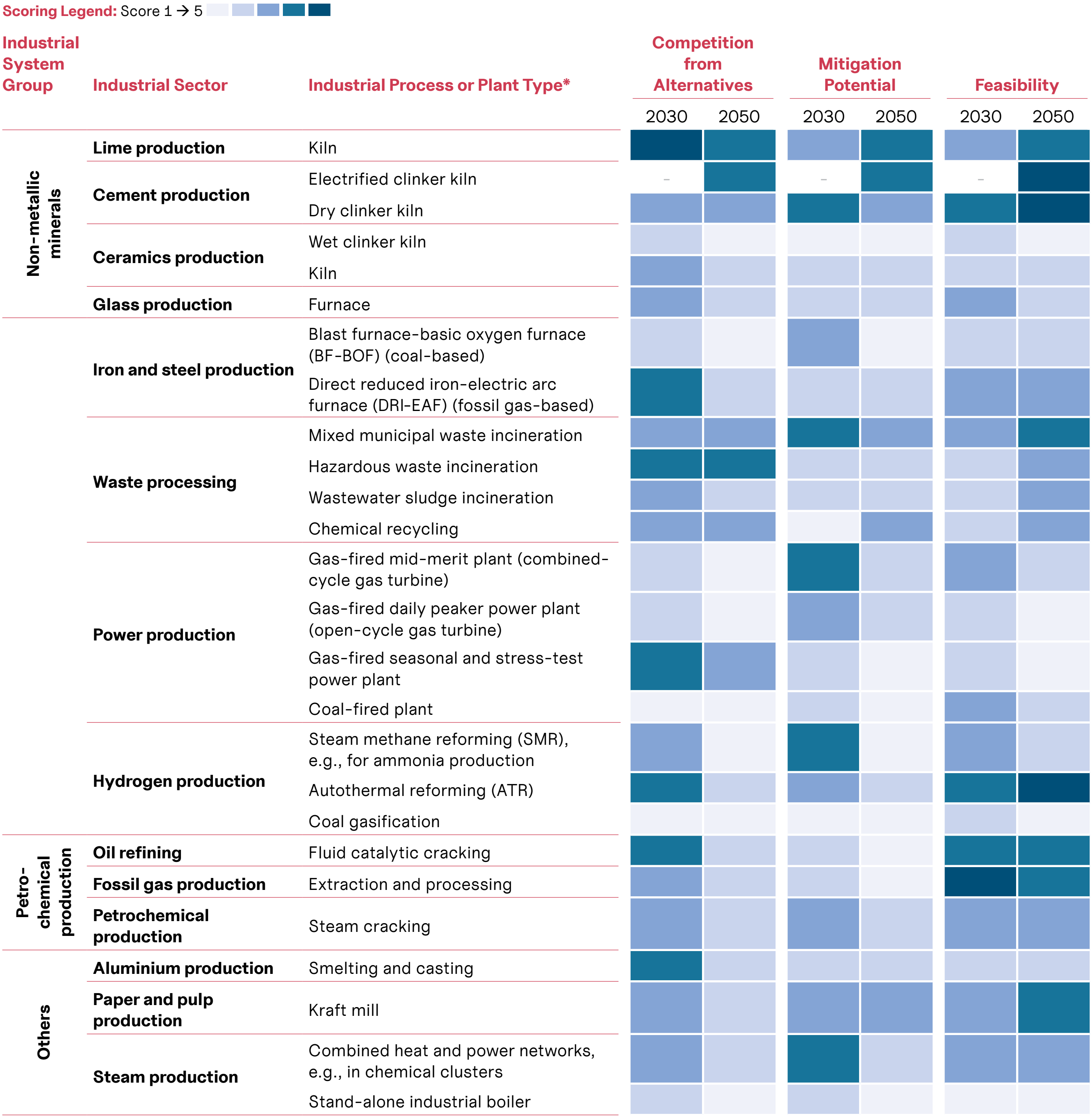
[24] We apply a double weighting to "Competition from Alternatives" to reflect that CCS is not impact-free: it requires significant transport and storage infrastructure, increases energy use, and – where fossil fuels remain – can prolong upstream and downstream impacts. CCS should not be the go-to solution where scalable, cost-effective alternatives exist; it sits lower in the mitigation hierarchy for that reason. The double weighting ensures this principle is clearly reflected in the assessment.

Insights from the updated carbon capture and storage ladders

The climate value of CCS varies widely across industrial sectors and processes and changes over time as alternative mitigation options develop. To illustrate these differences, our analysis first assessed how a range of industrial sectors and processes perform against three key criteria: competition from alternatives, climate-mitigation potential, and feasibility for 2030 and 2050. Table 1 presents this multi-criteria assessment, showing how each sector and process scores across these criteria (with a score of 5 as highest and 1 as lowest).

Table 1. Multi-criteria assessment of CCS climate value across industrial sectors and processes (2030–2050)



Scoring Legend: Score 1 → 5

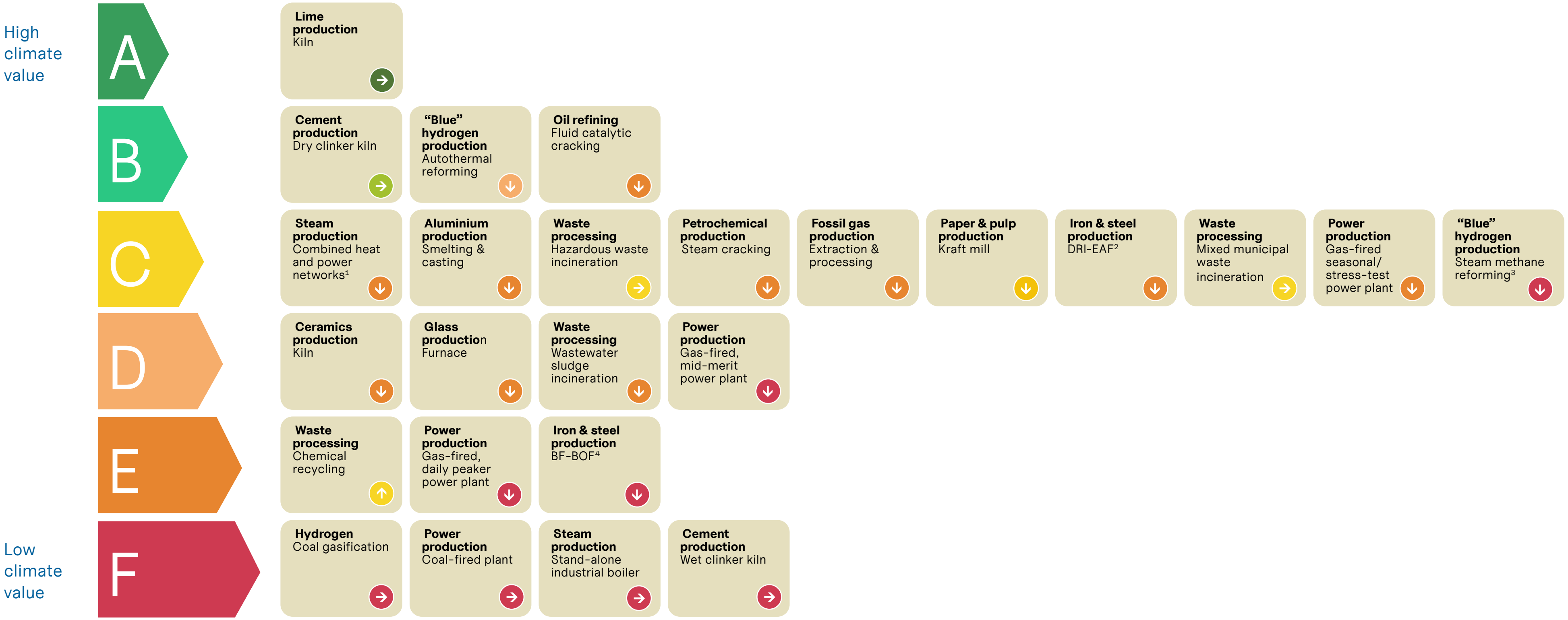
Industrial System Group	Industrial Sector	Industrial Process or Plant Type*	Competition from Alternatives		Mitigation Potential		Feasibility	
			2030	2050	2030	2050	2030	2050
Non-metallic minerals	**Lime production**	Kiln	5	4	3	4	3	4
	Cement production	Electrified clinker kiln	–	4	–	4	–	5
		Dry clinker kiln	3	3	4	3	4	5
	Ceramics production	Wet clinker kiln	2	1	1	1	2	1
		Kiln	3	2	2	2	2	2
	Glass production	Furnace	3	2	2	2	3	2
	Iron and steel production	Blast furnace-basic oxygen furnace (BF-BOF) (coal-based)	2	1	3	1	2	2
		Direct reduced iron-electric arc furnace (DRI-EAF) (fossil gas-based)	4	2	2	2	3	3
	Waste processing	Mixed municipal waste incineration	3	3	4	3	3	4
		Hazardous waste incineration	4	4	2	2	2	3
		Wastewater sludge incineration	3	2	2	2	2	3
		Chemical recycling	3	3	1	3	2	3
	Power production	Gas-fired mid-merit plant (combined-cycle gas turbine)	2	1	4	2	3	2
		Gas-fired daily peaker power plant (open-cycle gas turbine)	2	1	3	2	2	1
		Gas-fired seasonal and stress-test power plant	4	3	2	1	2	1
		Coal-fired plant	1	1	2	1	3	2
	Hydrogen production	Steam methane reforming (SMR), e.g., for ammonia production	3	1	4	1	3	2
		Autothermal reforming (ATR)	4	2	3	2	4	5
		Coal gasification	1	1	1	1	2	1
Petro-chemical production	**Oil refining**	Fluid catalytic cracking	4	2	2	1	4	4
	Fossil gas production	Extraction and processing	3	2	2	1	5	4
	Petrochemical production	Steam cracking	3	2	3	2	3	3
Others	**Aluminium production**	Smelting and casting	4	2	2	2	2	2
	Paper and pulp production	Kraft mill	3	2	3	3	3	4
	Steam production	Combined heat and power networks, e.g., in chemical clusters	3	2	4	2	3	3
		Stand-alone industrial boiler	2	1	2	1	1	1

Competition from Alternatives: 5 – no credible alternatives to fully decarbonise or substitute at scale/affordable cost; 1 – multiple alternatives exist that are scalable and cost-competitive.
Mitigation Potential: 5 – sector emits large volumes; CCS can cut the majority of both site-level and life-cycle emissions; 1 – sector is a small emitter; CCS would only marginally reduce total emissions.
Feasibility: 5 – high capture rates are technically and economically viable; sources are large and clustered near storage options; 1 – capture has low technology readiness, is costly or technically difficult; sources are small and/or widely dispersed.
* The 'industrial process or plant type' category reflects the level at which CCS feasibility, mitigation potential, and competition from alternatives are assessed, and therefore includes key industrial processes, complete industrial production pathways, and – where relevant – power-sector plant types.

These individual scores are then combined to construct the 2030 and 2050 CCS ladders, shown in Figure 1. Each industrial process's position reflects its weighted average score across the three variables, with "availability of alternatives" given double weight. This provides a comparative framework of where CCS is likely to offer the greatest climate value over time, and how this changes as other technologies and mitigation routes are expected to mature and scale. These ladders are not intended to be interpreted as precise rankings, rather, they offer a structured understanding of the relative climate value of different CCS applications.

Figure 1. CCS ladders: climate value of carbon capture and storage by industrial process (2030 and 2050)

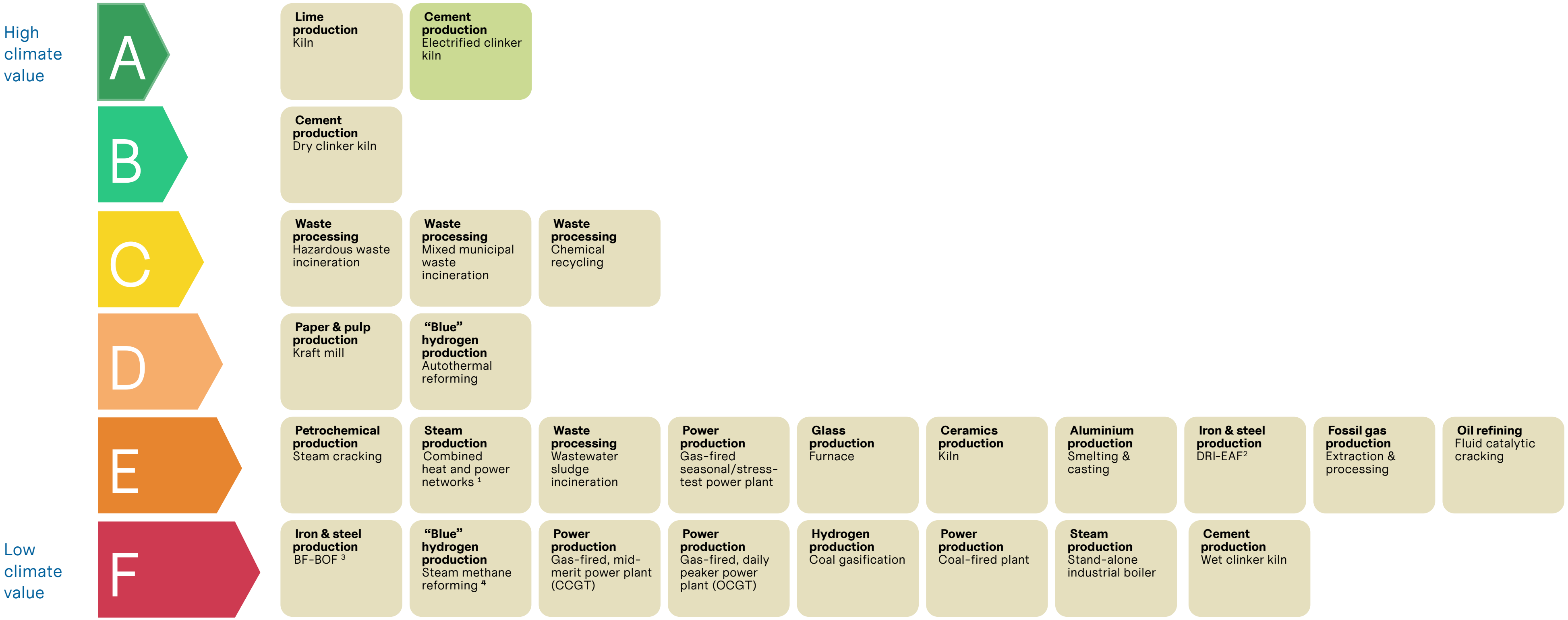
2030



High climate value A	**Lime production** Kiln →									
B	**Cement production** Dry clinker kiln →	**"Blue" hydrogen production** Autothermal reforming ↓	**Oil refining** Fluid catalytic cracking ↓							
C	**Steam production** Combined heat and power networks[1] ↓	**Aluminium production** Smelting & casting ↓	**Waste processing** Hazardous waste incineration →	**Petrochemical production** Steam cracking ↓	**Fossil gas production** Extraction & processing ↓	**Paper & pulp production** Kraft mill ↓	**Iron & steel production** DRI-EAF[2] ↓	**Waste processing** Mixed municipal waste incineration →	**Power production** Gas-fired seasonal/ stress-test power plant ↓	**"Blue" hydrogen production** Steam methane reforming[3] ↓
D	**Ceramics production** Kiln ↓	**Glass production** Furnace ↓	**Waste processing** Wastewater sludge incineration ↓	**Power production** Gas-fired, mid-merit power plant ↓						
E	**Waste processing** Chemical recycling ↑	**Power production** Gas-fired, daily peaker power plant ↓	**Iron & steel production** BF-BOF[4] ↓							
Low climate value F	**Hydrogen** Coal gasification →	**Power production** Coal-fired plant →	**Steam production** Stand-alone industrial boiler →	**Cement production** Wet clinker kiln →						

Notes: Coloured arrows indicate changes in relative ranking from 2030 to 2050 (up, down or stable. The ladders do not express how much CCS should or will be deployed in any application, nor whether CCS is the only or preferred mitigation lever. All applications assessed have at least some technological and non-technological mitigation alternatives, including those applications with higher rankings. Please see Box 1 for guidance on how to interpret and use the CCS ladders.) BF-BOF – blast furnace-basic oxygen furnace; CCGT – combined-cycle gas turbine; 2 DRI-EAF – direct reduced iron-electric arc furnace; OCGT – open-cycle gas turbine;
1 For example, in chemical clusters; 2 Fossil gas-based; 3 For example, for ammonia production; 4 Coal-based.

2050



High climate value

Low climate value

A	**Lime production** Kiln	**Cement production** Electrified clinker kiln								
B	**Cement production** Dry clinker kiln									
C	**Waste processing** Hazardous waste incineration	**Waste processing** Mixed municipal waste incineration	**Waste processing** Chemical recycling							
D	**Paper & pulp production** Kraft mill	**“Blue” hydrogen production** Autothermal reforming								
E	**Petrochemical production** Steam cracking	**Steam production** Combined heat and power networks [1]	**Waste processing** Wastewater sludge incineration	**Power production** Gas-fired seasonal/stress-test power plant	**Glass production** Furnace	**Ceramics production** Kiln	**Aluminium production** Smelting & casting	**Iron & steel production** DRI-EAF[2]	**Fossil gas production** Extraction & processing	**Oil refining** Fluid catalytic cracking
F	**Iron & steel production** BF-BOF [3]	**“Blue” hydrogen production** Steam methane reforming [4]	**Power production** Gas-fired, mid-merit power plant (CCGT)	**Power production** Gas-fired, daily peaker power plant (OCGT)	**Hydrogen production** Coal gasification	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln		

Notes: The ladders do not express how much CCS should or will be deployed in any application, nor whether CCS is the only or preferred mitigation lever. All applications assessed have at least some technological and non-technological mitigation alternatives, including those applications with higher rankings. Please see Box 1 for guidance on how to interpret and use the CCS ladders. BF-BOF – blast furnace-basic oxygen furnace ; CCGT – combined-cycle gas turbine; DRI-EAF – direct reduced iron-electric arc furnace; OCGT – open-cycle gas turbine.
1 For example, in chemical clusters; 2 Fossil gas-based; 3 Coal-based; 4 For example, in ammonia production.

Overall, this update confirms the structure and hierarchy of the 2023 CCS Ladder. While new evidence and feedback have refined certain scores and added granularity within sectors, the overall picture of a narrowing and increasingly targeted role for CCS remains consistent.

Table 2 summarises the climate value and indicative role of CCS across the main groups of applications assessed. It distils insights from the 2030 and 2050 ladders and highlights how CCS fits within the broader decarbonisation pathways of different sectors. More detailed analyses for several of these application groups are given in Sectoral deep dives.[25]

Table 2. Value and role of carbon capture and storage in application groups assessed

Industrial grouping/ sector	Value and role of CCS
Non-metallic minerals *(cement, lime, ceramics and glass production)* → See cement and lime production deep dive	Lime and cement production remain at the top of the updated CCS ladders for both 2030 and 2050 scenarios, reflecting these industries' dependence on carbon capture of CO_2 process emissions from limestone decomposition. For lime production, CCS is effectively indispensable to reach net-zero, as alternatives are nascent at best and mainly address fuel-related emissions. However, deployment will be complicated by the highly dispersed landscape of relatively small kilns, often distant from industrial clusters, and limited early transport and storage infrastructure, which raise costs. This makes planning access to shared pipelines, hubs, or multi-model ship and rail solutions a critical precondition for the decarbonisation of this sector. In cement production, a broader set of levers, such as clinker substitution, material efficiency and circular construction, could significantly reduce emissions and moderate European clinker production volume. While this can lower the need for carbon capture over time, a significant amount of clinker production will remain operational. By contrast, glass and ceramics production emit less process CO_2 and can rely to a large extent on electrification and recycling to significantly reduce these emissions.
Iron and steel production → See iron and steel production deep dive	The use of CCS in steel production does not score as a priority in 2030 and declines further by 2050. For the coal-based (blast furnace-basic oxygen furnace (BF-BOF)) process, achieving high CO_2 capture rates across all emission sources is technically difficult and costly. Moreover, upstream methane leakage limits the overall climate benefit, meaning CCS offers little value as a deep decarbonisation solution. For future ironmaking based on direct reduced iron-electric arc furnace (DRI-EAF routes), the picture is more complex. DRI-EAFs can run on either hydrogen or fossil gas, meaning that many upcoming European projects are likely to begin operation with natural gas while renewable hydrogen remains constrained by cost, scale and infrastructure availability. In such cases, CCS could be required to manage the resulting emissions – either applied on-site to the DRI-EAF process or upstream for blue-hydrogen production. The wider uncertainty is that neither fossil-gas CCS routes nor renewable hydrogen pathways are guaranteed to scale at the pace or cost required for deep decarbonisation, and both carry risks of technological or economic lock-in. The long-term role of CCS will also depend on where Europe locates new DRI-EAF capacity and how green iron trade develops, as renewable hydrogen availability and production costs vary strongly across regions. This underlines the importance of accelerating renewable hydrogen deployment for the steel sector while also recognising that transitional solutions may still need to play a role.
Waste processing → See waste processing deep dive	The use of CCS for waste processing sits upper-mid on the updated CCS ladders and maintains a broadly similar position over time, though system trends introduce uncertainty. While CCS is the only way to abate emissions from incineration, waste incineration with energy recovery is a relatively unfavourable choice for waste management. The priority remains to prevent, reduce and redesign waste, improve sorting and recycling, and minimising overall material throughput. However, progress to date has been uneven, and volumes of waste generated have remained largely stable in recent decades. This makes the long-term scale of incineration capacity – and with it the scale of CCS deployment necessary to address emissions – uncertain and dependent on how successfully waste prevention and circular economy measures are implemented. Within this space, CCS will need to play a complementary role for mixed municipal waste – as a necessary lever to manage emissions from the subset of plants that will continue to operate. The significance of this role will depend on the success of – and policy attention given to – upstream circularity and waste-prevention efforts, though a material volume of waste for incineration is likely to persist well beyond 2050. For hazardous waste incineration, CCS has a strong long-term case and a potentially growing role for chemical recycling routes, such as gasification. However, the scale, performance, and impact of chemical recycling routes remain highly uncertain.

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[25] The full justification for each industrial process or plant type can be accessed through this link.

Power production → See power production deep dive	The value of CCS in reducing emissions in power production ranks towards the bottom of the updated 2030 Ladder and declines further by 2050. Coal-fired power generation is already exiting Europe's power system, and CCS is both uneconomical and incompatible with deep decarbonisation. For gas-fired power plants, CO_2 capture is technically possible but economically weak, and retrofitting plants with CCS risks tension with Europe's electrification agenda. As renewables, interconnection, storage and demand-side flexibility expand, the utilisation and system role of gas-fired power should continue to fall, thus also eroding the business case for carbon capture. Yet some uncertainty remains: a residual fleet of back-up gas-fired power plants may persist through to the 2040s. Zero-carbon alternatives for long-duration storage are still maturing, and their eventual scale and cost remain unclear. In this narrow context, CCS could appear as a backstop option but would be costly and inefficient with limited climate value.
Hydrogen production → See hydrogen production deep dive	In general there is reasonable merit in applying CCS to hydrogen production in 2030 – shown in the upper-mid range of the updated 2030 CCS Ladder, though this declines by 2050 as renewable hydrogen is expected to scale and become more competitive. Retrofitting CCS to existing steam methane reforming (SMR) units can deliver meaningful near-term abatement, but achieving high capture rates is technically and economically challenging, and resulting residual emissions mean this route is unlikely to be compatible with net-zero in the long term or is outcompeted as carbon prices increase. Autothermal reforming (ATR) with CCS can, in principle, deliver higher capture rates at lower cost and energy penalties but would require building new gas-based assets, making it a difficult fit for Europe's climate transition. This "blue" hydrogen's climate value will ultimately depend on its ability to deliver consistently high CO_2 capture rates, very low upstream methane leakage and permanent storage – conditions that are not yet demonstrated at scale. As renewable hydrogen supply grows and costs fall – though future cost trajectories remain uncertain – and as demand evolves in sectors like refining and fertiliser production (which consume the vast majority of hydrogen in Europe), the relative climate value of CCS in hydrogen production will diminish, even if long-term competitiveness is not yet fully clear.
Petrochemical production *(oil refining, fossil gas extraction and steam cracking)* → See petrochemical production deep dive	Use of CCS in petrochemical production and the fossil industry ranks relatively high on the updated CCS Ladder in 2030 due to its high technical feasibility and limited on-site abatement alternatives, but its relative value declines by 2050 as demand for fossil-based products falls and Europe's economy electrifies. Refineries, gas-processing plants and steam crackers emit large, concentrated CO_2 streams well suited for capture. However, CCS's climate value is constrained as most emissions in these industries occur downstream when fuels or petrochemical products are ultimately used or disposed of. The real long-term solution lies in accelerating demand reduction and increasing substitution and circular economy measures that reduce the need for these processes altogether. Near-term CCS deployment may be warranted to manage emissions from facilities that will remain operational through the 2030s. For steam crackers, while electrifying process heat offers a clear opportunity, the broader transition pathway remains uncertain and hinges on how far and fast feedstocks can be defossilised.
Other industrial processes *(aluminium, paper and pulp, and steam production)*	Value of CCS in these industries is middle-to-lower in the updated CCS ladders and generally shows declining, though mixed, trajectories. Most – yet not all – processes rely on medium- to high-temperature heat – generated on-site or through shared steam or combined heat and power networks. Reducing CO_2 emissions from process heat is increasingly being addressed through electrification using industrial heat pumps, electric boilers, or plasma technologies, though costs and grid constraints remain short-term barriers. Solutions for industrial processes where direct or indirect electrification can only deliver partial decarbonisation are more complex. A good example is the paper kraft mill: much of its process-heat demand is low- to medium-temperature and, in principle, electrifiable, yet this overlooks two major emission sources: the recovery boiler, which burns on-site-generated black liquor, and the lime-sludge kiln, which has process emissions from calcination and can account for up to a quarter of total plant emissions. In cases where process emissions remain, CCS may be necessary – or emissions have to be compensated elsewhere – until alternatives can be developed.

Cross-cutting takeaways

The updated CCS Ladder offers a comparative picture of where CCS currently adds the greatest climate value and how that value may evolve over time. Together, the results reveal several cross-cutting insights with implications across sectors and processes.

Carbon capture and storage climate value: expected to decline if alternatives deliver

For many of the industrial processes analysed, the relative climate value of CCS is expected to decline over time as clean electricity, electrification, circularity, and shifts toward consuming lower-carbon products advance. In most sectors, under current trends, cheaper alternative mitigation technologies with stronger climate benefits and/or further co-benefits (e.g., avoidance of health impacts from continued combustion) should gradually diminish the role of CCS. Indeed, for an increasing number of cases – including the power sector and industrial processes that require only low- to medium-temperature heat or steam (such as in food, beverage and textile industries) – alternatives have already outcompeted CCS, and its role is unlikely to be significant.

However, this is not universal. For activities such as lime production, hazardous-waste incineration and clinker production in the cement sector, carbon capture will probably need to play a considerable role to deliver near-full decarbonisation. How this balance develops will ultimately depend on the pace of progress in other mitigation routes and their relative economics, which remain uncertain across some sectors.

Because the relevance of CCS is dynamic and uncertain in some areas, and because it is not a drop-in solution, prioritisation cannot be interpreted as a sequencing exercise where CCS is simply applied in the late 2040s to mop up residual emissions. Capture infrastructure, transport networks, and storage capacity take years to develop. Strategic planning must therefore proceed in parallel with other mitigation efforts, ensuring that CCS can be available where it is needed, while avoiding blanket support in sectors where its role is clearly diminishing.

This does not mean that when cost-effective alternatives are available at scale, policymakers should still offer support for CCS in such areas – such as most of the power sector. Rather, policy frameworks should put the onus on emitters if they wish – or claim to need – to address their emissions through CCS deployment when alternatives are competitively available, while focusing public support on alternative mitigation options. Strongly penalising (e.g. via an ambitious carbon price without free allowances) or, where appropriate, banning the use of unabated fossil fuels (that is, without CCS) in processes with well-established alternatives could also be considered.

The relevance of CCS will continue to evolve as technologies, costs, policies, and markets develop, and should therefore be revisited regularly.

Need and feasibility do not always align

The updated CCS Ladder also highlights that the sectors where CCS may be most critical are not always those where deployment is easiest or cheapest to deliver, e.g., due to small site sizes, limited technical capacity, or distance from infrastructure. Conversely, in some cases, CCS can be relatively feasible – such as at large concentrated sources, in cluster locations, or where large volumes of CO_2 are already being separated – yet overall mitigation value may be limited or alternatives scaling rapidly.

BOX 3: Geographical clusters: relevance for carbon capture and storage feasibility

In our methodology, industrial processes that are usually geographically 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 individual facilities that would otherwise struggle to implement CCS independently. This also reflects the fact that policy frameworks sometimes target clusters for initial investments in CO_2 transport infrastructure.[26]

While clusters offer some advantages, there are nuances. As capturing costs are typically higher than transportation costs, clusters will only slightly improve CCS feasibility for relatively large emitters. However, for smaller emitters, which would otherwise not gain access to pipeline infrastructure, a mutual cluster might be the only option to increase feasibility to the point where infrastructure providers will build a pipeline connection.

More details on the relevance of clusters can be found in the methodology note on the websites of E3G and Bellona.

This conflict between need and feasibility occurs both between and within industrial sectors. For example, CCS is relatively straightforward and inexpensive to implement for fossil gas extraction and processing,[27] but far more challenging for lime kilns which are geographically dispersed – yet alternatives to lime production are scarce, while fossil gas consumption is rapidly dropping as renewables and electricity scale, making CCS ultimately more valuable for lime than gas. Similar tensions arise within sectors: within the cement sector, while point sources are generally larger, there are numerous smaller or less well-located kilns that face higher costs and risk exclusion from subsidy competitions.

While cost-effectiveness is an important consideration in climate policy, there are risks when policy support is awarded purely based on lowest cost per tonne of CO_2 avoided. Funding will then mainly flow to projects where CCS is easiest and cheapest to deploy but fail to support more costly projects that are critical for deep decarbonisation. Subsidies should therefore aim to deliver CCS where it is genuinely needed, based on strategic prioritisation — not only where it is simplest or most cost-effective to build.

This, however, should not be read as suggesting that every application scoring highly on the Ladder automatically warrants subsidies or preferential policy treatment.[28] Climate value alone does not define the appropriate policy response. The design of policy instruments must also consider the business case, financial and technical capacity, and political acceptability of different actors and sectors. As a result, similar scores could translate into very different types of intervention – ranging from enabling support and infrastructure coordination to regulatory obligations and managed phase-down conditions.

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[26] Such as in the UK.

[27] A fossil-gas processing plant is a facility that receives raw fossil gas extracted from underground and purifies it into pipeline-quality “dry” gas, consisting primarily of methane. During this process, CO_2 and other impurities are routinely separated from the gas stream but are typically vented to the atmosphere. Because CO_2 is already separated in a concentrated form, these plants are generally well-suited for CCS, with relatively low additional capture costs compared to other applications.

[28] The 2023 Ladder placed CCS applications along an axis from “burden on emitter” to “encouragement for public support.” In hindsight, this framing was too linear. A high climate-value score does not automatically imply that an application deserves subsidies or preferential treatment. The Ladder intends to assess climate value, not prescribe policy entitlement.

BOX 4: Same ladders, different instruments

Lime producers face one of the strongest long-term cases for CCS. Process emissions from limestone calcination are unavoidable and cannot be eliminated through fuel switching or efficiency gains, and few viable substitutes exist. Yet the sector is characterised by many smaller and mid-sized companies, often located far from CO_2 transport and storage hubs, with limited technical capacity to manage complex capture projects. As a result, the business case is weak, and mandating CCS outright would likely result in plant closures rather than deployment. In this context, policy should focus on enabling participation — through shared infrastructure, multimodal CO_2 transport links, open-access storage, and targeted risk-sharing for first movers – combined with clear strategic prioritisation. Coordinated support will be essential to ensure that dispersed and smaller actors can decarbonise alongside larger industrial players.

By contrast, CCS on fossil-gas processing is technically straightforward and relatively low-cost. These facilities are typically operated by large, well-capitalised companies with strong engineering capacity and, in some cases, direct access to potential CO_2 storage sites. However, the overall mitigation benefit is limited, since most emissions arise downstream when the gas is combusted. The priority for this sector is therefore to phase down fossil-gas use, rather than extend its lifetime through subsidised abatement. In this case, there is a good case for CCS to be mandated as a condition of operation rather than subsidised – accompanied by strict methane and lifecycle accounting, and aligned with clear phase-out pathways for fossil production.

Sectoral deep dives

The CCS ladders provide a comparative, cross-sectoral view of where carbon capture and storage is likely to deliver the greatest climate value over time. Aggregate rankings, however, necessarily cover important sector- and process-specific dynamics. The industry deep dives therefore examine how the underlying drivers of climate value play out within the individual sectors, and why applications occupy their respective positions on the 2030 and 2050 ladders.[29]

Each deep dive shows the interaction between the three factors influencing CCS climate value: the availability and maturity of alternative mitigation routes; the scale and nature of mitigation potential; and feasibility constraints related to technology readiness, cost, infrastructure access, and regulatory context. Attention is given to how these factors evolve over time, as competing technologies mature, demands shift, and infrastructure systems develop. This enables a distinction to be drawn between applications where CCS remains structurally necessary from those where its value is transitional or expected to decline.

The deep dives also highlight that climate value does not map neatly onto ease of deployment. In several sectors, CCS is most valuable where alternatives are limited but feasibility is challenging due to dispersed assets, smaller site sizes, or distance from CO_2 transport and storage infrastructure. Conversely, applications characterised by large, concentrated emission sources and early access to infrastructure may score highly on feasibility while offering limited system-level mitigation value, particularly where downstream emissions dominate or where demand for the underlying product is expected to fall.

The sectoral analyses reinforce that CCS is neither a uniform solution to nor an option to be applied late in the transition process. Its role differs markedly across industries and over time: essential for addressing certain process emissions; potentially useful as a transitional or complementary measure in others; and structurally low value where alternatives are already available or expected to outcompete it.

The purpose of the deep dives is not to prescribe sectoral outcomes, but to clarify these distinctions and support more informed prioritisation decisions within a constrained carbon budget and a rapidly evolving decarbonisation landscape.

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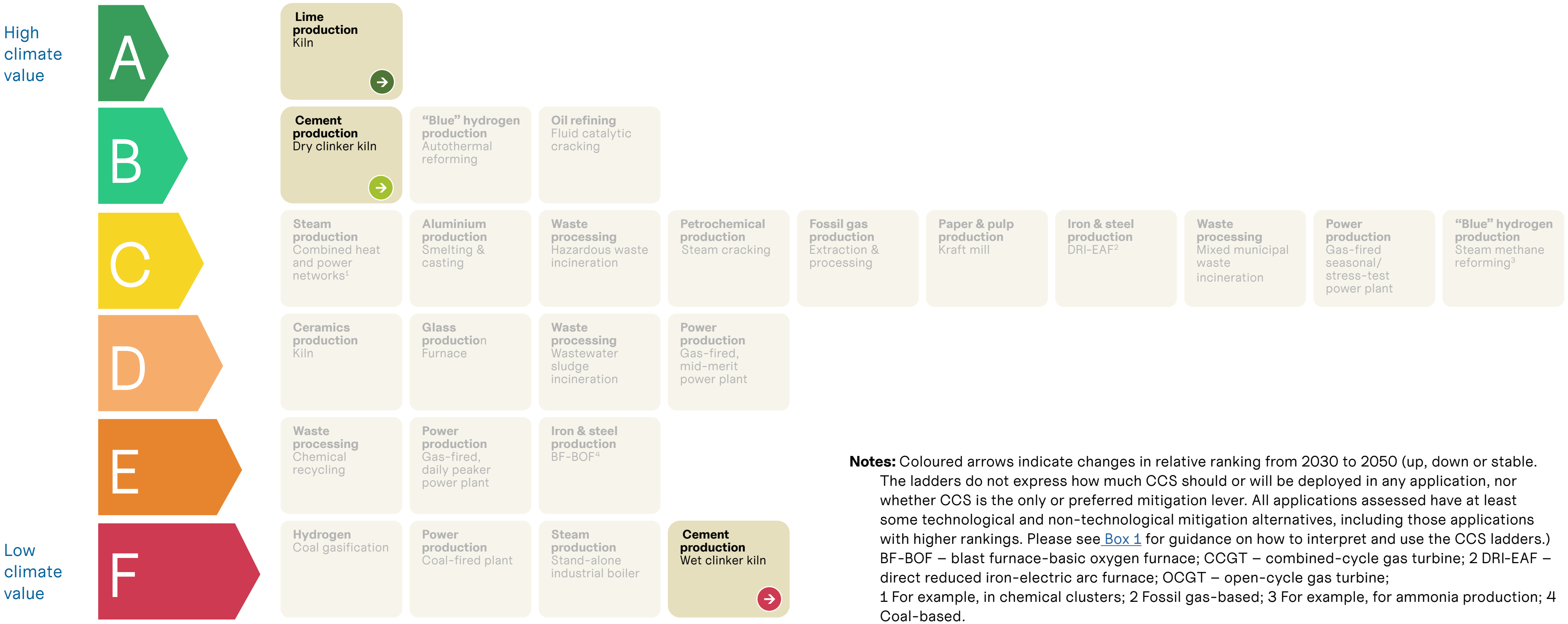
[29] The full justification for each industrial process or plant type can be accessed through this link.

Cement and lime production

Together, lime and cement production account for 115–125 Mt CO_2 emissions per year across Europe.[30] In both sectors, most of this is process CO_2– originating from the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$), a chemical reaction that releases CO_2 from the raw material itself. Significant CO_2 emissions also arise from the fuel combustion that drives the calcination. That most emissions are intrinsic to this material decomposition make both sectors challenging to decarbonise.

However, mitigation prospects are available. And while lime production has few viable alternatives beyond carbon capture,[31] cement production offers a broader set of levers –including clinker substitution, material efficiency, and circular design – which can significantly limit the need for CCS.

2030 CCS Ladder



High climate value

Low climate value

A	**Lime production** Kiln →									
B	**Cement production** Dry clinker kiln →	"Blue" hydrogen production Autothermal reforming	Oil refining Fluid catalytic cracking							
C	Steam production Combined heat and power networks[1]	Aluminium production Smelting & casting	Waste processing Hazardous waste incineration	Petrochemical production Steam cracking	Fossil gas production Extraction & processing	Paper & pulp production Kraft mill	Iron & steel production DRI-EAF[2]	Waste processing Mixed municipal waste incineration	Power production Gas-fired seasonal/stress-test power plant	"Blue" hydrogen production Steam methane reforming[3]
D	Ceramics production Kiln	Glass production Furnace	Waste processing Wastewater sludge incineration	Power production Gas-fired, mid-merit power plant						
E	Waste processing Chemical recycling	Power production Gas-fired, daily peaker power plant	Iron & steel production BF-BOF[4]							
F	Hydrogen Coal gasification	Power production Coal-fired plant	Steam production Stand-alone industrial boiler	**Cement production** Wet clinker kiln →						

Notes: Coloured arrows indicate changes in relative ranking from 2030 to 2050 (up, down or stable). The ladders do not express how much CCS should or will be deployed in any application, nor whether CCS is the only or preferred mitigation lever. All applications assessed have at least some technological and non-technological mitigation alternatives, including those applications with higher rankings. Please see Box 1 for guidance on how to interpret and use the CCS ladders.) BF-BOF – blast furnace-basic oxygen furnace; CCGT – combined-cycle gas turbine; 2 DRI-EAF – direct reduced iron-electric arc furnace; OCGT – open-cycle gas turbine;
1 For example, in chemical clusters; 2 Fossil gas-based; 3 For example, for ammonia production; 4 Coal-based.

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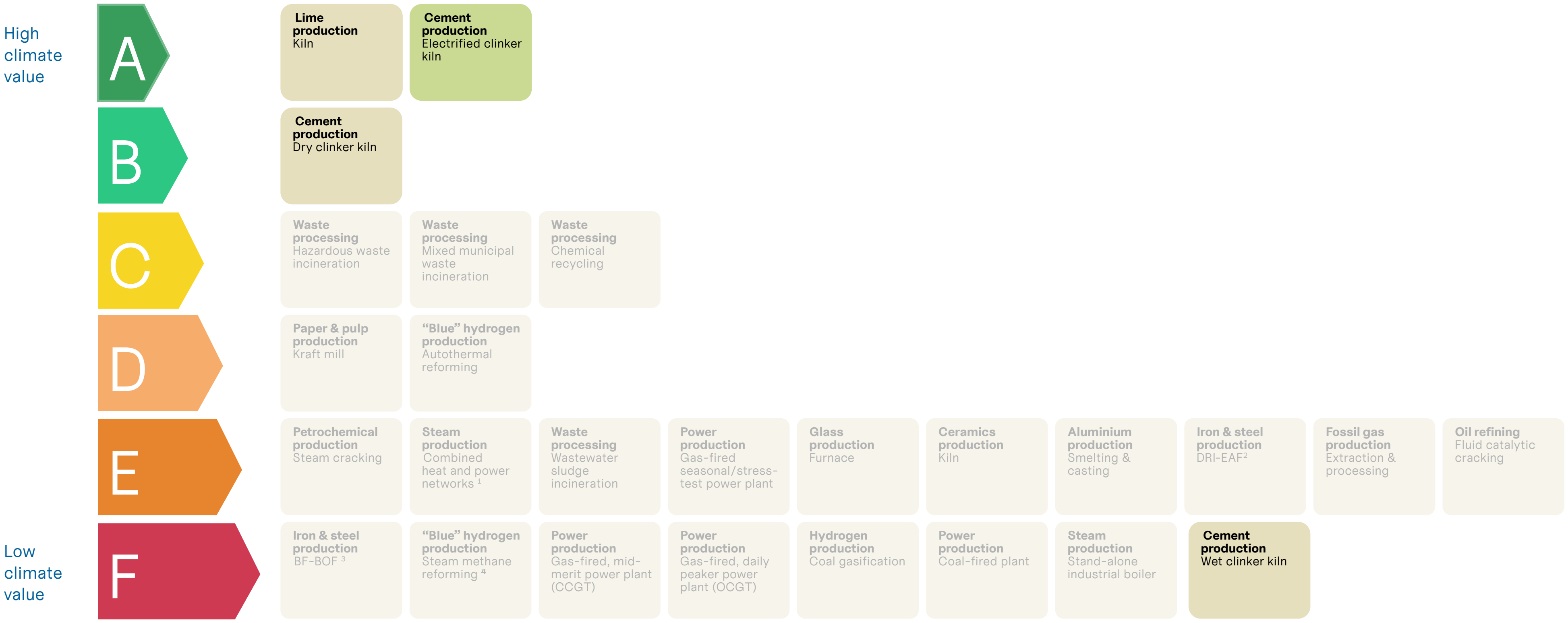
[30] EEA, 2025, EU Emissions Trading System (ETS) data viewer

[31] Simone et al., 2022, Decarbonising the lime industry: State-of-the-art

2050 CCS Ladder



High climate value	A	**Lime production** Kiln	**Cement production** Electrified clinker kiln								
	B	**Cement production** Dry clinker kiln									
	C	**Waste processing** Hazardous waste incineration	**Waste processing** Mixed municipal waste incineration	**Waste processing** Chemical recycling							
	D	**Paper & pulp production** Kraft mill	**"Blue" hydrogen production** Autothermal reforming								
	E	**Petrochemical production** Steam cracking	**Steam production** Combined heat and power networks [1]	**Waste processing** Wastewater sludge incineration	**Power production** Gas-fired seasonal/stress-test power plant	**Glass production** Furnace	**Ceramics production** Kiln	**Aluminium production** Smelting & casting	**Iron & steel production** DRI-EAF[2]	**Fossil gas production** Extraction & processing	**Oil refining** Fluid catalytic cracking
Low climate value	F	**Iron & steel production** BF-BOF [3]	**"Blue" hydrogen production** Steam methane reforming [4]	**Power production** Gas-fired, mid-merit power plant (CCGT)	**Power production** Gas-fired, daily peaker power plant (OCGT)	**Hydrogen production** Coal gasification	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln		

Notes: The ladders do not express how much CCS should or will be deployed in any application, nor whether CCS is the only or preferred mitigation lever. All applications assessed have at least some technological and non-technological mitigation alternatives, including those applications with higher rankings. Please see Box 1 for guidance on how to interpret and use the CCS ladders. BF-BOF – blast furnace-basic oxygen furnace ; CCGT – combined-cycle gas turbine; DRI-EAF – direct reduced iron-electric arc furnace; OCGT – open-cycle gas turbine.

1 For example, in chemical clusters; 2 Fossil gas-based; 3 Coal-based; 4 For example, in ammonia production.

Lime: high dependence amid dispersed production

Lime is used across multiple value chains – from steelmaking and chemicals to construction and environmental applications. Its emissions are dominated by calcination, with over two-thirds of total CO_2 released from the limestone decomposition.

Efficiency improvements and partial fuel switching can cut total emissions but they do not affect process CO_2. Electrified or indirectly heated kilns and novel calcination concepts are being explored, but these technologies remain at early demonstration stage and far from commercial readiness – and many would still result in emissions.

Substituting lime as a material is constrained by its widespread use in industrial processes. As a result, lime production is one of the sectors where CCS is expected to play a critical role in achieving deep decarbonisation.

Feasibility, however, is a key challenge. The European lime industry comprises many smaller, geographically dispersed kilns, often distant from planned CO_2 transport and storage infrastructure. This fragmentation increases capture costs and complicates logistics. Consequently, shared infrastructure solutions, such as multi-modal transport via rail or ship and regional CO_2 hubs, are essential to CCS deployment. The relatively small size of most lime companies gives them limited resources to test multiple capture approaches, so first-time deployment carries high financial risk. These structural constraints underscore the importance of coordinated support mechanisms and accessible infrastructure to ensure that smaller actors can adopt CCS.

Cement: multiple levers, but capture remains part of the puzzle

In cement, around 60% of CO_2 emissions stem from limestone decomposition during clinker production. Mitigation measures include substituting clinker with lower-carbon supplementary cementitious materials to create lower-clinker cements and reducing clinker demand through material efficiency in the use of cement and through circular construction.[32]

The introduction of low-clinker cements (e.g., limestone calcined clay cement or Portland-composite cement with reduced clinker content (replaced by slag or fly ash)) can substantially cut emissions,[33] but progress depends on modernising standards, building codes and procurement practices that still limit their uptake. While traditional sources of supplementary cementitious materials are gradually declining as coal-based power generation and coal-based steel production falls, large historical stockpiles of fly ash and other by-products remain available.

Beyond supplementary cementitious materials, emerging approaches such as clinker recycling and alkali-activated cements could further reduce the need for primary clinker production. A recent analysis by the European Joint Research Centre on circular economy pathways in cement highlights how these technologies – together with reclaimed materials and recycling of cement fines – could significantly enhance circularity and cut clinker demand in half over time.[34]

However, even with strong progress on substitution and efficiency, a substantial amount of clinker production will remain, and its process emissions will require carbon capture.

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[32] UNIDO, 2025, A Snapshot of Cement and Concrete Decarbonization Technologies

[33] Hosen, K., & Chen, B., 2025, Limestone calcined clay cement (LC3): A review of materials, properties, production and environmental impact; Hron et al., 2025, Application of low-emission cement CEM II/C in concrete made with low-effort processed recycled aggregates

[34] JRC, 2025, Environmental and Socio-Economic Impacts of the Circular Economy Transition in the EU Cement and Concrete Sector

Outlook

For cement, progress will hinge on policy and regulatory reform that unlocks substitution and material efficiency. Updating product standards and public procurement rules to reward performance rather than composition will be key to scaling low-clinker solutions and enabling circular practices. At the same time, planning and investment frameworks should ensure that remaining clinker plants are well-positioned to access capture and storage infrastructure, enabling CCS to complement other mitigation measures.

By mid-century, remaining clinker production in Europe could be expected to consolidate into fewer, larger sites, strategically located near industrial clusters, ports, or CO_2 transport corridors. Smaller sites and firms are likely to face higher transition barriers as larger actors possess greater capacity to experiment and invest in first-of-a-kind capture projects. Market consolidation is therefore a plausible outcome, particularly if rising carbon prices outpace support for technology adoption and infrastructure access. Ensuring that smaller producers can connect to shared transport networks and receive targeted support for capture retrofits will be critical to avoid uneven impacts across the sector.

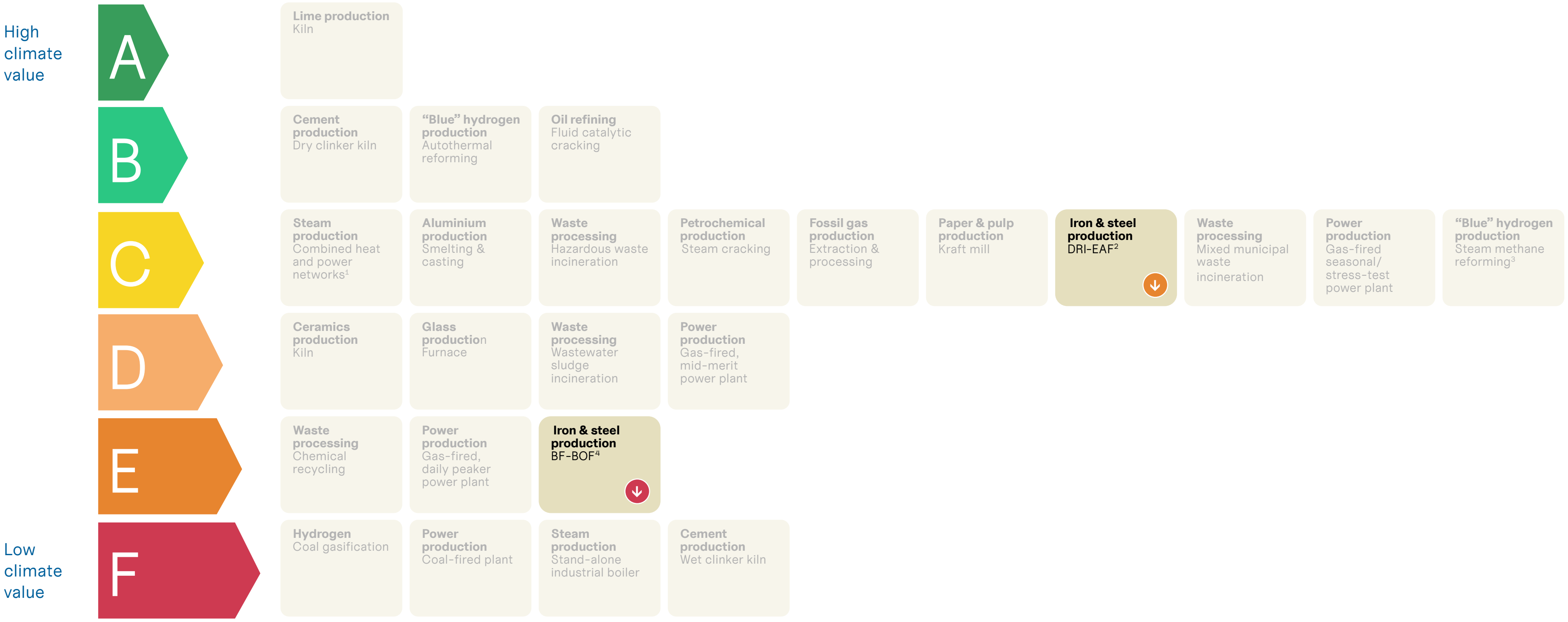
For lime, the main challenge is similar: ensuring that dispersed and mid-sized emitters gain access to infrastructure, through multi-modal transport links and shared collection hubs. Without these, one of Europe’s most CCS-dependent sectors risks being left behind.

Together, lime and cement illustrate how differing process constraints and infrastructure access shape the role of CCS across hard-to-abate industries. Achieving deep reductions will depend on coordinated infrastructure development, regulatory reform, and industrial planning that integrate these approaches rather than treat them in isolation.

Iron and steel production

Steelmaking is responsible for roughly 145 Mt CO_2 emissions per year across Europe.[35] Most of these emissions come from BF-BOF plants that rely on coal as both fuel and as a reducing agent. Europe currently operates around 50 BF-BOFs, with much of this fleet aging and requiring major reinvestment or relining decisions before 2035.[36]

2030 CCS Ladder



A	**Lime production** Kiln									
B	**Cement production** Dry clinker kiln	**“Blue” hydrogen production** Autothermal reforming	**Oil refining** Fluid catalytic cracking							
C	**Steam production** Combined heat and power networks[1]	**Aluminium production** Smelting & casting	**Waste processing** Hazardous waste incineration	**Petrochemical production** Steam cracking	**Fossil gas production** Extraction & processing	**Paper & pulp production** Kraft mill	**Iron & steel production** DRI-EAF[2] ↓	**Waste processing** Mixed municipal waste incineration	**Power production** Gas-fired seasonal/ stress-test power plant	**“Blue” hydrogen production** Steam methane reforming[3]
D	**Ceramics production** Kiln	**Glass production** Furnace	**Waste processing** Wastewater sludge incineration	**Power production** Gas-fired, mid-merit power plant						
E	**Waste processing** Chemical recycling	**Power production** Gas-fired, daily peaker power plant	**Iron & steel production** BF-BOF[4] ↓							
F	**Hydrogen** Coal gasification	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln						

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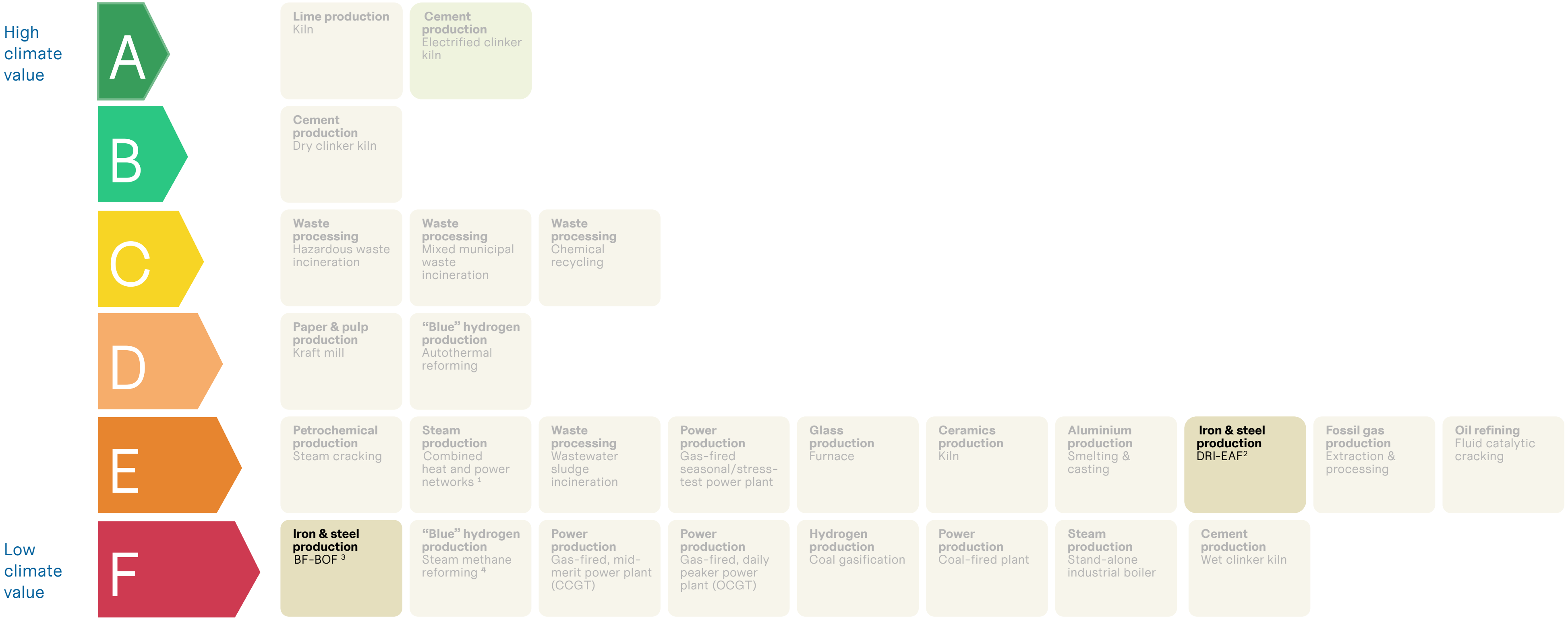
35 After the closure of Port Talbot in the UK, almost all of these emissions are in the EEA; see E3G et al., 2025, The State of the European Steel Transition

36 E3G et al., 2025, The State of the European Steel Transition

In recent decades, Europe has gradually increased secondary steelmaking as scrap availability has risen, and electric arc furnaces (EAFs) now account for a growing share of European steel output.[37] Moreover, in line with Europe's climate target and the rising exposure to the EU Emissions Trading System as free allocation is phased down, steel producers have begun investing in direct reduced iron (DRI) capacity. If supplied with renewable hydrogen, the DRI-EAF[38] route can deliver near-zero-emissions in primary steelmaking.

2050 CCS Ladder



High climate value

Low climate value

A	**Lime production** Kiln	**Cement production** Electrified clinker kiln								
B	**Cement production** Dry clinker kiln									
C	**Waste processing** Hazardous waste incineration	**Waste processing** Mixed municipal waste incineration	**Waste processing** Chemical recycling							
D	**Paper & pulp production** Kraft mill	**"Blue" hydrogen production** Autothermal reforming								
E	**Petrochemical production** Steam cracking	**Steam production** Combined heat and power networks [1]	**Waste processing** Wastewater sludge incineration	**Power production** Gas-fired seasonal/stress-test power plant	**Glass production** Furnace	**Ceramics production** Kiln	**Aluminium production** Smelting & casting	**Iron & steel production** DRI-EAF[2]	**Fossil gas production** Extraction & processing	**Oil refining** Fluid catalytic cracking
F	**Iron & steel production** BF-BOF [3]	**"Blue" hydrogen production** Steam methane reforming [4]	**Power production** Gas-fired, mid-merit power plant (CCGT)	**Power production** Gas-fired, daily peaker power plant (OCGT)	**Hydrogen production** Coal gasification	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln		

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[37] Roland Berger, 15 July 2025, Building resilience in your steel supply chain

[38] There are other DRI-based routes possible next to DRI-EAF, such as the DRI-SMELT route which combines the DRI with a BOF for the steelmaking process. In this route, the emissions from operating the BOF remain, unless addressed through additional measures.

Yet economic and geographic constraints, together with uncertainty over the scale and cost of renewable hydrogen, cast doubt on the speed and extent to which this pathway can develop. The utility of CCS in decarbonisation will therefore depend on the location of DRI plants, the timeframe for their use of natural gas, and the speed at which renewable hydrogen becomes available at competitive cost – in addition to industrial and trade policy choices.

Blast furnace-basic oxygen furnace (coal-based): limited value

Applying CCS to BF-BOF plants is technically possible in principle but constrained in practice. Emissions arise from multiple low-concentration sources across the blast furnace, stoves, sinter plants, coke ovens, and power units, making whole-site capture complex and expensive. Retrofitting CCS to existing BF-BOF routes can cut around 40–70%[39] of direct CO_2 emissions, depending on configuration, but leaves substantial residual emissions. No integrated site-wide capture has ever been attempted. Existing pilots have focused on partial capture or specific off-gas streams, and only a single BF-BOF CCS project is currently planned globally, versus many dozens of DRI projects.[40]

Even with partial or moderate-to-high capture rates, BF-BOF would remain fundamentally misaligned with deep decarbonisation. High residual stack emissions next to significant upstream methane emissions from metallurgical coal mining[41] sharply reduces the net climate benefit of CCS. Combined with high energy demand, the risk of extending the lifetime of coal-based assets and strong competition from hydrogen-based DRI and scrap-EAF routes, the overall climate and system value of CCS on BF-BOF is limited.

Direct reduced iron-electric arc furnace (fossil gas-based): transitional role amid hydrogen constraints?

Europe's primary steel transition is increasingly centred on replacing ageing blast furnaces with new DRI capacity. However, the outlook for DRI hinges on the cost and availability of renewable hydrogen. Several high-profile "green steel" projects have recently been delayed or scaled back as rising costs and wider pressures on the steel sector have cooled investor confidence.[42] While renewable hydrogen-based DRI can, in principle, compete with conventional steel under moderately high carbon prices,[43] the availability of renewable hydrogen will remain constrained by cost, scale and infrastructure availability in much of Europe.

As a result, many DRI projects are likely to initially use natural gas. Depending on when a switch to renewable hydrogen were possible, CCS could be required to manage the resulting emissions – either applied on-site to reformer and shaft off-gases, or upstream through blue-hydrogen production. Both options, however, are expensive and have an uncertain long-term role: on-site CCS risks locking in gas-based designs intended to switch to hydrogen, while blue hydrogen carries efficiency losses, methane-leakage concerns and its own risks of fossil lock-in. These fossil-based DRI options would also struggle to remain competitive in the long term if renewable hydrogen-based DRI expands in regions with structurally lower renewable energy costs, both within Europe and beyond.

Neither fossil-based CCS routes nor renewable hydrogen pathways are guaranteed to scale at the speed or cost required for a smooth transition, underscoring the importance of accelerating renewable hydrogen deployment while accepting that some transitional solutions may still be needed to avoid delaying CO_2 emissions cuts.

[39] IEAGHG, 2013, Iron and Steel CCS Study (techno-economics integrated steel mill); Agora Industry, Wuppertal Institute and Lund University, 2024, Low-carbon technologies for the global steel transformation. A guide to the most effective ways to cut emissions in steelmaking.

[40] Agora Industry, 2023, Global Steel Transformation Tracker

[41] Ember, 2025, The EU's steel industry and its methane problem

[42] GMK Center, 8 October 2025, Major pause in EU steel industry decarbonization projects

[43] Johnson et al., 2025, Emerging green steel markets surrounding the EU emissions trading system and carbon border adjustment mechanism

Outlook

By mid-century, Europe's primary steel production is likely to be geographically reconfigured. For Europe's steel transition to succeed, DRI-EAF plants will need to be strategically located near abundant affordable renewables and hydrogen – for example in parts of Iberia and the Nordic countries – and supported by a liquid market for low-carbon intermediates such as hot-briquetted iron. [44] Under such a strategy, the role of CCS in steelmaking could be limited or largely redundant.

If, however, political and social barriers delay this regional reallocation, or if electrolytic hydrogen cost reductions fail to materialise, CCS may still play a longer-term role – on-site to manage emissions from gas-based DRI installations, or upstream to produce blue hydrogen. The role of CCS in steel will thus depend less on technical feasibility than on industrial strategy choices. Policymakers can minimise long-term CCS dependence by prioritising scrap utilisation and targeting support to low-carbon primary production in regions with high potential for affordable renewables and hydrogen production, alongside trade and infrastructure policies that enable cross-border green hot-briquetted iron flows.

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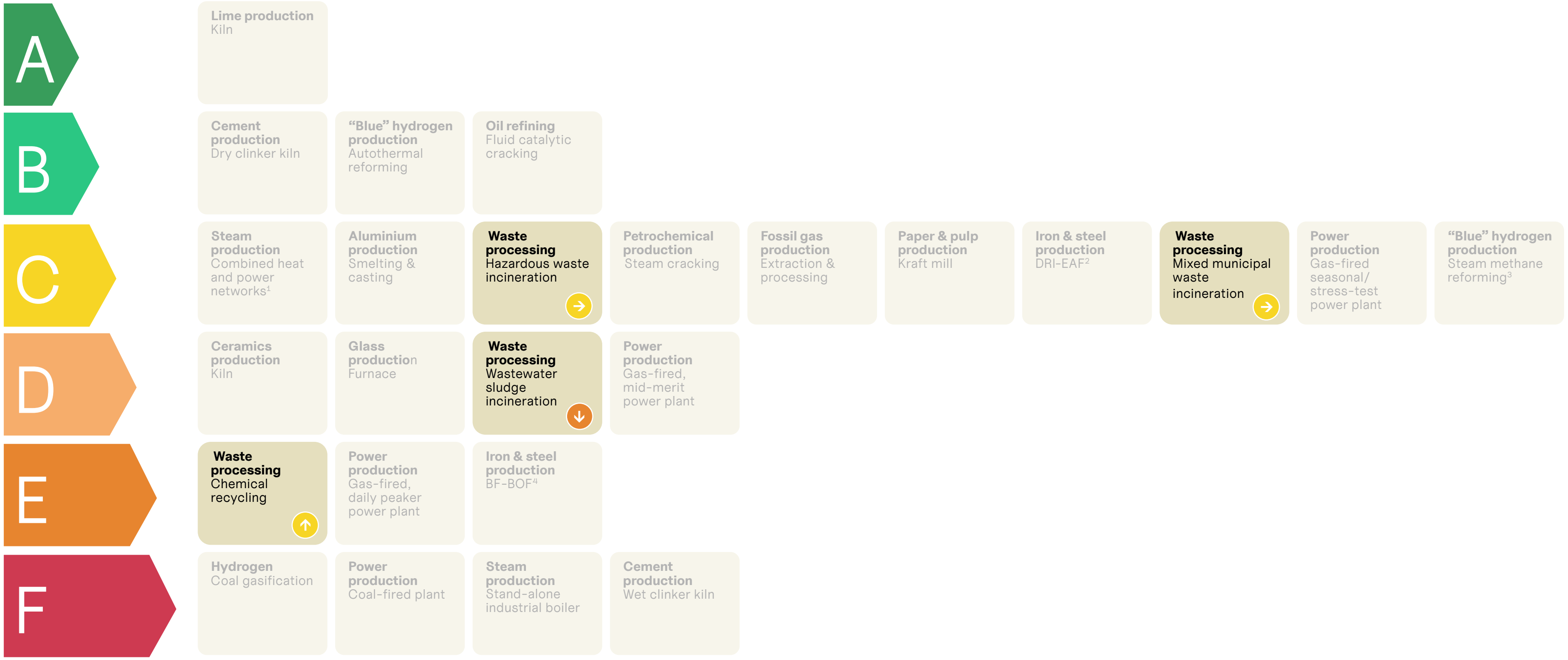
[44] Agora, 2025, The role of green iron trade in accelerating competitive steel transformation

Waste processing

Waste treatment and disposal account for around 120–130 Mt of CO_2 emissions per year across Europe. Across all waste streams, CO_2 emissions typically comprise a 40% fossil and 60% biogenic share.[45]

2030 CCS Ladder



High climate value

A	**Lime production** Kiln									
B	**Cement production** Dry clinker kiln	**"Blue" hydrogen production** Autothermal reforming	**Oil refining** Fluid catalytic cracking							
C	**Steam production** Combined heat and power networks[1]	**Aluminium production** Smelting & casting	**Waste processing** Hazardous waste incineration →	**Petrochemical production** Steam cracking	**Fossil gas production** Extraction & processing	**Paper & pulp production** Kraft mill	**Iron & steel production** DRI-EAF[2]	**Waste processing** Mixed municipal waste incineration →	**Power production** Gas-fired seasonal/ stress-test power plant	**"Blue" hydrogen production** Steam methane reforming[3]
D	**Ceramics production** Kiln	**Glass production** Furnace	**Waste processing** Wastewater sludge incineration ↓	**Power production** Gas-fired, mid-merit power plant						
E	**Waste processing** Chemical recycling ↑	**Power production** Gas-fired, daily peaker power plant	**Iron & steel production** BF-BOF[4]							
F	**Hydrogen** Coal gasification	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln						

Low climate value

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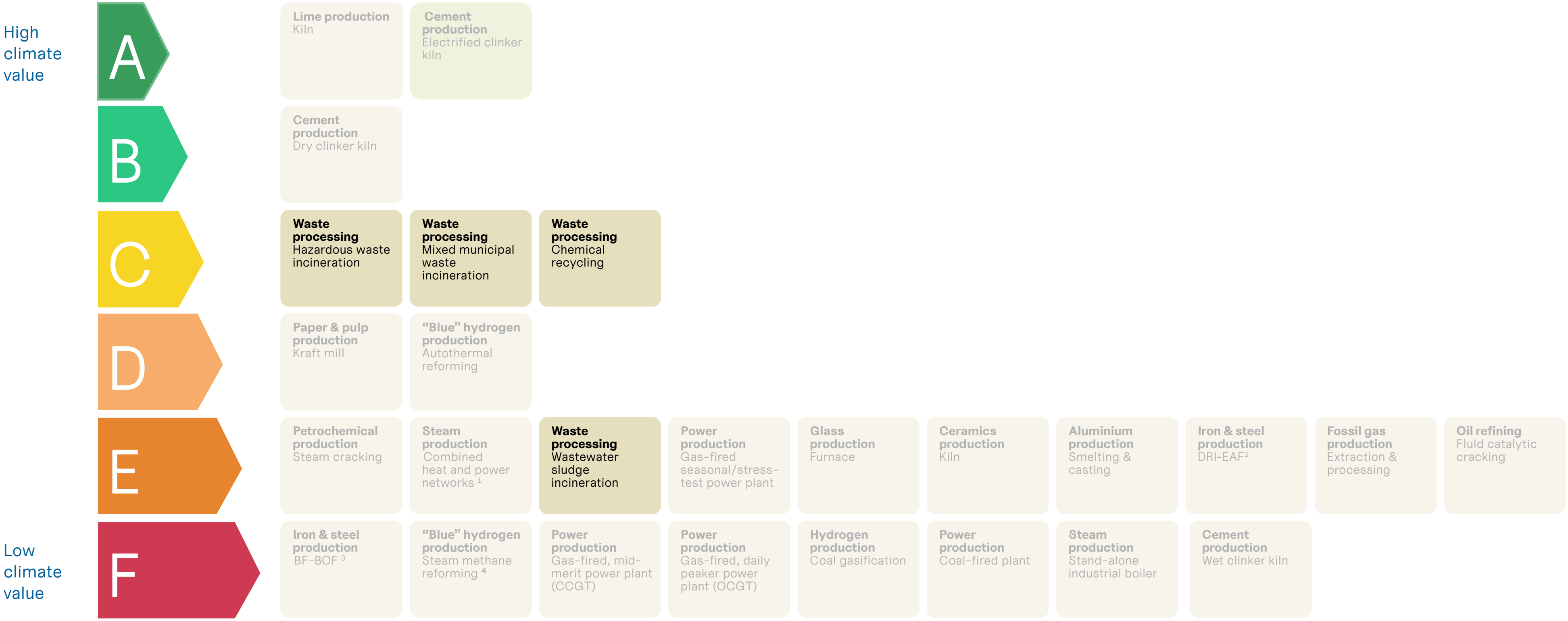
45 CEWEP, 2022, Waste-to-Energy Climate Roadmap - Technical Annex

While CCS is the only way to address emissions stemming from incineration, waste incineration sits towards the bottom of the waste hierarchy[46] (above landfilling and dumping into the environment). The priority remains to prevent, reduce and redesign waste, improve sorting and recycling, and minimise overall material throughput.[47] Within this system, chemical recycling remains a wildcard, with uncertain scale, performance, and system impact; its future influence could either meaningfully reduce residual waste or leave overall volumes largely unchanged.

In a net-zero scenario, waste prevention and circular economy measures should sharply limit both the volume of fossil and biogenic waste requiring treatment, while remaining treatment and disposal plants are likely to become larger, more centralised, and their emissions addressed through CCS.

2050 CCS Ladder



A	Lime production Kiln	Cement production Electrified clinker kiln								
B	Cement production Dry clinker kiln									
C	**Waste processing** **Hazardous waste incineration**	**Waste processing** **Mixed municipal waste incineration**	**Waste processing** **Chemical recycling**							
D	Paper & pulp production Kraft mill	"Blue" hydrogen production Autothermal reforming								
E	Petrochemical production Steam cracking	Steam production Combined heat and power networks [1]	**Waste processing** **Wastewater sludge incineration**	Power production Gas-fired seasonal/stress-test power plant	Glass production Furnace	Ceramics production Kiln	Aluminium production Smelting & casting	Iron & steel production DRI-EAF [2]	Fossil gas production Extraction & processing	Oil refining Fluid catalytic cracking
F	Iron & steel production BF-BOF [3]	"Blue" hydrogen production Steam methane reforming [4]	Power production Gas-fired, mid-merit power plant (CCGT)	Power production Gas-fired, daily peaker power plant (OCGT)	Hydrogen production Coal gasification	Power production Coal-fired plant	Steam production Stand-alone industrial boiler	Cement production Wet clinker kiln		

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[46] eur-lex.europa.eu/EN/legal-content/glossary/waste-hierarchy.html

[47] EEA, 2024, Waste recycling in Europe

Mixed municipal waste incineration: mid-level value within significant uncertainties

Mixed municipal and commercial waste incineration remains the largest CO_2 contributor, emitting over 90 Mt CO_2 annually. Typical plants are modest in scale (emitting 100–400 Kt CO_2 per year) and widely dispersed, which complicates capture and transport logistics.

The main decarbonisation levers lie upstream: prevention, separate collection, mixed-waste sorting, product redesign, and recycling processes can all reduce the need for dedicated incineration. While these measures have strong theoretical potential to shrink residual waste streams, progress in practice has been uneven, and overall waste generation has remained stable in recent years.[48] This creates genuine uncertainty about how quickly, and to what extent, municipal waste volumes can fall.[49]

Over time, some high-caloric waste streams may also increasingly be redirected toward industrial processes such as cement production,[50] reducing the need for dedicated waste-to-energy production,[51] and thus CCS in this area, while co-firing high-caloric waste in coal power plants will largely disappear with the phaseout of these plants.

In this evolving system, CCS plays a complementary role — not the priority for policy support, but a valuable and necessary option to manage emissions from the significant subset of plants that continue to operate, where capturing the resulting emissions is the only option.

Hazardous waste incineration: limited scale but enduring need

Hazardous-waste plants incinerate materials that cannot be safely recycled or landfilled, destroying toxic or persistent residues from chemical and industrial processes. Alternatives, such as chemical neutralisation or solvent recovery, cannot be applied to all streams, while emerging methods, such as plasma or supercritical oxidation, are costly and still release CO_2.[52]

Hazardous-waste plants emit roughly 5–8 Mt CO_2 per year across the EU – small in scale and hard to avoid. Here, the role of CCS is not transformative in scale, but likely unavoidable. The co-location of these facilities within industrial clusters or chemical parks potentially eases access to shared CO_2 transport and storage networks, increasing overall feasibility. A relevant fraction of hazardous waste, especially within such clusters, could eventually be rerouted to gasification-based chemical recycling routes if and when these mature, though this remains highly uncertain.

Wastewater sludge incineration: small volumes, diverse pathways

European wastewater sludge incineration[53] accounts for only a few million tonnes of CO_2 emissions annually. Dedicated mono-incinerators increasingly handle sewage-sludge streams that cannot be safely recycled or land-applied, particularly in countries restricting agricultural land application due to contamination risk (by microplastics, heavy metals, or persistent organic pollutants).[54] These mono-incinerators increasingly replace in (lignite) coal power plants.[55, 56] Many of these plants are smaller than mixed municipal waste incinerators and are often located inland, raising transport and logistical costs for CCS.

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[48] EEA, 2024, Waste generation in Europe

[49] EEA, 2022, Reaching 2030's residual municipal waste target - why recycling is not enough

[50] Called "co-processing"; see for example Sarc, R., & Viczek, S., A., 2024, Co-processing of solid recovered fuels from mixed municipal and commercial waste in the cement industry

[51] As a rough estimate, 1 t of high-caloric waste used in applications like cement plants frees up about 2 t of incinerator capacity, as these can only process waste mixtures up to a certain energy density.

[52] Kumar et al., 2023, A critical review on sustainable hazardous waste management strategies: a step towards a circular economy

[53] Even though largely bio-based, this application is included due to its specific nature and linkage to general waste incineration.

[54] JRC, 2023, Feasibility study in support of future policy developments of the Sewage Sludge Directive (86/278/EEC)

[55] Bund, Wohin mit dem Klärschlamm? - accessed on 17 November 2025

[56] EUWID, 23 September 2024, RWE beantragt zwei weitere Linien zur Klärschlamm-Monoverbrennung in Knapsack

Anaerobic digestion with biogas recovery is now widespread and increasingly paired with nutrient and phosphorus recycling systems.[57] Emerging options such as pyrolysis and biochar production offer additional resource-recovery benefits.[58] However, these competing pathways are still not yet universal or suitable for all sludge types,[59] meaning incineration (and thus CCS) remains relevant, especially where contamination prevents other uses.

Chemical recycling: emerging sector with growing carbon capture and storage needs?

Chemical recycling of plastics via pyrolysis or gasification currently processes only 0.3 Mt of waste per year in Europe,[60] with a projected pipeline of a further 2.5 Mt – far below the capacity of mechanical recycling. The share of carbon converted to CO_2 varies depending on the specific process, the mixture of waste and the amount of oxygen within.[61] Pyrolysis currently dominates but produces dilute flue gases with low CO_2 concentration. Gasification, though less mature, can integrate CO_2 capture at pre-combustion stages.[62] Here the gas stream is more concentrated and pressurised, improving capture efficiency.

Chemical recycling is a genuine "wild card".[63] The underlying technology mix – gasification, multiple pyrolysis variants, and solvent-based depolymerisation – varies widely in maturity and performance. The overall effect on residual waste volumes could range from marginal changes to substantial displacement of conventional and hazardous waste incineration, depending on whether large-scale, integrated pilot clusters can be realised and replicated.

As investment pipelines develop, sector capacity could increase multi-fold over the next decades. If that expansion materialises, CCS could become an integral enabler to ensuring such recycling routes remain aligned with climate goals. Even then, mechanical or solvent-based recycling, reuse and product redesign will remain the primary levers for CO_2 reduction. CCS on waste-to-chemicals should therefore be viewed as a strategic complement, strengthening the climate performance of any routes that scale.

Outlook

In a circular economy future, municipal waste-to-energy should steadily decline, while material prevention, reuse, and recycling take precedence. Whether and how quickly this occurs will depend on the consistency of policy signals and investments in upstream measures.

Chemical recycling introduces additional uncertainty. Depending on which technologies succeed, its impact on residual-waste volumes could remain modest or become significant, shaping the type of waste processing facilities that will require CCS deployment.

Across the sector, CCS is expected to play a supporting rather than central role — essential for certain hazardous-waste streams and potentially for chemical-recycling plants, and relevant for a subset of municipal and sludge incinerators.

This creates a policy tension: while upstream circularity and prevention measures must expand rapidly, plant-level CCS remains one of the few mitigation levers plant operators can deploy directly. These approaches need not compete. With adequate political will, they can and should be pursued in parallel as part of a coherent strategy for the waste sector.

Together, these dynamics depict a sector where CCS is technically feasible and sometimes necessary, but structurally limited – the final rung of the waste hierarchy, supporting rather than substituting Europe's transition to a fully circular economy.

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[57] Central Baltic, 2022, Sustainable disposal and use of sludge-based biomasses

[58] And, in some cases, can result in net-negative emissions; see Lenk et al, 2024, Biochar carbon removal from residues in Germany - assessment from environmental and economic perspectives

[59] Novafert, 2023, Report on EU nutrient recovery technologies and derived products

[60] Frauenhofer Umsicht, 2025, Interactive Map of Chemical Recycling Facilities and Projects - accessed on 16 November 2025

[61] Hussain Shah et al, 2023, A review on gasification and pyrolysis of waste plastics

[62] Ayuso-Diaz et al., 2025, Progress on waste plastics gasification process: A review of operating conditions, reactors and catalysts for clean syngas production and tar abatement

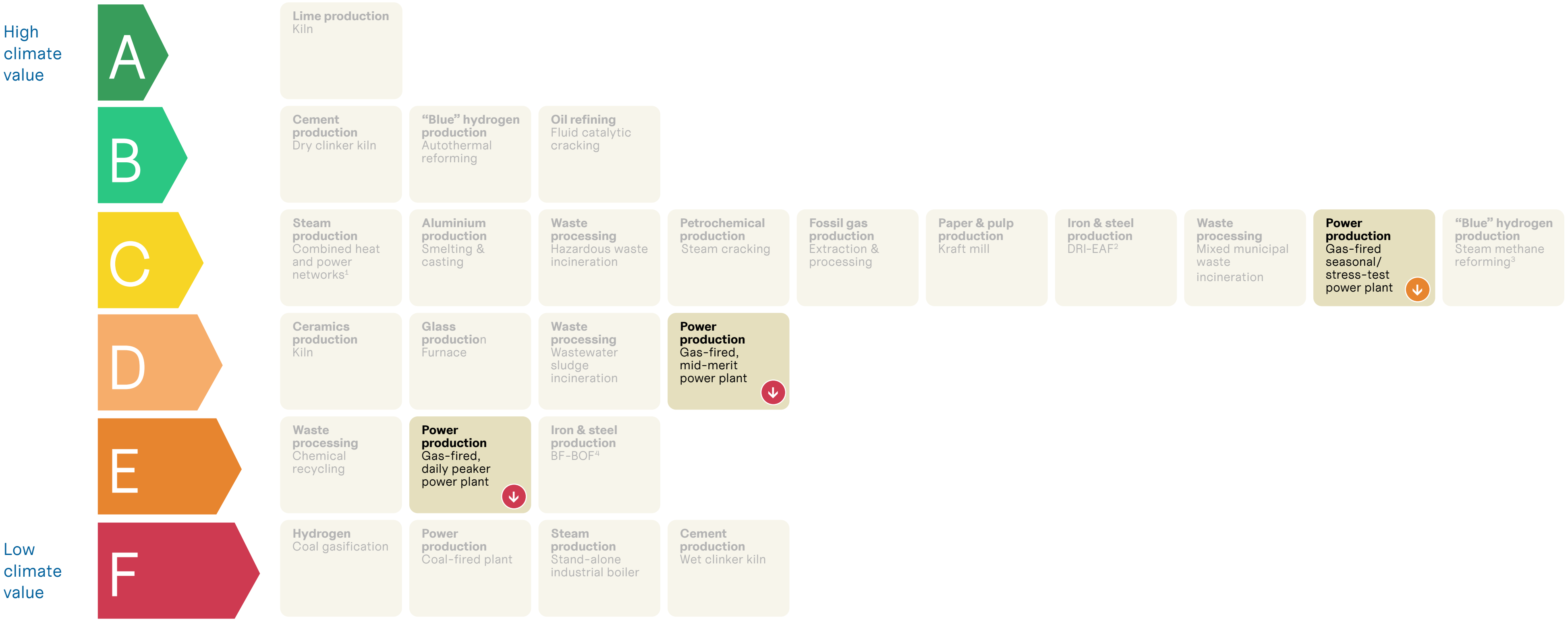
[63] Klotz et al, 2024, The role of chemical and solvent-based recycling within a sustainable circular economy for plastics

Power production (gas-fired)

Gas-fired electricity generation remains a significant share of Europe's power mix (~one-sixth of electricity generation and roughly 150-190 Mt CO_2 per year),[64] but demand is already declining and is expected to fall dramatically over the coming decades as renewables continue to expand and flexibility and storage solutions mature. CCS on gas power has long been discussed as a potential decarbonisation route, but in practice its climate value is limited. Falling utilisation rates, the rapid cost decline of alternatives, and the growing importance of electrification across the economy make CCS on gas power a poor strategic fit for Europe's transition.

While the broad trend is clear – CCS for gas power generation is expensive, misaligned with system needs and has limited climate value – differences in gas plants types their specific roles in operations bring some nuance to the discussion.

2030 CCS Ladder



High climate value

Low climate value

A	**Lime production** Kiln									
B	**Cement production** Dry clinker kiln	**"Blue" hydrogen production** Autothermal reforming	**Oil refining** Fluid catalytic cracking							
C	**Steam production** Combined heat and power networks[1]	**Aluminium production** Smelting & casting	**Waste processing** Hazardous waste incineration	**Petrochemical production** Steam cracking	**Fossil gas production** Extraction & processing	**Paper & pulp production** Kraft mill	**Iron & steel production** DRI-EAF[2]	**Waste processing** Mixed municipal waste incineration	**Power production** Gas-fired seasonal/stress-test power plant ↓	**"Blue" hydrogen production** Steam methane reforming[3]
D	**Ceramics production** Kiln	**Glass production** Furnace	**Waste processing** Wastewater sludge incineration	**Power production** Gas-fired, mid-merit power plant ↓						
E	**Waste processing** Chemical recycling	**Power production** Gas-fired, daily peaker power plant ↓	**Iron & steel production** BF-BOF[4]							
F	**Hydrogen** Coal gasification	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln						

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[64] Assuming an emission intensity range of 0.35 to 0.45 t CO_2/MWh in 2024; gas-fired power generation data for the EEA from ACER, 2025, Key developments in European electricity and gas markets and for the UK from UK Department for Energy Security and Net-Zero, 2025, Digest of UK Energy Statistics (DUKES): electricity

2050 CCS Ladder

High climate value

A
- **Lime production** Kiln
- **Cement production** Electrified clinker kiln

B
- **Cement production** Dry clinker kiln

C
- **Waste processing** Hazardous waste incineration
- **Waste processing** Mixed municipal waste incineration
- **Waste processing** Chemical recycling

D
- **Paper & pulp production** Kraft mill
- **“Blue” hydrogen production** Autothermal reforming

E
- **Petrochemical production** Steam cracking
- **Steam production** Combined heat and power networks[1]
- **Waste processing** Wastewater sludge incineration
- **Power production** Gas-fired seasonal/stress-test power plant
- **Glass production** Furnace
- **Ceramics production** Kiln
- **Aluminium production** Smelting & casting
- **Iron & steel production** DRI-EAF[2]
- **Fossil gas production** Extraction & processing
- **Oil refining** Fluid catalytic cracking

F
- **Iron & steel production** BF-BOF[3]
- **“Blue” hydrogen production** Steam methane reforming[4]
- **Power production** Gas-fired, mid-merit power plant (CCGT)
- **Power production** Gas-fired, daily peaker power plant (OCGT)
- **Hydrogen production** Coal gasification
- **Power production** Coal-fired plant
- **Steam production** Stand-alone industrial boiler
- **Cement production** Wet clinker kiln

Low climate value

Mid-merit plants (combined-cycle gas turbine): technically feasible but increasingly obsolete

Large combined-cycle plants were once seen as candidates for baseload or mid-merit generation with CCS. In theory, they could capture a large share of their emissions at relatively low cost when running steadily. In practice, however, steady high utilisation is precisely what is disappearing from European power markets. Renewables are increasingly displacing gas in the merit order, and combined-cycle gas-turbine capacity factors have fallen sharply as grids integrate more wind and solar – across Europe, the average yearly capacity utilisation rate of gas-fired power has already dropped to 20% in 2024.[65]

This erosion of running hours undermines the business case for capture, becoming prohibitively more expensive at low load factors.[66] Meanwhile, upstream methane emissions and the increasing availability of clean power make the climate benefit smaller relative to other mitigation routes. In short, CCS on mid-merit gas may work on paper but does not align with the economic or system realities of Europe's power transition.

Daily peaker plants (open-cycle gas turbines): flexible but role eroding

Open-cycle gas turbines play a critical role in covering short-term demand peaks and rapid ramps in electricity systems. In recent years, their contribution during peak hours has actually increased,[67] reflecting the limits of current flexibility options and the continued need for reliable backup capacity. This underlines that alternatives, while advancing, are not yet available at full scale.

However, this role is expected to diminish quickly as batteries, demand response, and smart grid management expand across Europe.[68] As short-duration storage becomes cheaper and more widespread, fossil peakers will face steep declines in operating hours. Under these conditions, applying CCS becomes highly uneconomical: fixed costs would be spread across very few operating hours, delivering only marginal abatement.

In short, while open-cycle gas turbines remain useful today for system stability, their operational and economic rationale is steadily eroding – and with it any credible case for CCS deployment on such units.

Seasonal and stress-test plants: uncertain niche, uncertain alternatives

A residual fleet of large gas units may continue to provide back-up for rare, system-wide shortages of renewables, especially through the 2030s. Credible zero-carbon options for multi-day or seasonal balancing remain limited, and technologies such as hydrogen turbines, sustainable biofuels, or long-duration storage are still maturing.[69] In this narrow context, CCS could appear as one way to address occasional emissions from emergency operations. Yet the very low utilisation of these units would make capture costly and infrastructure-intensive for limited climate benefit.

Looking ahead, the precise mix of solutions for long-duration flexibility remains uncertain. CCS on the plant itself, however, is unlikely to be the optimal answer given the inefficiency of equipping rarely used assets with capture systems. Hydrogen or bio-based turbines could become viable, though their availability and cost remain unclear. While hydrogen-based routes are also unlikely to be cheaper than fossil gas with CCS,[70] they are better aligned with a net-zero power system and carry a lower risk of fossil lock-in. Europe thus faces a set of imperfect long-duration balancing options – all characterised by high fixed costs and low annual utilisation.

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[65] ACER, 2025, Key developments in European electricity and gas markets

[66] Mullen, D., & Lucquiaud, M., 2024, On the cost of zero carbon electricity: A techno-economic analysis of combined cycle gas turbines with post-combustion CO_2 capture

[67] ACER, 2025, Key developments in European electricity and gas markets

[68] Ember, 2024, EU battery storage is ready for its moment in the sun

[69] Zeng, Y., et al, 2025, Long-Duration Energy Storage: A Critical Enabler for Renewable Integration and Decarbonization

[70] IEAG, 2024, The Role of Low Emissions Dispatchable Power Generation in the Lowest Cost Net Zero System

Outlook

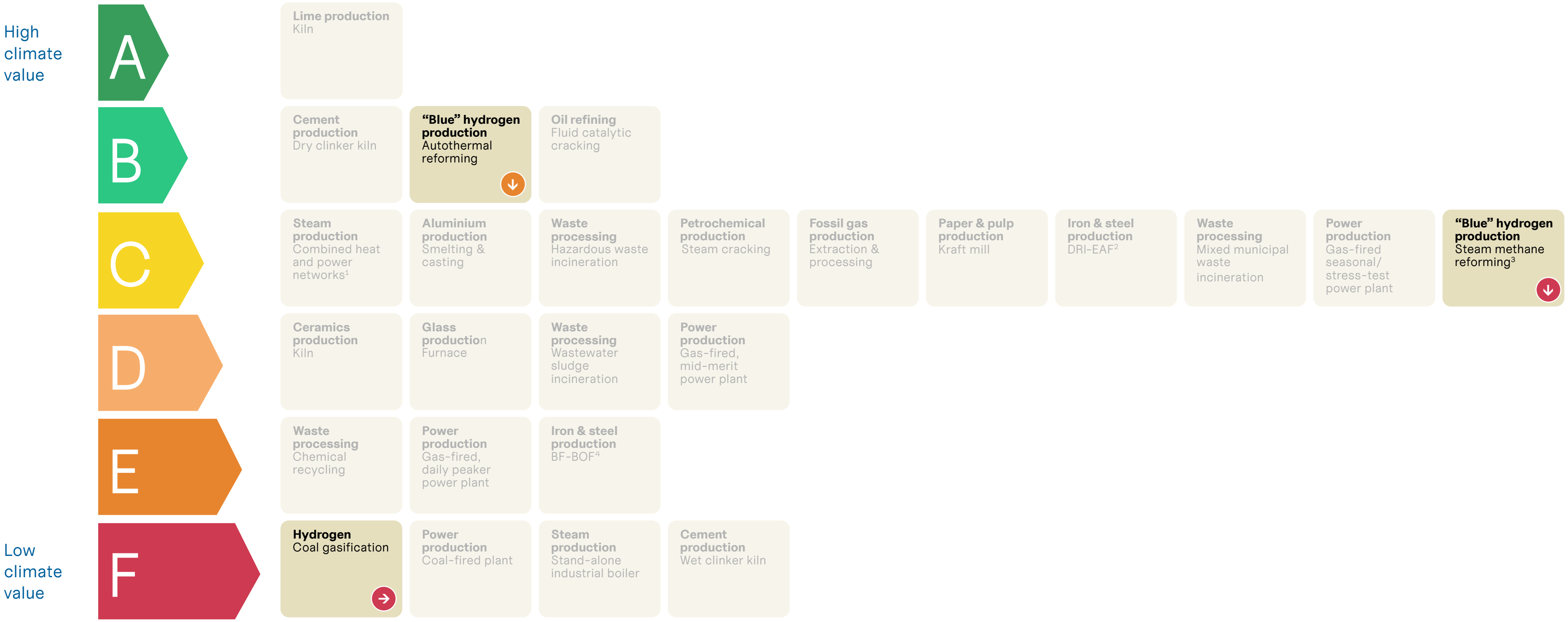
The economics of gas-fired power in Europe are rapidly eroding as renewables, storage, and flexibility options expand. As Europe rightly shifts its focus from decarbonising electricity to electrifying the wider economy, investing in costly mitigation options such as CCS on gas-fired power risks backfiring. While it could reduce direct emissions, it would also raise power prices, reinforcing gas's role as the marginal price setter and dampening incentives for electrification across industry, heating, and transport.

Policy should therefore prioritise a rapid reduction in both the volume of gas generation and its influence on the power system – accelerating deployment of storage, interconnection, demand-side flexibility, and clean firm capacity. If, in the longer term, some of these alternatives fail to scale or cost reductions stall – leaving seasonal adequacy gaps – CCS on gas plants themselves would still not be the preferred solution. In such cases, fuel-side approaches (such as renewable or blue hydrogen where it already supports industrial demand) or offsetting residual emissions may offer more realistic and cost-efficient pathways to manage the final remnants of fossil use in power generation.

Hydrogen production

Hydrogen production is one of Europe's largest industrial emission sources, responsible for around 55 Mt CO_2 per year[71], almost entirely from fossil gas-based steam methane reforming (SMR) units in refineries and ammonia plants. Retrofitting existing SMR plants with CCS could deliver significant absolute emission cuts, but achieving consistently high capture rates would be challenging. Autothermal reforming (ATR) could in principle deliver higher capture rates at lower energy costs, though would require building new fossil-gas based assets.

2030 CCS Ladder



High climate value

A	**Lime production** Kiln									
B	**Cement production** Dry clinker kiln	**"Blue" hydrogen production** Autothermal reforming ↓	**Oil refining** Fluid catalytic cracking							
C	**Steam production** Combined heat and power networks[1]	**Aluminium production** Smelting & casting	**Waste processing** Hazardous waste incineration	**Petrochemical production** Steam cracking	**Fossil gas production** Extraction & processing	**Paper & pulp production** Kraft mill	**Iron & steel production** DRI-EAF[2]	**Waste processing** Mixed municipal waste incineration	**Power production** Gas-fired seasonal/stress-test power plant	**"Blue" hydrogen production** Steam methane reforming[3] ↓
D	**Ceramics production** Kiln	**Glass production** Furnace	**Waste processing** Wastewater sludge incineration	**Power production** Gas-fired, mid-merit power plant						
E	**Waste processing** Chemical recycling	**Power production** Gas-fired, daily peaker power plant	**Iron & steel production** BF-BOF[4]							
F	**Hydrogen** Coal gasification →	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln						

Low climate value

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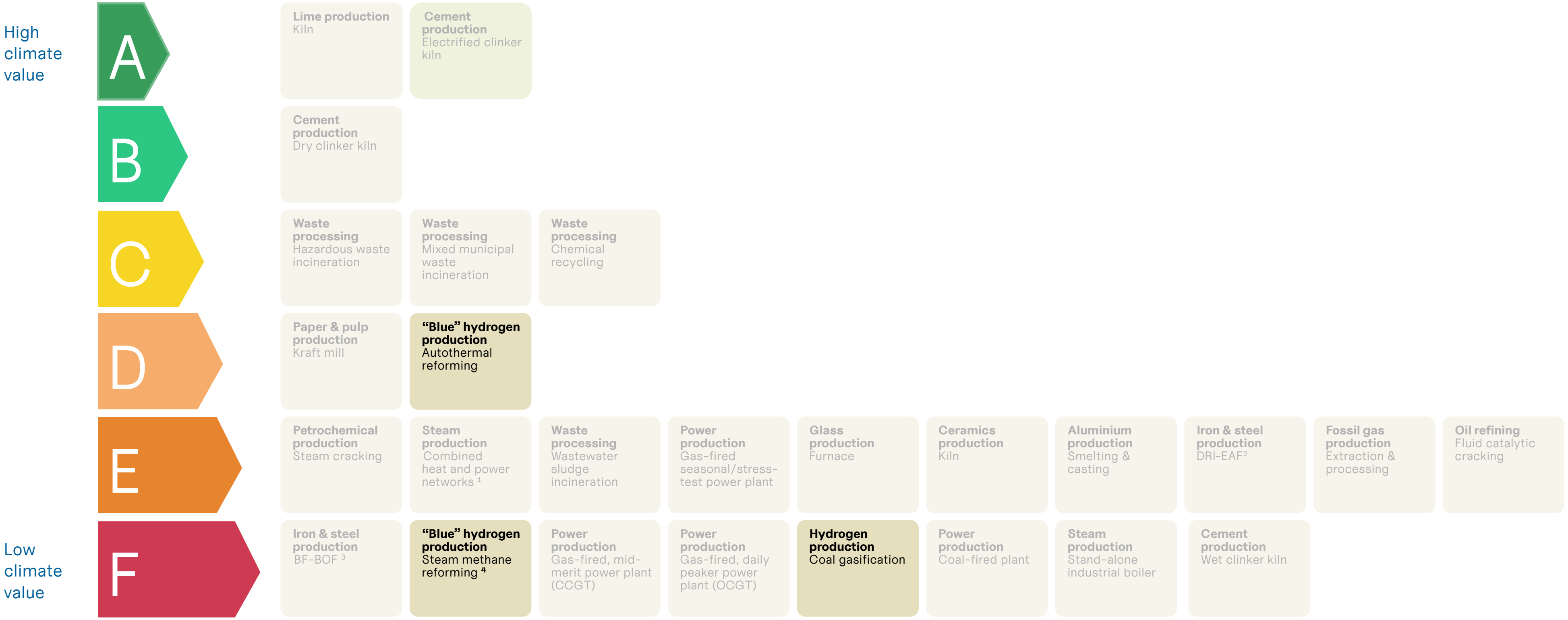
[71] Oxford Institute for Energy Studies, 2024, 2024 State of the European Hydrogen Market Report

The priority in Europe remains to scale renewable hydrogen production and consumption, the only way to fully decarbonise hydrogen. In principle, renewable hydrogen can replace today's fossil-based hydrogen use in refineries and fertiliser production, while also enabling deep decarbonisation of other sectors, such as primary iron and steel production.

However, scaling renewable hydrogen at the speed, cost and locations required is proving difficult. Electrolytic hydrogen in Europe remains considerably more expensive than grey hydrogen (and – at least in theory – blue hydrogen) in most markets, and a growing number of large-scale green hydrogen projects have been delayed or downsized amid weak demand and high costs. This update therefore places hydrogen slightly higher in 2030 than in the previous edition, reflecting both its large mitigation potential and the persistent uncertainty around renewable hydrogen deployment in Europe. Within this context, CCS could play an important – but clearly transitional and contested – role, with different implications for SMR retrofit and new ATR routes.

2050 CCS Ladder



High climate value

Low climate value

A
- **Lime production** Kiln
- **Cement production** Electrified clinker kiln

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- **Paper & pulp production** Kraft mill
- **"Blue" hydrogen production** Autothermal reforming

E
- **Petrochemical production** Steam cracking
- **Steam production** Combined heat and power networks[1]
- **Waste processing** Wastewater sludge incineration
- **Power production** Gas-fired seasonal/stress-test power plant
- **Glass production** Furnace
- **Ceramics production** Kiln
- **Aluminium production** Smelting & casting
- **Iron & steel production** DRI-EAF[2]
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- **Steam production** Stand-alone industrial boiler
- **Cement production** Wet clinker kiln

Steam methane reforming with carbon capture and storage: near-term abatement potential, limited long-term role

Most of Europe's existing hydrogen production capacity is based on SMR units integrated into refineries and ammonia plants. The process generates CO_2 in two places:[72] the process gas stream, where carbon monoxide is converted to CO_2 during the water-gas shift reaction; and in the flue gas from the fired heater that provides high-temperature heat to the reformer.

Capturing CO_2 from the process stream only is relatively straightforward and can abate around 50–60% of total emissions at moderate additional cost. However, achieving high overall capture rates requires capturing emissions from both streams – significantly increasing costs while adding substantial energy penalties.

As a result, retrofitting CCS to existing SMR units can deliver meaningful short-term emission reductions in, e.g., refineries and ammonia plants, but long-term value is constrained by structural shifts in hydrogen demand, increasing competition from renewable hydrogen, and rising pressure on residual emissions. Refining capacity is expected to decline as fossil fuel use falls,[73] especially in transport, while fertiliser-related hydrogen demand could shrink through reduced fertiliser use and more efficient, less nitrogen-intensive agricultural practices.[74] These developments weaken the case for major reinvestment in ageing SMR assets.

Further, as achieving capture rates above 90% on SMR units will be technically and operationally difficult, a meaningful share of CO_2 will remain uncaptured. As carbon prices rise, paying for these residual emissions will become increasingly costly, eroding the competitiveness of SMR-CCS relative to renewable hydrogen, imported low-carbon derivatives, and new ATR-CCS projects designed for higher capture performance. Moreover, SMR-CCS does not address upstream methane leakage in the gas supply chain, which can significantly undermine the net climate benefit of blue hydrogen.

Autothermal reforming with carbon capture and storage: higher performance, uncertain outlook

ATR-based hydrogen production paired with CCS is technically more promising in some respects. ATR combines steam reforming and partial oxidation within a single reactor, generating a high-pressure synthesis gas that contains most of the CO_2. Because no separate fired heater is needed, almost all emissions occur in one concentrated process stream. This results in somewhat lower energy penalties than for SMR retrofits, and process integration is simpler, making achieving capture rates around 95% more realistic.[75]

However, deploying ATR-CCS in Europe would mean building entirely new gas-based hydrogen assets rather than retrofitting existing ones, creating tension in a net-zero transition that aims to move away from fossil feedstocks. To what extent this route will be cost-competitive with renewable hydrogen in the long-term remains uncertain and will be highly dependent on regional conditions.

The long-term cost-competitiveness of ATR-based blue hydrogen relative to renewable hydrogen remains highly uncertain and will depend on gas prices, CO_2 transport and storage availability, renewable electricity costs, and carbon pricing. Gas-based hydrogen with CCS can currently be cheaper in some contexts, but this advantage will narrow over time and disappear in regions with optimal conditions for low-cost renewables, likely constraining its long-term value.

Moreover, the climate value of ATR-CCS would hinge on consistently high capture performance, reliable permanent storage, and ultra-low upstream methane leakage, conditions that have not yet been demonstrated in practice.[76] No large-scale ATR-CCS plant with high capture has so far been built, which adds further uncertainty.

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[72] Apart from upstream methane emissions.

[73] BCG, 1 April 2025, Costs and Margins Dictate the future of Refiners

[74] Easac, 2022, Regenerative agriculture in Europe

[75] Fraunhofer Institute ISI, 2022, Carbon Capture in Hydrogen Production - Review of Modelling Assumptions

[76] Bauer, C et al., 2022, On the climate impacts of blue hydrogen production

Outlook

Hydrogen sits at the intersection of high strategic importance and unresolved transition pathways. Renewable hydrogen is expected to expand and fall in cost through the 2030s, but deployment, infrastructure, costs, and demand creation lag policy ambitions, making its trajectory uncertain. The long-term cost-competitiveness of blue vs. renewable hydrogen remains uncertain.[77]

Where Europe has access to excellent renewable resources – such as in Iberia, and the Nordics – the economic case for blue hydrogen will weaken significantly over time. Industrial strategy should therefore better integrate these regional cost-advantages into European value-chains, while also building external partnerships with countries with better renewable resources to enable trade in derivatives such as green ammonia or iron. Such an approach could reduce costs and ease infrastructure pressures, though it raises political concerns around external dependencies, competitiveness and the offshoring of industrial value chains.

Within this landscape, the role of CCS in hydrogen production is ambiguous. In the near term, retrofitting CCS to existing SMR units may offer real emission reductions, but is unlikely to represent a climate-neutral end state. ATR-CCS could in principle achieve higher capture rates at lower cost, but only under strict conditions on upstream methane leakage and permanent storage.

Europe's long-term objective rightly remains a predominantly renewable hydrogen system. What is increasingly uncertain is the pathway to that goal, given unresolved questions about future costs and the difficulty of ensuring that blue hydrogen can achieve near-zero emissions. In this context, the role of CCS in hydrogen is as much political as technical. Its future hinges on whether policymakers enable value-chain restructuring that aligns hydrogen production and use with regions offering strong renewable resources – within Europe or through external partnerships – or whether they prioritise keeping existing fossil-based assets in operation. These choices will ultimately determine how significant CCS becomes in Europe's hydrogen transition.

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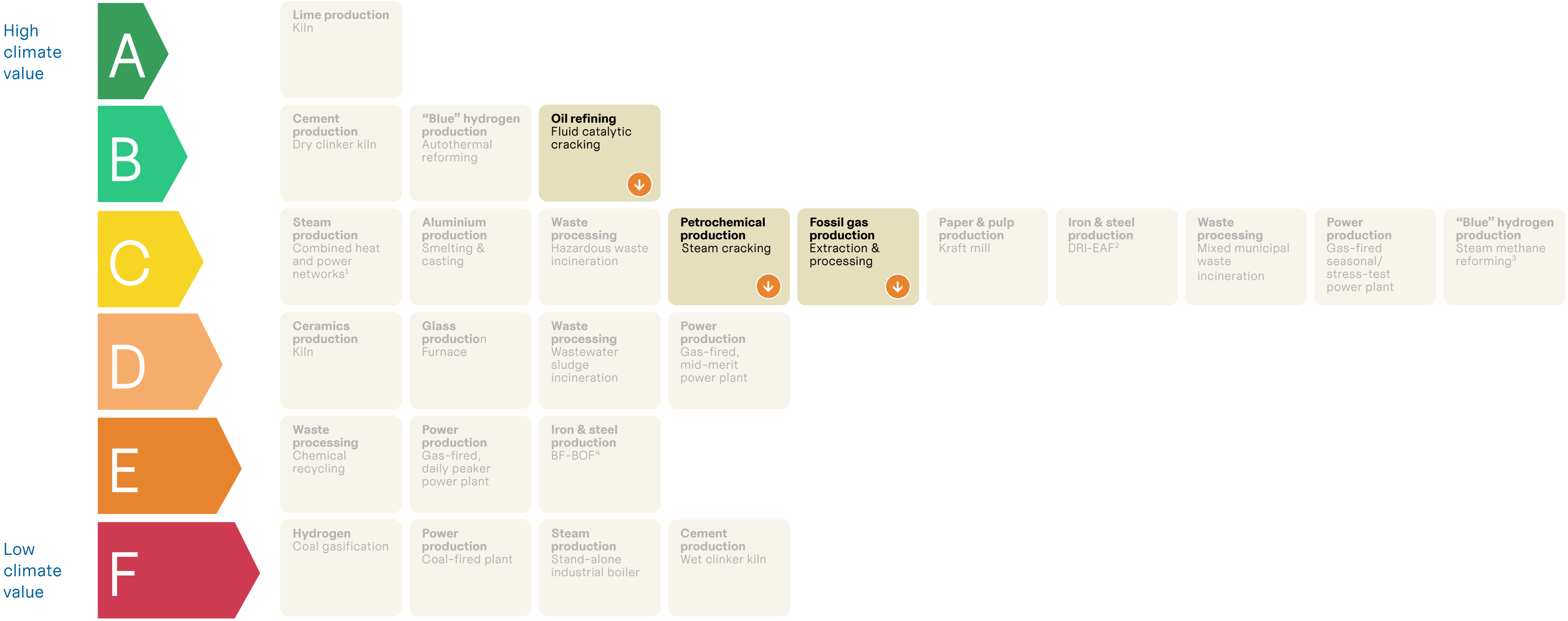
[77] Recent cost revisions from BloombergNEF indicate that green hydrogen remains significantly more expensive than previously projected. BNEF now estimates current renewable-electrolysis hydrogen at USD 3.7–11.7/kg, and expects 2050 costs in the range of USD 1.6–5.1/kg; around 35% higher than their 2022 outlook – see Bloomberg, 23 December 2024, Green Hydrogen Hype Is Giving Way to Reality;
A 2021 study from the UK department for Business, Energy & Industrial Strategy found that only renewable Hydrogen production using only otherwise curtailed renewable electricity would be cheaper than ATR- or SMR-CCS in the long-term – see BEIS, 2022, Hydrogen Production Costs 2021;
A recent study by Oeko-Institut and Deloitte estimates medium term costs for renewable hydrogen between 4.5-6 EUR/kg (in Germany) and 2-5 EUR/kg (in "optimal" regions); and between 2.5-4 EUR/kg and 1.5-3.5 EUR/kg in the long-term; compared to 3-4 EUR/kg in the medium term and 2.5-4 EUR/kg in the long-term for hydrogen from steam reforming – see Oeko-Institut & Deloitte, 2025, Hydrogen production costs

Petrochemical production

The petrochemical industry encompasses upstream fossil-gas extraction, oil refining, and petrochemical production through steam cracking. This represents a sizeable share of Europe's industrial emissions and sits at the forefront of fossil value chains.

2030 CCS Ladder



High climate value

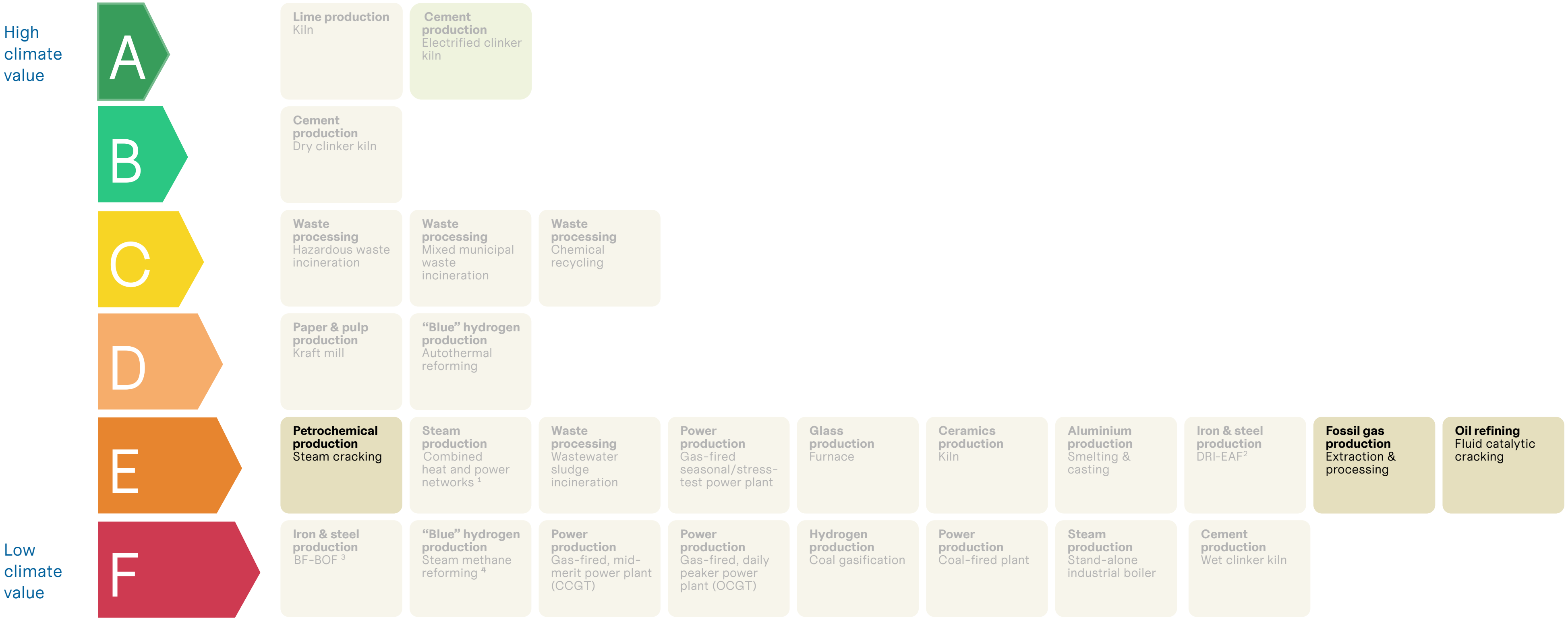
A	**Lime production** Kiln									
B	**Cement production** Dry clinker kiln	**"Blue" hydrogen production** Autothermal reforming	**Oil refining** Fluid catalytic cracking ↓							
C	**Steam production** Combined heat and power networks[1]	**Aluminium production** Smelting & casting	**Waste processing** Hazardous waste incineration	**Petrochemical production** Steam cracking ↓	**Fossil gas production** Extraction & processing ↓	**Paper & pulp production** Kraft mill	**Iron & steel production** DRI-EAF[2]	**Waste processing** Mixed municipal waste incineration	**Power production** Gas-fired seasonal/stress-test power plant	**"Blue" hydrogen production** Steam methane reforming[3]
D	**Ceramics production** Kiln	**Glass production** Furnace	**Waste processing** Wastewater sludge incineration	**Power production** Gas-fired, mid-merit power plant						
E	**Waste processing** Chemical recycling	**Power production** Gas-fired, daily peaker power plant	**Iron & steel production** BF-BOF[4]							
F	**Hydrogen** Coal gasification	**Power production** Coal-fired plant	**Steam production** Stand-alone industrial boiler	**Cement production** Wet clinker kiln						

Low climate value

These processes generate continuous, concentrated CO_2 streams, which are technically well suited for capture. CCS can be the only mitigation lever to address the emissions at site level, e.g., for fluid catalytic crackers (FCC)[78] in refineries and CO_2 separation in gas processing. In contrast, for steam cracking, several low-carbon pilot routes – most notably electrified furnaces[79] – are emerging, but their deployment remains limited and costs, particularly for electricity, remain difficult to overcome.[80]

However, these on-site emissions represent only a small share of the total climate impact of petrochemical production. The real long-term solution lies in reducing fossil-product demand through electrification, efficiency and circularity. Still, fossil installations will not disappear immediately, and their collective emissions will be large enough that excluding them from early CCS deployment could jeopardise Europe's interim climate targets. In this sense, CCS can play a bridging role for selected facilities that remain in operation through the 2030s.

2050 CCS Ladder



High climate value	A	Lime production Kiln	Cement production Electrified clinker kiln								
	B	Cement production Dry clinker kiln									
	C	Waste processing Hazardous waste incineration	Waste processing Mixed municipal waste incineration	Waste processing Chemical recycling							
	D	Paper & pulp production Kraft mill	"Blue" hydrogen production Autothermal reforming								
	E	**Petrochemical production** **Steam cracking**	Steam production Combined heat and power networks [1]	Waste processing Wastewater sludge incineration	Power production Gas-fired seasonal/stress-test power plant	Glass production Furnace	Ceramics production Kiln	Aluminium production Smelting & casting	Iron & steel production DRI-EAF[2]	**Fossil gas production** **Extraction & processing**	**Oil refining** **Fluid catalytic cracking**
Low climate value	F	Iron & steel production BF-BOF [3]	"Blue" hydrogen production Steam methane reforming [4]	Power production Gas-fired, mid-merit power plant (CCGT)	Power production Gas-fired, daily peaker power plant (OCGT)	Hydrogen production Coal gasification	Power production Coal-fired plant	Steam production Stand-alone industrial boiler	Cement production Wet clinker kiln		

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[78] TNO, 2020, Decarbonisation options for the Dutch refinery sector

[79] BASF, 17 April 2024, BASF, SABIC, and Linde celebrate the start-up of the world's first large-scale electrically heated steam cracking furnace

[80] Technip Energies, 2021, Decarbonisation of steam crackers

Oil refining: high volumes, low life-cycle value

Oil refineries remain among Europe's largest industrial emitters, emitting around 110 Mt CO_2 per year,[81] with major contributions from units such as FCCs, hydrogen plants and fuel-fired heaters. These are large, steady point sources, typically located in industrial clusters or coastal regions, making CCS technically feasible. However, CCS's system-wide climate value is limited. FCC emissions represent a small fraction of the full lifecycle emissions of oil products; most CO_2 is released downstream when fuels are combusted in transport, heating, and industry.[82] Structural alternatives such as the electrification of transport, heating and industry will steadily shrink demand for refined products. Remaining facilities may ultimately consolidate around bio-based or synthetic feedstocks, where CCS could support net-zero fuel production.

Fossil gas extraction and processing: concentrated sources, marginal mitigation

Upstream oil and gas extraction and processing in Europe emit on the order of 30–35 Mt CO_2 per year, with most emissions coming from offshore oil operations. Only a small share – mainly from CO_2 removed during gas processing – is readily suitable for capture. The overwhelming majority of these emissions comes from offshore operations in the UK and Norway. With permanent storage locations often in near proximity, capture and permanent storage are both technically straightforward and low-cost.

Yet these emissions represent only a fraction of the life-cycle emissions of natural gas. Most CO_2 is released downstream when the gas is burned. [83] As such, CCS at the extraction stage offers limited overall mitigation, even if it can reduce emissions from production during the energy transition. Long-term decarbonisation ultimately depends on the decline of fossil-gas demand through renewable energy deployment, efficiency and electrification.

Steam cracking for high-value petrochemicals: transitional role amid electrification and circular feedstocks

Steam cracking forms the backbone of petrochemical production, converting fossil naphtha, ethane, or LPG into ethylene, propylene, and other high-value chemicals used for plastics, fibres, and solvents. The process emits around 30 Mt CO_2 per year in Europe,[84] mainly from the fuel-fired furnaces that provide high-temperature heat.

Electrified cracker furnaces, hydrogen-fired concepts, and alternative routes such as methanol-to-olefins are advancing but remain at pilot to early commercial stages. Even with successful electrification, crackers would continue to rely on fossil feedstocks unless deeper systemic changes occur. Long-term decarbonisation requires a shift to non-fossil carbon feedstocks—including circular feedstocks (mechanically and chemically recycled materials), bio-based feedstocks, and synthetic feedstocks derived from captured CO_2, and renewable hydrogen. While such pathways could ultimately enable a climate-positive petrochemical industry,[85] it remains speculative whether, how quickly and to what extent a large-scale feedstock switch will become technically and economically viable.

CCS can technically capture most direct emissions from existing steam crackers, especially within industrial clusters with shared CO_2 transport and storage infrastructure.[86] However, the majority of emissions associated with petrochemical products arise downstream[87] – from product use, waste handling and disposal – meaning that CCS at the cracker addresses only a fraction of the life-cycle footprint. That's why, in parallel, reducing

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[81] EEA, 2025, EU Emissions Trading System (ETS) data viewer

[82] CONCAWE, 2022, Estimating the CO_2 intensities of EU refinery products

[83] US Department of Energy, 2014, Life Cycle Analysis of Natural Gas Extraction and Power Generation

[84] EEA, 2025, EU Emissions Trading System (ETS) data viewer

[85] See for example Agora Industry, Carbon Minds, & EPSE, 2023, Chemicals in transition. The three pillars for transforming chemical value chains [Impulse].; or Agora Industrie, Carbon Minds, & Fraunhofer IKTS, 2025, Innovationen für morgen: Chancen für eine klimaneutrale Chemieindustrie

[86] Such as Antwerp, Rotterdam or Ludwigshafen.

[87] Young et al., 2022, Environmental life cycle assessment of olefins and by-product hydrogen from steam cracking of natural gas liquids, naphtha, and gas oil

demand for (virgin) plastics and other petrochemical products will be essential to limit the scale of (primary) production and emissions caused by this sector.

In 2030, alternatives such as electrified furnaces, hydrogen firing, and methanol-to-olefins remain at pilot or early commercial stage, keeping CCS relevant for legacy plants. By 2050, however, these low-carbon routes can be expected to be more widely available, supported by abundant renewable power and an increased share of circular feedstocks.

Outlook

CCS in the petrochemical industry embodies the tension between near-term carbon-budget constraints and long-term structural transition. CCS may be technically straightforward and help reduce emissions from facilities that will continue operating into the 2030s, but its long-term strategic value is limited in sectors where the primary objective is to reduce and ultimately phase down fossil-product demand.

Policy frameworks should therefore not seek to avoid deploying carbon capture in these sectors, especially for large, emissions-intensive facilities that are likely to remain in operation in the mid-term. They should, however, primarily rely on carbon pricing and regulatory obligations rather than subsidies to drive deployment. Making CCS a condition of continued fossil operation helps internalise its costs into product prices and avoids extending asset lifetimes through public support, reinforcing wider efforts to curb demand for fossil-derived fuels and petrochemicals.

At the same time, safeguards are needed to ensure that CCS deployment is not misused to delay or dilute phase-down pathways, capacity reductions, or asset retirements. Robust life-cycle accounting should prevent upstream carbon capture from being leveraged to obstruct downstream demand reduction or to misrepresent fossil-based products as “clean” or “abated” when most of their emissions occur at the point of use or disposal. As with gas-fired power and hydrogen, infrastructure planning must anticipate declining fossil throughput, ensuring that CO_2 transport and storage networks developed for current fossil assets can be reused or reallocated over time for higher-priority industrial applications.

Only under such conditions can CCS in petrochemicals and refining play a targeted role in managing near-term emissions without undermining the structural transition away from fossil energy and feedstocks. As demand falls, the role of CCS should diminish accordingly.

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