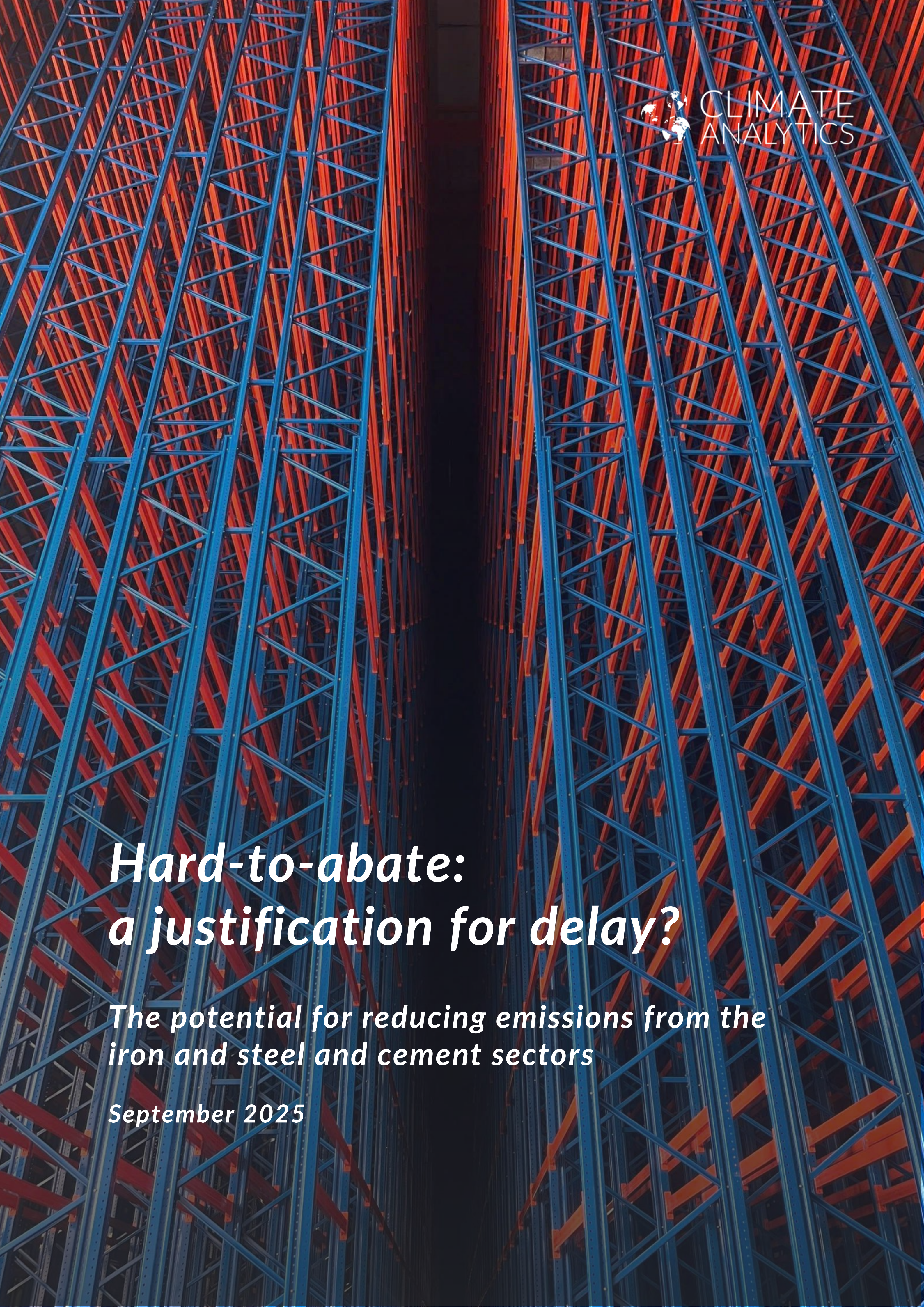

CLIMATE ANALYTICS

Hard-to-abate: a justification for delay?

The potential for reducing emissions from the iron and steel and cement sectors

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AUTHORS: Bill Hare, Hannah Grant, James Bowen

REVIEWERS: Michiel Shaeffer, Neil Grant

CONTRIBUTORS: Cindy Baxter, Victor Maxwell, Nandini Das

EDITING: Cindy Baxter

ABOUT CLIMATE ANALYTICS

Climate Analytics is a global climate science and policy institute. Our mission is to deliver cutting-edge science, analysis and support to accelerate climate action and keep warming below 1.5°C.

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Executive summary

'Hard-to-abate' is an ill-defined but widely applied term. Industry members — and their government supporters — often describe their sector as hard-to-abate to argue against having to reduce emissions quickly, or to justify continued faith in carbon capture utilisation/storage (CCUS) breakthroughs, or using offsets to meet climate goals.

Sectors described as hard-to-abate include cement, iron and steel, fertilisers, petrochemicals, aviation, and shipping. These collectively generate about 21-25% of global greenhouse gas (GHG) emissions.

Achieving global net zero CO_2 emissions by around mid-century is critical to the Paris Agreement's goal of limiting the global temperature rise to 1.5°C above pre-industrial levels and bringing total GHG emissions to net zero in the second half of the century. Continuing to classify highly emitting sectors as hard-to-abate – and failure to make use of emissions reduction potentials – jeopardises this.

The iron and steel and cement sectors provide valuable case studies of how the 'hard-to-abate' label has shaped both policy and industrial actions, in ways that risk undermining the urgency and effectiveness of global climate mitigation efforts.

While the technical and process-related challenges in these sectors are non-trivial, the evidence presented in this report demonstrates that their decarbonisation is not only possible but highly achievable with existing and emerging technologies — especially when guided by integrated, whole-of-system approaches and supported by robust policy frameworks.

We find that while there is no single pathway to decarbonising the iron and steel and cement sectors, the continued framing of these sectors as inherently hard to abate is both scientifically inaccurate and politically counterproductive. The evidence is clear: many of the most impactful abatement measures are available today, and their deployment is limited primarily by policy, investment, and institutional inertia.

Reframing the real challenge

Achieving net zero GHG emissions globally requires considering how fast real emissions can be reduced to as close to zero as possible across all sectors, once all feasible abatement options have been deployed.

Residual GHG emissions will require negative CO_2 emissions through carbon dioxide removal (CDR) to counteract their warming effect. This will be critical to bringing global greenhouse gas emissions to net zero in the second half of this century, as required under the Paris Agreement.

Residual emissions in any sector must be very low, if not eliminated, to keep within the limits of what is possible with global CDR deployment. In other words, negative CO_2 emissions through CDR – which is subject to serious limitations – should only be used to counterbalance truly unavoidable residual GHG emissions, mainly those from non-fossil fuel sources, to achieve net zero GHG emissions globally.

Not all sectors can reduce emissions at the same rate. This leads to two key policy questions: "how quickly can all available abatement options be achieved?" and "what level of residual CO_2 and/or GHG emissions are truly unavoidable by 2050?"

In this context, this report critically examines the hard-to-abate claims of the two key sectors of iron and steel, and cement, which collectively account for about 15% of global CO_2 emissions. We illustrate how the hard-to-abate label has often served to lower expectations, delays viable emission reductions and weakens incentives for long-term transformation. To date, the perceived economic and/or political indispensability of iron and steel, and cement has decreased the pressure they face to decarbonise.

Industry members often use the hard-to-abate label to justify overreliance on offsets and CCUS technologies to counterbalance or abate purportedly unavoidable emissions. As this study shows, there are substantial opportunities to reduce emissions relatively quickly in both the iron and steel, and cement sectors, minimising the need for CCUS and, over time, resulting in low residual emissions.

Zero-emissions steel technologies are already commercially available but need strong policy support to scale-up. For the cement sector, studies with more focus on high deployment of production-side measures still show that incremental changes could enable significant emission reductions at source, for example, a 55% reduction in total emissions without CCUS, compared to 46% in the IEA NZE scenario, by 2050. Yet many studies underplay the added potential of demand-side actions like material efficiency and circularity in reducing residual emissions.

Reliance on CCUS poses substantial technical, economic and scalability risks. It cannot capture 100% of emissions; residual emissions are inevitable. The IEA's latest NZE scenario, for example, downgraded its estimates for captured CO_2 by 39% for 2030 and 22% for 2050 compared to the first NZE scenario released in 2021.

It is also becoming increasingly clear that humanity will need substantial CDR capacity to respond to likely feedback from warming, whereby the Earth system is expected to absorb an ever-smaller fraction of emitted CO_2 over time. The limited and uncertain availability of CDR means it should not be counted on to counter-balance residual fossil fuel emissions that could otherwise have been eliminated.

Based on current policies, iron and steel emissions will be just 10% lower, and cement emissions 4% higher, in 2050. In top-down scenarios that limit warming to 1.5°C, such as the IEA's NZE roadmap, combined CO_2 emissions for iron and steel and cement fall by about 23% by 2030 below 2023 levels, 46% by 2035 and 94% by 2050.

The IEA NZE relies on significant CCUS, particularly for cement, to address process emissions. By contrast, bottom-up studies show faster emissions reduction is possible through enhanced focus on demand-side measures such as material substitution and efficiency for each sector, with a much-reduced need for CCUS.

A whole-of-system approach could deliver deeper cuts and reduce reliance on CCUS. Close inspection of production pathways, and the broader economic and political landscape surrounding each sector reveals framing these sectors as hard-to-abate has lowered ambition and encouraged unnecessary dependence on CCUS, delaying the deeper transformations needed to reach net zero.

Iron and steel

The iron and steel sector accounts for 7-8% of global greenhouse gas emissions. Technologies for achieving zero emissions in steel production are currently available at commercial scale, but strong policy support is needed. The claim that iron and steel production is hard-to-abate is therefore misleading. It mainly rests on the incumbency advantages of a particularly fossil fuel-intensive production route, for which there are technologically viable substitutes.

The iron and steel industry is dominated by the carbon-intensive blast furnace-basic oxygen furnace (BF-BOF) production method, which accounts for about 72% of production. Yet there are proven alternatives such as electric arc furnaces (EAF), which can help significantly increase the ratio of recycled to new steel production, while progressively deploying renewable power. EAFs can also produce new steel with direct reduced iron (DRI) made with zero emission inputs, such as green hydrogen.

The iron and steel sector could feasibly reach near zero residual CO_2 emissions by around 2050 based on currently available technologies and, if complemented by strong demand side interventions without large-scale CCUS, could potentially eliminate the need for negative CO_2 emissions for this sector. Demand reduction measures, such as increased use of secondary steel and improving material efficiency, could reduce steel requirements by up to 20% by 2050, making deep decarbonisation even more achievable. Substantial emissions reductions could be achieved through circular economy strategies that reduce steel demand, such as cutting the 'overspecification' of steel in construction, which could lower steel use by 35–45%.

Adopting a whole-of-system approach, including key measures such as extensive scrap steel recycling and materials efficiency, will make this easier to achieve. Achieving near zero steel will require substantial additional policy support, including 'carrots' such as investment in low emissions production, and 'sticks' of regulatory restrictions on high emissions production.

Decarbonising iron and steel is likely to take longer than for sectors such as power generation. However, bottom-up studies show the potential for relatively rapid action if appropriate policies are put in place.

A recent bottom-up study of steel plants globally shows that advanced retrofitting of existing plants could help limit warming to 1.5°C. Substitution of green hydrogen and, where necessary, CCUS, could lead to large reductions of up to 66% of cumulative emissions from this sector between 2020-2050, compared to estimated emissions levels without any interventions.

Cement

The cement sector contributes 5-8% of global CO_2 emissions. Concrete produced with cement is the second most widely consumed material after water.

Industry members can use cement's current economic importance and its largely self-appointed hard-to-abate status to reduce policy ambition, facing little pressure or incentive to upset a successful but emissions-intensive business model. Current sectoral plans lean especially heavily on CCUS, even though there are very few examples of actual deployment.

What is clear from the available literature is that two broad approaches can be taken to decarbonise the cement sector. One approach heavily emphasises reducing emissions through production-side measures. The other takes a whole-of-system approach, which, along with ambitious production-side measures, also extends to expansive demand-side measures, such as lean construction, material substitution, and lifetime extension of buildings.

On the production side, cement's core climate challenge of needing to reduce process emissions in clinker production is substantial. But numerous options exist for reducing emissions at source, sector-wide. These include enhanced materials efficiency and substitution, such as reducing cement ratios in concrete, clinker ratios in cement, and developing alternative cements with non-clinker binders; improving energy efficiency, electrification, and fuel switching; and improving recycling/circular economy commitments.

Options already exist at the protoype stage for eliminating cement's energy-related emissions (~40% of total emissions) and more than half of overall sector emissions could be eliminated through a combination of material and energy efficiency, clinker substitution, novel cements, fuel switching, and electrification by 2050.

Available studies suggest that production-centric approaches could enable significant emission reductions over time. The top-down IEA NZE pathway indicates a 24% reduction of CO_2 by 2030, 47% by 2035, and 97% by 2050 from 2023 level, with a heavy emphasis on decarbonisation of the energy supply and CCUS for process emissions. This could still leave large demand for CDR to balance residual emissions.

In addition to production-side measures, reducing overall utilisation, particularly by curbing overbuilding, is vital. By reducing unnecessary demand for new construction, the sector can avoid excessive consumption of cement, further reducing emissions associated with cement production.

A whole-of-system approach could, on the other hand, reduce emissions by about 40% by mid 2030s and about 72% by 2050, compared to 2018 levels, without any plant-level dependence on CCUS. The cement sector could be carbon negative by around 2060. A much-reduced level of CCUS would be needed in this approach, compared to the production-oriented approach. The whole-of-system approach would require more complex policies and larger engagement with stakeholders outside of the cement production sector.

Decarbonising cement requires a wider and more coordinated range of policies over a longer period compared with iron and steel. Accelerated research and development of further breakthroughs is also a priority. Industry attempts to limit attention to their own supply chains will frustrate quick abatement and help sustain considerable 2050 residual emissions.

Avoiding strategies of delay

The iron and steel and cement sectors illustrate how the hard-to-abate label can act, or is even designed to act, to delay climate action, justifying continued reliance on future CCUS and offsets rather than prioritising immediate emissions reduction.

While transformative abatement options exist, they require significant scaling up from the business-as-usual operations, which is resisted by industry actors who claim emissions are unavoidable.

Despite frequent promotion, CCUS deployment in supposed hard-to-abate sectors — or indeed any sector — remains minimal for abatement purposes. Industry recourse to future CCUS deployment and offsets must also be put in context of doubts about the legitimate mitigation potential of these pathways. CCUS deployment in the iron and steel and cement sectors, despite much talk, has barely occurred. CCUS has also consistently failed to meet its promised potential in a more general sense.

Offsets, by design, allow CO_2 emissions to occur that would not otherwise have occurred in their absence and often lack additionality, permanence, and verifiability, thus failing to deliver real mitigation.

Together, CCUS and offsets allow companies to delay investment in transformative solutions. Strong policy and regulation should instead aim to turn today's claim by so-called hard-to-abate sectors into typical sectors with 1.5°C-compatible emissions reduction obligations, reducing dependence on negative emissions by mid-century.

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Introduction

Limiting human-caused global warming to 1.5°C, with no or limited overshoot, requires reaching net zero CO_2 emissions globally by around mid-century and net zero greenhouse gas (GHG) emissions soon after.[1] This requires rapid, deep and immediate global emissions reductions across all sectors.

"Residual emissions" are anthropogenic emissions that cannot be feasibly eliminated, and must be counterbalanced by carbon dioxide removals (CDR) to reach net zero emissions globally.[2] As the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) noted, *"The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved."* [3]

It is important to distinguish residual emissions from "unabated" emissions, which are emissions that persist under current or projected policies due to delayed mitigation action, infrastructure lock-in, or lack of policy support.

Throughout this report, we critique the misuse of the term "residual" to justify inaction or reliance on CCUS and offsets. In many cases, emissions presented as unavoidable are in fact abatable—either through deployment of existing technologies, material efficiency, or demand reduction.

There are substantial practical difficulties with relying on large-scale CDR to compensate in the long-term for a lack of emission reductions in the short-term and/or compensate for high levels of contemporaneous GHG emissions in the long-term. Residual emissions must be minimised to render achievement of net zero GHG emissions globally feasible. This requires residual emissions to be limited to those that truly are "hard-to-abate".

While the IPCC refers to "hard-to-abate" residual emissions and their potential role in determining the scale of CDR needed to meet climate targets, it does not offer a precise definition of this term. However, the International Organization on Standardization (ISO) definition of residual emissions provides some useful guidance. It describes

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[1] IPCC, *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland.*
[2] IPCC, "Summary for Policymakers."
[3] IPCC, "Summary for Policymakers."

residual emissions as those that remain after taking all ‘technically and scientifically feasible’ actions to implement emission reductions.[4]

Evaluating the potential for minimising residual emissions in individual sectors is difficult. Different parties have different interpretations of which, and what level of, emissions are hard to abate. For example, the German government assesses that only 5% of global emissions are unavoidable residual emissions; in contrast, the CEO of German manufacturer Man Energy Solutions argues 30% of global emissions are unavoidable.[5]

Some of the most contestable applications of the ‘hard-to-abate’ terms refer to decarbonising fossil fuel supply chains, which would largely cease to exist under 1.5°C-aligned scenarios, and sectors such as power generation and transport, which are among the most easy and affordable to fully decarbonise.[6]

Members of sectors expected to take longer to reduce emissions often use the hard-to-abate term. These sectors include aviation, shipping, agriculture, and industrial processes such as iron and steel and cement production,[7] together constituting around 21-25% of global emissions.[8] As of today, replacing emissions-intensive processes with direct electrification using renewables is the most difficult and expensive in these sectors.

Yet describing any sector as hard-to-abate appears to reduce ambition for near-term emissions reductions from various actors, including governments. Those using the term typically do not identify specific applications or industry dynamics expected to sustain mid-century residual emissions. They often overlook options that exist for considerable near-term emission reductions, and correspondingly fail to incorporate these in long-term decarbonisation roadmaps.

There is also a tendency for members of proclaimed hard-to-abate sectors to present their goods and services as economically or socially indispensable. This can minimise attention on transformative 1.5°C-aligned options for these sectors, including reducing

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[4] ISO, *International Workshop Agreement (IWA 42): Net Zero Guidelines*.
[5] Arendt, “Residual Carbon Emissions in Companies’ Climate Pledges.”
[6] In December 2021, then Western Australian Minister for Environment and Climate Action, Amber-Jade Sanderson, argued new carbon farming support would provide opportunities for offsetting emissions from hard-to-abate sectors, “in particular, oil and gas” (Milne, “Three Million Hectares of WA Land to Be Released for Carbon Farming.”; In February 2024, Japan’s Ministry of Economy, Trade and Industry described new hydrogen and carbon capture and storage legislation as designed to aid sectors where “decarbonization is difficult” and referred to power and mobility among these (METI, “Cabinet Approvals on the ‘Bill for the Act on Promotion of Supply and Utilization of Low-Carbon Hydrogen and Its Derivatives for Smooth Transition to a Decarbonized, Growth-Oriented Economic Structure’ and the ‘Bill for the Act on Carbon Dioxide Storage Businesses.’”
[7] IPCC, “Summary for Policymakers.”
[8] Ritchie, “Sector by Sector”; Khaiyum et al., “Evaluation of Carbon Emission Factors in the Cement Industry.”

demand through material efficiency or substitution, behavioural change, and technological substitution.[9]

Maintaining hard-to-abate designations in turn allows overdependence on some form of “carbon management”, e.g. carbon capture utilisation/storage (CCUS) and carbon offsets, for what are feasibly avoided residual emissions.

Beyond the question of defining what hard-to-abate means are some more fundamental issues. These are outlined at the beginning of this report and are important for framing the analysis of what level of abatement should be targeted.

While commonly used in many different contexts, scientifically **net zero** refers to a situation where CO_2 and/or greenhouse gas emissions are balanced by anthropogenic CO_2 or GHG removals over a specified period. What this means is that a **sector is net zero** when its remaining emissions are balanced by anthropogenic CO_2 removals, with these removals occurring outside of the direct jurisdiction of the sector concerned.

This can be achieved by purchasing land-based offsets or direct capture units. In order to minimise residual emissions then, hard-to-abate sectors need to be examined in terms of the real emissions reductions they can achieve, not “net-emission reductions”. Where a sector is able to bring its CO_2 or greenhouse gas emissions to zero without recourse to external CO_2 removals it can be said to be “real zero”.

A further consequence of this is that where an entity or sector deploys carbon capture and storage (CCS) to capture CO_2 emissions and store them in a secure geological repository, this is to be considered a real emission reduction and not a net reduction. As should be clear from these definitions, reducing residual emissions can also be achieved by deployment of CCS. This is separate from the question of the desirability of deploying CCS, which is questionable in most cases, as discussed in this report. When CCUS is deployed, there can be real questions about the scale which CO_2 is captured and isolated from the atmosphere. In many cases little real CO_2 reduction may occur.

There is, then, a need for far greater scrutiny of sectors and individual applications classed as hard-to-abate. This must seek to determine whether and where residual emissions are truly inevitable.

This analysis is key to determining the types and levels of policy responses that might be applied to activities considered hard-to-abate. This report explores these issues, with specific reference to iron and steel and cement, both typically described as hard-to-

[9] Creutzig et al., “Towards Demand-Side Solutions for Mitigating Climate Change”; Bashmakov et al., “Industry.”

abate sectors. Yet, as explored below, this does indeed obscure options in both sectors for eliminating significant emissions, including via additional policy support.

At the same time, there are highly sector-specific considerations around viable decarbonisation pathways for iron and steel versus cement. This provides further valuable insight into how the hard-to-abate term might be applied, or not, in future and what the policy implications of these designations might be.

‘Hard-to-abate’ sectors under 1.5°C compatible pathways

Residual emissions in 1.5°C scenarios

Describing sectors as hard-to-abate should not imply any allowances for residual emissions in achieving net zero emissions by mid-century. All sectors contribute to decarbonising the global economy under 1.5°C-aligned scenarios.

Globally, CO_2 emissions from energy and industrial processes rose by around 1% in 2023, reaching 38 $GtCO_2$.[10] Electricity and heat accounted for 40% of this total, while the industry, transport and buildings sectors accounted for 24%, 22% and 7%, respectively. In the IEA’s Net Zero Emissions by 2050 (NZE) scenario, CO_2 emissions from energy and industrial processes fall 33% below 2023 levels by 2030.[11]

It is true that the power sector is most critical to reducing global and national economy-wide emissions. In the NZE scenario, CO_2 emissions from electricity and heat fall 42% below 2023 levels by 2030, and 80% by 2035. Moreover, decarbonising electricity and heat contributes the majority of near-term (out to 2030) emissions reduction. This is roughly in line with the IPCC’s AR6 findings.[12]

The IPCC’s AR6 *Synthesis Report* shows the use of solar and wind energy offers the lowest cost and highest potential contribution to net emissions reduction by 2030. This in turn supports another key mitigation option, fuel switching in industry.[13]

Yet deep cuts also occur across all end-use sectors in 1.5°C scenarios. This includes those that currently claim to be hard-to-abate. The NZE scenario sees CO_2 emissions from industry fall 22% below 2022 levels by 2030. This is roughly equivalent to the 24% reduction in transport CO_2 emissions.

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[10] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[11] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[12] See Figure SPM.5: Illustrative Mitigation Pathways (IMPs) and net zero CO_2 and GHG emissions strategies, in IPCC, “Summary for Policymakers.”
[13] See Figure 4.4: Multiple Opportunities for scaling up climate action, in IPCC, *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland.*

While power sector emissions fall rapidly, deep cuts occur in all sectors

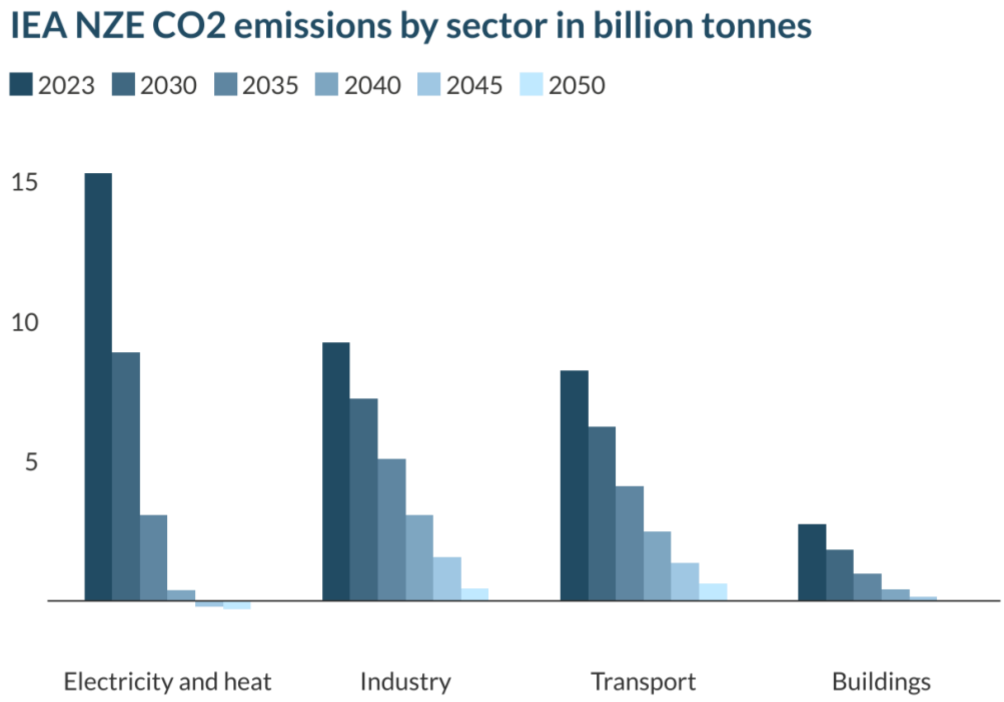

Figure 1: Energy and industrial process CO_2 emissions across electricity and heat and end-use sectors in IEA's Net Zero Emissions scenarios, 2022 to 2050. Source: IEA World Energy Outlook 2024.[14]

Rapid abatement is necessary and possible

Under 1.5°C scenarios, rapid emissions reductions still occur in sectors which claim to be hard-to-abate. Iron and steel and cement perfectly illustrate this. CO_2 emissions from both fall by around a quarter between 2023 and 2030 in the IEA's NZE.

Residual emissions are still expected from both sectors in 2050 under the NZE. Yet these are relatively small, at less than 10% of current emissions for both sectors. Iron and steel emissions would fall from 2.8 $GtCO_2$ in 2023 to 224 $MtCO_2$ in 2050. Cement emissions would fall from 2.4 $GtCO_2$ in 2023 to 65 $MtCO_2$ in 2050.[15]

However, currently projected CO_2 emissions for both sectors are decidedly out of line with 1.5°C pathways. Under the IEA's Stated Policies (STEPS) scenario, which reflects implications of current policies, CO_2 emissions from iron and steel would be just 10%

[14] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[15] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).

lower in 2050 than in 2023 and cement CO_2 emissions would be 4% *higher*.[16] Urgent, transformative change is required to align both sectors with a 1.5°C trajectory.

Iron & steel and cement emissions under current policies greatly exceed net zero scenarios

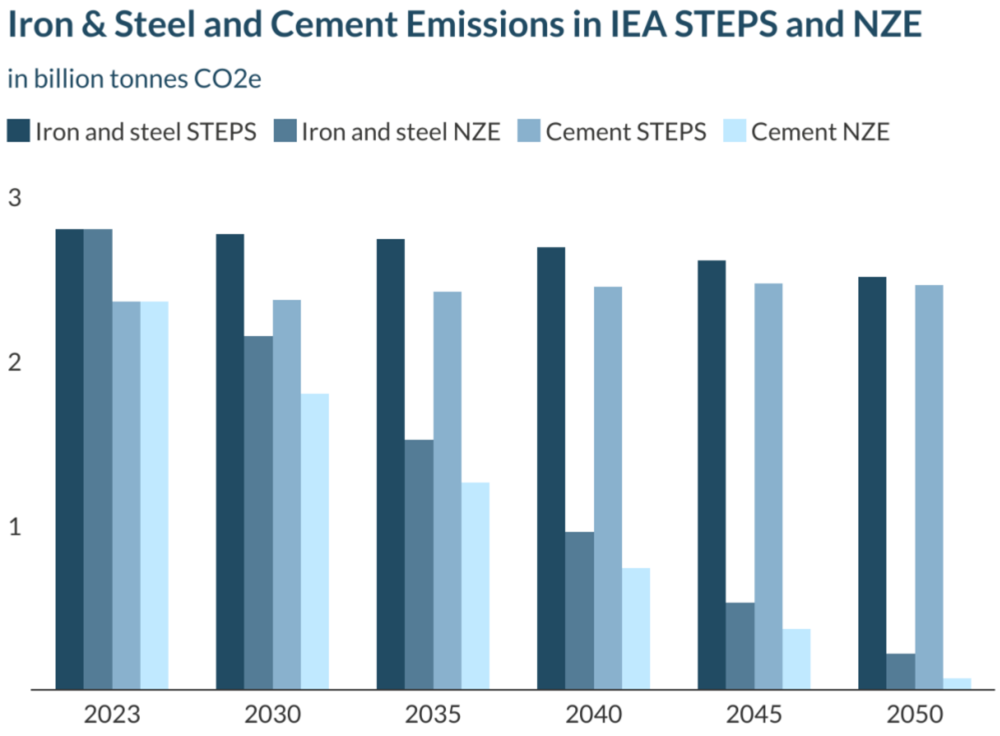

Figure 2: Energy and industrial process CO_2 emissions from the iron and steel and cement sectors in IEA's Net Zero Emissions (NZE) and Stated Policies (STEPS) scenarios, 2010 to 2050. Source: IEA World Energy Outlook 2024.[17]

An alternative to the IEA's NZE scenario is the ensemble of illustrative pathways published by the Network for Greening the Financial System (NGFS). The NGFS Phase V pathways rely on integrated assessment models (IAMs) used to produce scenarios considered by the IPCC in its AR6. They are essentially updated runs of IPCC illustrative mitigation pathways using new scenarios developed by NGFS, which reflect the latest economic and climate data and technology trends.

We consider the NGFS Phase V REMIND pathways,[18] in addition to the IEA's NZE scenario, because they provide a range of possible 1.5°C-aligned pathways and include

[16] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[17] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[18] We exclude GCAM pathways since they do not include process CO_2 emissions from the cement sector, only energy CO_2. We further exclude MESSAGE pathways as MESSAGE does not

more granular data. The NGFS Phase V scenario data includes both energy-related CO_2 and process CO_2 emissions, which result from the chemical transformation of raw materials.

model cement production explicitly and instead uses industrial activity (specifically industrial thermal demand) as a proxy for cement production. This leaves an ensemble of six REMIND pathways.

CO_2 falls rapidly in the steel and cement sectors under 1.5°C compatible pathways

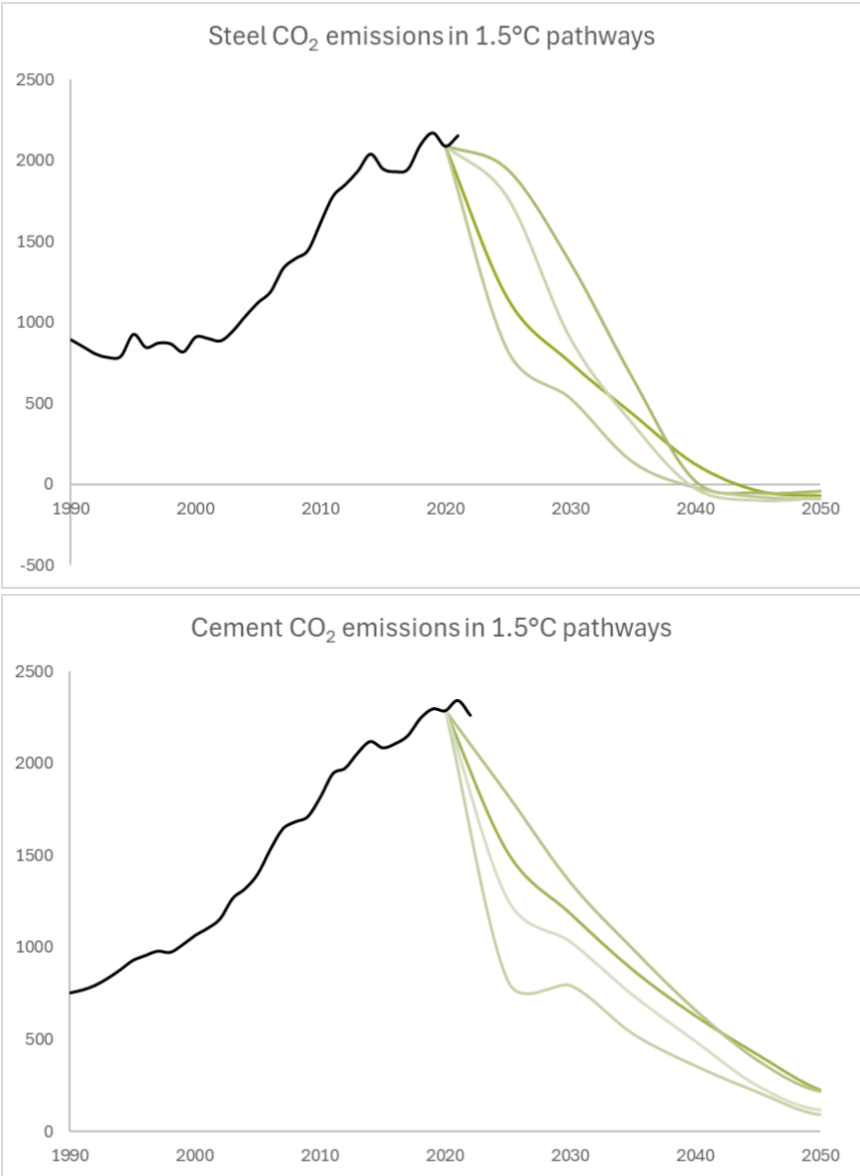

Figure 3: CO_2 emissions from the global steel and cement industries, historical and projected under 1.5°C compatible pathways. Sources: Historical steel data from IEA GHG Emissions from Energy[19], historical cement data from Chen et al. 2022[20], and 1.5°C pathways from Network for Greening the Financial System (NGFS) Phase V scenarios.[21]

[19] IEA, *Greenhouse Gas Emissions from Energy*.
[20] Chen et al., "A Striking Growth of CO2 Emissions from the Global Cement Industry Driven by New Facilities in Emerging Countries."
[21] NGFS, "NGFS Scenarios Portal."

Iron and steel decarbonise rapidly in 1.5°C-aligned pathways. Energy-related CO_2 emissions fall 60% (median) below 2020 levels by 2030 under the REMIND pathways.[22] This corresponds to 831 $MtCO_2$/year energy-related CO_2 emissions in 2030, compared to 2.1 $GtCO_2$/year[23] in 2020.

A 1.5°C compatible pathway for cement would also see deep emissions reductions. CO_2 emissions from both process and energy use decline 52% (median) below 2020 levels by 2030 under the REMIND pathways.[24] In absolute terms, this would mean CO_2 emissions fall from 2.3 $GtCO_2$/year[25] in 2020 to around 1 $GtCO_2$/year by 2030.

Process CO_2 emissions are, in general, not as easily eliminated as energy emissions. They account for around 60% of direct cement production emissions,[26] but only around 7% of direct steel production emissions.[27] Industry members use the substantial process emissions in cement making to justify their 'hard-to-abate' status. Yet, as noted below, there are considerable opportunities to minimise even these process emissions.

Raising climate ambition

The case studies below provide a more detailed investigation of the hard-to-abate statuses of iron and steel and cement and their relationships with a 1.5°C pathway. It is clear, however, that global emissions reduction ambition must rise across all sectors. The cumulative CO_2 volume emitted before the world reaches net zero emissions will heavily influence the level at which the global temperature rise peaks. The pathway to getting to net zero matters, as does the year in which it is reached.

More rapid elimination of residual emissions is important. Corporations are on the front line of this challenge. The United Nations' High-Level Expert Group on the Net Zero Emissions Commitments of Non-State Entities (UN HLEG) recommends companies adopt plans to reach net zero in line with IPCC or IEA pathways that limit warming to 1.5°C with no or limited overshoot. Yet few companies currently meet this standard.

The Net Zero Tracker assesses over 2000 companies' commitments. As of 2023, only 56% of companies in the materials sector, which includes cement and steel, had net

[22] This is the median reduction in energy-related steel CO_2 emissions in REMIND pathways from the NGFS Phase V scenarios.
[23] IEA, *Greenhouse Gas Emissions from Energy*.
[24] This is the median reduction in energy-related and process cement CO_2 emissions in pathways from the NGFS Phase V scenarios.
[25] Chen et al., "A Striking Growth of CO2 Emissions from the Global Cement Industry Driven by New Facilities in Emerging Countries."
[26] Bashmakov et al., "Industry."
[27] Bataille et al., *Global Facility Level Net-Zero Steel Pathways*.

zero targets.[28] This was even lower for manufacturing (48%) and infrastructure (38%), which are key consumers of these materials.

Those net zero and interim emissions reduction targets that companies do have are often ambiguous and unambitious.[29] A recent assessment of 115 companies[30] found that of 69 with net zero pledges, only 22% aimed to reduce emissions to residual levels - and they compensate for these with CDR.[31] Climate pledges from companies across all sectors envisioned having residual emissions. This included sectors with few abatement concerns, such as information technology, communication, and finance.

The Transition Pathway Initiative, linked to the Grantham Research Institute on Climate Change and the Environment and the London School of Economics, evaluates alignment of nearly 400 companies' emission pathways with the Paris Agreement. As of 2024, only 16% of steel companies assessed and 9% of cement companies had targets aligned with Paris Agreement benchmarks in both the medium (2035) and long term (2050).[32]

Both the ISO Net Zero Guideline and Science-Based Targets Initiative's Corporate Net-Zero Standard set minimum emissions reduction targets of 90% before removals.[33]

To reduce, capture, offset or remove?

Sustaining a perception that certain sectors are hard-to-abate increases the risk of industry members unnecessarily delaying emissions reductions. As noted, this in turn increases reliance on CDR to achieve mid-century net zero emissions. It also allows for industry reliance on forms of managing, rather than eliminating, emissions, principally carbon capture and storage/utilisation (CCUS) and carbon offsets.

The hard-to-abate conversation often confuses and conflates CDR and carbon management and overlooks their challenges. It is important to rectify this.

CDR refers to anthropogenic activities that remove CO_2 from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products. This creates net negative emissions. CDR includes technological processes—such as bioenergy with CCS (BECCS), direct air carbon capture and storage (DACCS)—and biological processes such as afforestation, reforestation, and enhanced rock weathering.

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[28] Net Zero Tracker, *Net Zero Stocktake 2023*.
[29] New Climate Institute and Carbon Market Watch, *Corporate Climate Responsibility Monitor 2024*.
[30] This paper analysed the ten largest companies by market capitalisation across eleven sectors, plus five additional companies from the cement or fertiliser sector.
[31] Arendt, "Residual Carbon Emissions in Companies' Climate Pledges."
[32] Transition Pathway Initiative Centre, *TPI State of Transition Report 2024*.
[33] Net Zero Tracker, *Net Zero Stocktake 2023*.

All IPCC-assessed 1.5°C compatible pathways rely on some degree of CDR to reach net zero emissions. However, achieving the anticipated levels may not be feasible or sustainable.[34] Excessive CDR involves environmental, technical and social risks, particularly around land requirements for afforestation and bioenergy crops.[35] The most robust strategy thus remains cutting emissions at source as fast as possible.[36]

Carbon capture and storage, meanwhile, refers to separating CO_2 from industrial or energy-related sources, transporting and injecting it into long-term geological storage, often depleted oil reservoirs or aquifers. Carbon capture and utilisation entails using captured CO_2, as a feedstock to other industrial processes or enhanced oil recovery (EOR), rather than permanently storing it. Both processes are often grouped as CCUS.

CCUS still creates net positive emissions. Only a fraction of CO_2 generated is prevented from reaching the atmosphere. The emissions from the combination of industrial facility and CCUS are only lower than if CCUS were not applied.

Members of sectors described as hard-to-abate, such as iron and steel and cement, lean heavily on CCUS for managing emissions considered unavoidable. Yet, as is also outlined, CCUS application has been disappointing, and its future emissions reduction impact seems limited.

Offsets purport to allow purchasers to counterbalance the emissions they generate by supporting the avoidance, reduction, or removal of atmospheric emissions elsewhere.[37] Offset projects purporting to avoid emissions are assessed relative to a hypothetical alternative, such as a renewable energy project built in place of fossil fuel power.

Projects purporting to reduce emissions include installing CCS on an industrial facility or fossil fuel power plant. Projects purporting to remove emissions deploy CDR approaches such as afforestation, reforestation, DACCS or BECCS. Issues with offsets are explored further in the Offsets section below.

Offsets are popular in industry, particularly in sectors described as hard-to-abate. Purchasers can typically avoid higher costs of eliminating emissions at source. Yet there is considerable doubt around offsets' mitigation effectiveness. UN HLEG advises that offsets "cannot be counted toward a non-state actor's [such as a company's] interim

[34] Climate Analytics, "2030 Targets Aligned to 1.5°C."
[35] Edelenbosch et al., "Reducing Sectoral Hard to Abate Emissions to Limit Reliance of Carbon Dioxide Removal in 1.5°C Scenarios."
[36] Climate Analytics, "2030 Targets Aligned to 1.5°C."
[37] Myles Allen et al., "The Oxford Principles for Net Zero Aligned Carbon Offsetting"; Josh Gabbatiss et al., "In-Depth Q&A: Can 'Carbon Offsets' Help to Tackle Climate Change?"

emissions reductions required by its net zero pathway."[38] It recommends companies instead "prioritise urgent and deep reduction of emissions across their value chain."

[38] UN High-Level Expert Group on Net Zero Emissions Commitments of Non-State Entities, *Integrity Matters: Net Zero Commitments by Businesses, Financial Institutions, Cities and Regions*.

Case study 1: Iron and steel

Iron and steel are critical to national industrialisation. Emerging industrial nations have historically been both leading producers and consumers of steel.

The iron and steel sector accounts for 7-8% of global greenhouse gas emissions. Globally, 1.89 billion tonnes of crude steel was produced in 2022.[39] Steel demand growth is expected to remain strong between now and 2050.

In 2022, China accounted for 54% of global crude steel production and 52% of finished steel use.[40] India, which accounted for 7% of production in 2022,[41] is the fastest growing steel producer, accounting for over one-third of global announced or under construction steelmaking capacity.[42]

Current process

For iron and steel, the decarbonisation potential, and thus the validity of hard-to-abate claims can best be assessed by considering its essential qualities and production processes.

Steel is an alloy of iron and carbon, typically with 0.1-2% carbon[43] depending on the grade of steel. There are two main steps in producing 'primary', i.e. non-recycled, steel: ironmaking and steelmaking. Ironmaking involves 'reduction' of iron ore (e.g. Fe_2O_3) into iron (Fe). This is facilitated by a reductant, most commonly carbon monoxide and/or hydrogen. Steelmaking involves converting iron to molten steel in a furnace powered by either fossil fuels or electricity.

Today, steel is produced via three main production routes: blast furnace to basic oxygen furnace (BF-BOF), direct reduced iron to electric arc furnace (DRI-EAF), and recycled scrap steel to electric arc furnace (scrap-EAF). Most steel (72% in 2022) is produced via the BF-BOF route, followed by scrap-EAF (21%) and DRI-EAF (7%).[44]

[39] World Steel Association, *World Steel in Figures 2023*.
[40] World Steel Association, *World Steel in Figures 2023*.
[41] World Steel Association, *World Steel in Figures 2023*.
[42] Armbruster et al., *Pedal to the Metal 2024. Building Momentum for Iron and Steel Decarbonization.*
[43] Bataille et al., *Facility Level Global Net-Zero Pathways under Varying Trade and Geopolitical Scenarios: Final Technical & Policy Report for the Net-Zero Steel Project, Part II*.
[44] World Steel Association, *World Steel in Figures 2023*.

The BF-BOF route is heavily reliant on fossil fuels, using coal as both fuel and reductant. Carbon monoxide produced from coke is used to reduce the iron ore to iron. Coke is derived from the emissions-intensive process of heating metallurgical coal above 1000°C. Coal typically also powers the BOF, in which smelting/steelmaking occurs. BF-BOF production generates CO_2 at all these stages, making it especially emissions-intensive.

In DRI-EAF steelmaking, iron ore is reduced in a direct reduction furnace in a solid, rather than molten, state using a reduction gas such as hydrogen or syngas (a blend of carbon monoxide and hydrogen, often derived from fossil fuels, e.g. steam methane reforming of fossil gas, or coal gasification). Iran and India each operate around a quarter of global DRI capacity. Most Middle Eastern DRI production is methane-based due to an abundance of cheap fossil gas. India operates mostly coal-based DRI furnaces.[45] As the name implies, electric arc furnaces are powered by electricity, which may be generated from either renewable or non-renewable sources.

BF-BOF and DRI-EAF are both primary steelmaking methods, requiring iron ore feedstock. Secondary steel is produced by feeding recycled scrap steel directly into an EAF (scrap-EAF). Scrap steel can also be used in primary steelmaking (BF-BOF and DRI-EAF) to supplement or reduce the amount of iron ore feedstock.

The share of steel produced in EAFs fell from 35% in 2001 to 28% in 2022 as new BF-BOF capacity outstripped growth in EAFs.[46] However, there has been a more recent shift to lower emissions production routes. Half of steelmaking capacity under development today is EAF-based.[47] Over a third of ironmaking capacity under development is DRI-based, though this is still mostly methane or coal-based.

[45] Armbruster et al., *Pedal to the Metal 2024. Building Momentum for Iron and Steel Decarbonization.*
[46] World Steel Association, *World Steel in Figures 2023*.
[47] Armbruster et al., *Pedal to the Metal 2024. Building Momentum for Iron and Steel Decarbonization.*

Most coal-based steelmaking capacity is in China, but India also has an enormous pipeline of planned BOF capacity

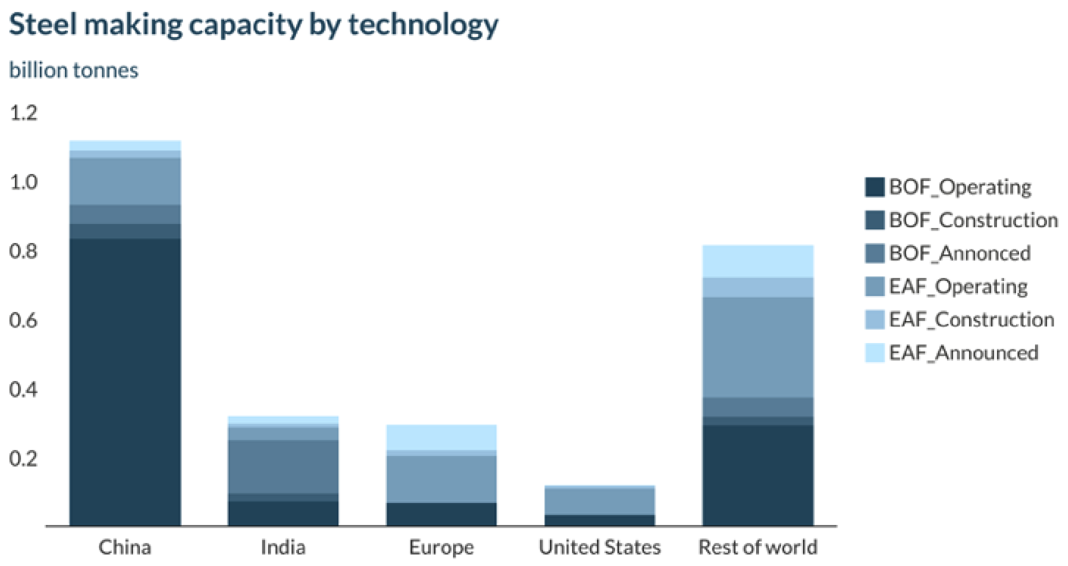

Figure 4: Global steelmaking capacity by region and technology. Source: Global Energy Monitor.[48]

Technology for zero emissions steel

Iron and steel is frequently described as a hard-to-abate sector. Yet technology exists today for low-to-zero emissions steel production at commercial scale. Policy support, including carbon pricing, targeted financial support, and further research and development, could help bring down costs and increase deployment relative to carbon—intensive production.

Secondary steel production via scrap-EAFs requires 2.1 GJ of energy per tonne of steel and results in 0.3 tCO_2/tonne steel produced (including indirect electricity emissions).[49] This is one-tenth of the energy and 86% lower CO_2 emissions than BF-BOF production requires. As electricity is decarbonised, the emissions intensity of this route will fall further. Secondary steelmaking is also more efficient from a material perspective than primary steelmaking, making it a priority route for sectoral decarbonisation.

The scrap-EAF route is well-established and currently accounts for around a fifth of steel production globally. But its expansion is limited by the availability of suitable quality scrap steel. EAF steelmaking is sensitive to impurities in recycled steel, particularly copper and

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[48] Global Energy Monitor, "Global Steel Plant Tracker."
[49] IEA, *Iron and Steel Technology Roadmap*.

tin content. Scrap availability is constrained by recycling rates and, in some cases, trade. The share of scrap-EAF steel production in 2050 could vary between 7-80% for individual countries, based on local scrap availability.[50]

On the primary steel production front, green hydrogen-based DRI-EAF steelmaking has significant potential for deep emissions reductions. When pure hydrogen is used as the reductant for DRI, the only byproduct is water vapour. If hydrogen is produced using renewable energy, i.e. green hydrogen, and the remainder of applications are electrified with renewable energy, net zero emissions, or 'green', steel is possible.[51]

H2 Green Steel is currently constructing a commercial-scale green hydrogen-based DRI-EAF plant in northern Sweden.[52] Production is expected to commence in 2025 and ramp up to 5 Mt/year of steel by 2030.[53] Globally, nine hydrogen-based DRI plants are under development, with operations set to commence between 2025-2030. A further 12 'hydrogen ready' DRI plants are under construction with plans to transition from fossil gas-based DRI.[54]

Green hydrogen-DRI development is promising. Yet widespread deployment is constrained by availability of cost-competitive green hydrogen. Green hydrogen produced from renewable energy via electrolysis accounts for only around 1% of hydrogen produced today. The cost of green hydrogen averages two to three times that of grey or blue hydrogen.[55]

More novel options for net zero steel production include aqueous/molten oxide electrolysis reduction, where electricity is used directly to reduce iron ore for EAF steelmaking. This route requires a small amount of supplemental carbon for strength, since this is not present in feedstock materials, unlike fossil-based steelmaking. Both aqueous and molten oxide electrolysis offer significant energy efficiency improvements compared to DRI and BF-BOF routes.[56] However, they are currently at a lower technical maturity.

Aqueous electrolysis was piloted at small-scale as part of the SIDERWIN programme, funded under the EU Horizon 2020 program. The process uses electrolysis powered by renewable energy to transform iron directly into steel plate and has the potential to reduce the carbon footprint of steel by more than 60%. ArcelorMittal and technology partner John Cockerill plan to build a demonstration scale project using the technology.

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[50] Climate Action Tracker, *Paris Agreement Compatible Sectoral Benchmarks Elaborating the Decarbonisation Roadmap*.
[51] Vogl et al., "Assessment of Hydrogen Direct Reduction for Fossil-Free Steelmaking"; Bataille et al., *Global Facility Level Net-Zero Steel Pathways*.
[52] "H2 Green Steel Raises More than €4 Billion in Debt Financing - Stegra."
[53] "H2 Green Steel to Build Green Steel Plant in Northern Sweden - Stegra."
[54] LeadIT, "Green Steel Tracker."
[55] IRENA, "Hydrogen."
[56] Bashmakov et al., "Industry."

Startup is targeted for 2027 with an initial production capacity of 40-80 kt of iron, intended to scale to 0.3-1 Mt.[57]

The DRI-EAF production route is also constrained in terms of feedstock. It requires a higher grade of iron ore (at least 67% iron content) compared to the BF-BOF route.[58]

Electric smelting furnaces (ESF), which are currently under development, have a higher tolerance than EAFs for lower grade iron ore.[59] However, unlike an EAF, the output from an ESF must still be refined into liquid steel for casting in either a BOF or EAF, limiting its utility for zero emissions steel production. The HIsarna process developed by Tata Steel is an example of the ESF route. Iron ore and coal are fed directly to the HIsarna reactor, replacing both the blast furnace and certain agglomeration steps (coking and sintering/pelletising). The HIsarna process has potential to reduce emissions by 20% relative to BF-BOF production.[60] Proponents claim CCS addition could increase this to 80%.[61]

There are, then, several alternative technological pathways for producing lower and potentially zero emissions steel. This already points to issues with the blanket application of a hard-to-abate label to the iron and steel sector. There is no non-substitutable carbon-emitting step in the production process that will inevitably produce residual emissions. Challenges with sectoral abatement are more associated with deploying these alternative technologies at the speed and scale required.

Blast furnaces, fossil DRI-EAF and CCS

Alongside cost and capacity constraints for net zero production, the dominance of the incumbent BF-BOF model is the other main factor informing the iron and steel's hard-to-abate classification. With 70% of steel currently produced in blast furnaces, and a relatively young global fleet of BF-BOF plants, there continues to be a heavy industry focus on deeply reducing emissions from these facilities. In China, where around half the world's steel is produced, the average age of operating BF-BOF plants is just 12 years, while the global average is 23 years.[62] This is relative to a typical blast furnace lifetime of 40 years.[63]

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[57] ArcelorMittal, "ArcelorMittal and John Cockerill Announce Plans to Develop World's First Industrial Scale Low Temperature, Iron Electrolysis Plant."
[58] Nicholas and Basirat, *Solving Iron Ore Quality Issues for Low-Carbon Steel*.
[59] "Pathways to Decarbonisation Episode Seven."
[60] Tata Steel, "HIsarna. Building a Sustainable Steel Industry."
[61] Bashmakov et al., "Industry."
[62] Armbruster et al., *Pedal to the Metal 2024. Building Momentum for Iron and Steel Decarbonization.*
[63] IEA, *Iron and Steel Technology Roadmap*.

Decarbonisation options for BF-BOF steelmaking are far narrower than for EAF-based steelmaking due to its heavy reliance on coal. They lean heavily on CCS.

Some companies are trialling hydrogen for co-firing in BF-BOFs at rates of up to 20-30%,[64] displacing some coal used for heat and reduction. The upper limit of hydrogen co-firing is set by the furnace stack integrity, with coke required to provide the structure and function of the blast furnace process. Nippon Steel is piloting this approach as part of it Course50 program.[65] However, given the ongoing need for a significant proportion of coke, this technology is not compatible with net-zero emissions without excessive CDR.[66]

Existing BF-BOF facilities might also be retrofitted with carbon capture technology. But research suggests this would struggle to capture more than 50% of facility emissions.[67] This is partly due to the numerous point sources of CO_2 in a typical BF-BOF plant, for example, from the BF, BOF, coke oven and sinter plant. This increases the process complexity and economic burden of capturing off-gases effectively.[68]

Retrofitting existing plants with CCS requires suitable geological storage in commercial proximity to steelmaking plants, which presents greater technical and economic challenges than the capture process itself. Because at least 50% of facility emissions would remain even with retrofitted CCS, this strategy alone is also incompatible with net-zero emissions without excessive CDR.[69]

New BF-BOF plants could theoretically incorporate bioenergy with carbon capture and storage (BECCS).[70] This would hinge on the contested assumption that BECCS can deliver net-negative emissions and thereby offset some of the residual emissions from BF-BOF steelmaking. It also assumes facilities would be purpose-built to minimise the number of CO_2 point sources. However, little assessment of the economic viability and sustainability of this option has been undertaken. BECCS is also untested, and there are serious concerns about the amount of biomass it would require, and the negative impacts on agricultural land and food security. Global steelmakers have not shown the

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64 Bataille et al., *Facility Level Global Net-Zero Pathways under Varying Trade and Geopolitical Scenarios: Final Technical & Policy Report for the Net-Zero Steel Project, Part II*.
65 Nippon Steel, "Promotion of Innovative Technology Development."
66 Bataille et al., *Facility Level Global Net-Zero Pathways under Varying Trade and Geopolitical Scenarios: Final Technical & Policy Report for the Net-Zero Steel Project, Part II*.
67 Fan and Friedmann, "Low-Carbon Production of Iron and Steel"; Bashmakov et al., "Industry."
68 Tanzer et al., "Can Bioenergy with Carbon Capture and Storage Result in Carbon Negative Steel?"; Fan and Friedmann, "Low-Carbon Production of Iron and Steel."
69 Bataille et al., *Facility Level Global Net-Zero Pathways under Varying Trade and Geopolitical Scenarios: Final Technical & Policy Report for the Net-Zero Steel Project, Part II*.
70 Fan and Friedmann, "Low-Carbon Production of Iron and Steel."

investment interest necessary to commercialise it by mid-century.[71] In summary, this is an implausible option given its misalignment with climate and sustainability objectives.

Some companies are also exploring CCS as an option for syngas-based DRI-EAF steelmaking. This is currently the dominant DRI production process and relies on either fossil gas or coal. CCS can be applied to capture part of the post-reduction CO_2 from the DRI process. This is the case at the Emirates Steel Arkan DRI-EAF in Abu Dhabi – one of only two steel plants with CCUS in operation today. The captured CO_2 is used by Abu Dhabi National Oil Company (ADNOC), for enhanced oil recovery.[72] The announced CO_2 capture capacity is 800 $ktCO_2$/year.

There is limited publicly disclosed data on the performance of this CCUS project. Investor presentations from Emirates Steel Arkan indicate capture of 30-45% of CO_2 emissions from the DRI plant, which are a subset of the total facility emissions.[73] Publicly disclosed corporate data indicates that less than 20% of total facility Scope 1 and 2 emissions were captured in 2020 and 2021.[74] This rate increased to 26% in 2022, but this was due to reduced facility emissions from procuring electricity from nuclear and solar power generation, rather than increased CCUS effectiveness.[75]

The other steel plant with operational CCUS facilities is the ArcelorMittal blast furnace facility in Ghent, Belgium. It is at the centre of several pilots and corporate partnerships investigating steel decarbonisation.

The €200 million "Steelanol" project commenced pilot operation in 2023. It aims to use captured CO_2 to produce ethanol, with an announced production capacity of 80 million litres per year. The project aims to reduce emissions from the blast furnace by 125 $ktCO_2$ per year, which equates to just 2% of the plant's total emissions.[76] However, CO_2 is still released when the ethanol is combusted.

A separate one-to-two-year pilot of a carbon capture unit commenced at the ArcelorMittal Gent blast furnace in May 2024.[77] The first phase intends to capture 300 $kgCO_2$ a day from blast furnace top gas – i.e. the equivalent of 110 tCO_2 per year. To put these CCUS trials into perspective, ArcelorMittal's Scope 1 and 2 footprint from steel facilities in 2023 was 108 $MtCO_2e$.[78]

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[71] Bataille et al., *Facility Level Global Net-Zero Pathways under Varying Trade and Geopolitical Scenarios: Final Technical & Policy Report for the Net-Zero Steel Project, Part II*.
[72] Scottish Carbon Capture & Storage, "Al Reyadah Details."
[73] Nicholas and Basirat, *Carbon Capture for Steel?*
[74] Nicholas and Basirat, *Carbon Capture for Steel?*
[75] Nicholas and Basirat, *Carbon Capture for Steel?*
[76] Nicholas and Basirat, *Carbon Capture for Steel?*
[77] ArcelorMittal, "Trial Carbon Capture Unit Begins Operating on Blast Furnace at ArcelorMittal Gent, Belgium."
[78] ArcelorMittal, *Fact Book 2023*.

Expectations for CCS in the steel sector must be anchored against the current project pipeline of CCS projects. The combined announced capacity for CCUS projects that are operating, planned or under construction in the steel sector is 9 $MtCO_2$/year.[79] This is just 0.3% of total steel sector emissions of 2.6 $GtCO_2$/year in 2022.[80]

Aside from two operational CCUS projects in the global iron and steel sector, there are 11 planned projects and one (two-stage) project under construction.[81] This is compared to more than 1000 steel plants operating or under development globally.[82]

The World Steel Association is doubtful that CCUS on its own will be able to make a "material impact" to net zero emissions.[83] The very low number of new projects underway, or even planned, appear to reflect this view.

Considerable economic, political, and other challenges motivate the sector's resistance to substituting fossil- with renewable-based iron- and steelmaking. Yet regulatory requirements and complementary enabling frameworks could help overcome most of these. In their continued absence, industry members profess significant faith in CCUS for decarbonising BF-BOF production. But this shows little promise of helping achieve the deep decarbonisation necessary to put iron and steel on a 1.5°C-aligned pathway.

If policies and regulations to support low emissions production and restrict high emissions production are put in place, the iron and steel sector could reduce emissions quickly and have minimal residual CO2 emissions by 2050.

The need for demand reduction and whole-of-system policies

Transitioning the iron and steel production process towards net zero compliance is mostly a challenge of quickly scaling up 'green' production assets and retiring 'brown' assets. The final product of rival processes has the same essential characteristics and end uses, though differences in production methods brings new cost and technical considerations. Production-centric challenges need not, however, lead to overemphasis on CCUS to decarbonise BF-BOF steel plants or other carbon-intensive assets. As well as opportunities for timely replacement of steelmaking capacity outlined above, there are opportunities to significantly reduce steel demand.

A rising share of secondary steel in consumption will already mitigate demand for new iron ore or, more importantly, iron, as the most-intensive production stage. Demand for

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[79] IEA, "CCUS Projects Database."
[80] IEA, *World Energy Outlook 2023*.
[81] IEA, "CCUS Projects Database."
[82] Global Energy Monitor, "Global Steel Plant Tracker."
[83] World Steel Association, *Carbon Capture and Use and Storage (CCUS) Factsheet*.

iron and steel in aggregate could also be significantly reduced relative to baseline projections.

In the IEA's NZE scenario, the scrap share of metallic inputs to steel rises from 33% in 2022 to 48% by 2050. Steel production rises from 1892 Mt in 2023 to 1954 Mt in 2035, but falls to 1925 Mt by 2050. This compares with the IEA STEPS scenario, in which steel production continually rises from 2023, to reach 2424 Mt in 2050.[84] The 20% of avoided demand by 2050 in the NZE scenario is achieved through material efficiency strategies, including increasing steel and product manufacturing yields, light-weighting vehicles, extending building lifetimes and direct reuse of steel without melting.[85]

Demand reduction strategies, combined whole-of-system approaches, with more significant policy intervention, can enhance at-source emissions reduction. Lei et al. found business-as-usual iron and steel plant operation would generate a cumulative 106.3 $GtCO_2$ over 2020-2050. The potential to reduce this total varied considerably depending on the timeline of replacing high with low emissions production. As little as a 47% reduction could result cumulatively over this period, if low carbon strategies were applied five years later than scheduled plant retrofitting allowed, but up to 66% reduction was possible if available solutions—including advanced deployment of 100% green hydrogen-based production and targeted CCUS—was applied five years ahead of scheduled retrofitting.[86]

Wang et al. noted the GHG intensity of iron and steelmaking decreased ~67% between 1900-2015 through process efficiency, but net emissions increased 17 times, in line with a 44-fold increase in production. The study concluded that 'spatial-temporal' factors were most responsible for iron and steel's considerable emissions growth since 1995 in particular. The locus of production shifting to emerging economies, which had higher carbon intensity primary production and insufficient generation of scrap steel for secondary production, outweighed any generic sense of the industry being hard-to-abate. Wang et al. argued for global whole-of-system approaches to integrate ambitious supply- and demand-side measures, to help align iron and steel with 1.5°C warming. For example, the study noted that significant demand-side potential lay in lighter vehicle construction, which could reduce steel requirements by a factor of four.[87]

Ellen McArthur Foundation has also assessed considerable emissions savings as possible through a range of steel demand-reducing circular economy strategies. This includes reducing the 'overspecification' of steel content in construction projects, which leads to about 35-45% higher use than strictly necessary. A combination of materials efficiency,

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[84] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[85] IEA, "Iron & Steel."
[86] Lei et al., "Global Iron and Steel Plant CO2 Emissions and Carbon-Neutrality Pathways."
[87] Wang et al., "Efficiency Stagnation in Global Steel Production Urges Joint Supply- and Demand-Side Mitigation Efforts."

substitution, and circularity strategies was estimated capable of avoiding 500 Mt of primary steel demand, and more than 1 $GtCO_2$ of emissions, per year by 2050.[88]

Assessing iron and steel's hard-to-abate claims

There is proven capacity to produce iron and steel with low to zero emissions. Maximising rates of recycled steelmaking and accelerating development and deployment of alternative net zero technologies are critical. Enhancing the cost-competitiveness for green steelmaking is a priority.

The dominance and relatively young fleet of BF-BOF steel plants, and the sizeable pipeline of new BF-BOF plants, has seen considerable industry focus on decarbonising these assets. However, there are limited options for doing so. Many industry members have put considerable faith in CCS, but it is unlikely to achieve the deep decarbonisation required for a 1.5°C-aligned steel sector.

Rapidly phasing down BF-BOF capacity is necessary for a 1.5°C compatible steel sector.[89] No new BF-BOF plants should be built, and some existing plants must be decommissioned before the end of their economic life. This is particularly true in China, which has a relatively young fleet of emissions-intensive blast furnaces.

Encouragingly, China issued no new permits for coal-based steelmaking in the first half of 2024.[90] New projects totalling 7.1 Mt/year steel production capacity were approved, but all were EAF projects. Emissions from the Chinese steel sector are forecast to fall 200 $MtCO_2$ by 2025 due to reduced output and increased scrap-EAF secondary steel production. This is approximately equal to annual EU steel emissions.

BF-BOFs require furnace relining every 15-25 years,[91] at a capital cost of one-third to one-half of constructing a new blast furnace. This also incurs several months of lost production revenue during the relining process.[92] This provides opportunities for decisions that can either lock in or retire carbon-intensive production, including, potentially, via investment in marginal abating CCS technology.

There are numerous examples of relatively quick steel industry adoption of new technologies even absent a climate incentive. The BOF replaced previous open-hearth furnaces in a two-decade period beginning in the 1960s, and the period between its conceptualisation and implementation was just five years.[93] Steelmaking also suffers

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[88] Ellen MacArthur Foundation, *Completing the Picture*.
[89] Climate Action Tracker, *Decarbonising Steel - National Circumstances and Priority Actions*.
[90] Shen and Schäpe, *Turning Point: China Permitted No New Coal-Based Steel Projects in H1 2024 as Policies Drive Decarbonisation*.
[91] Bashmakov et al., "Industry."
[92] Vogl et al., "Phasing out the Blast Furnace to Meet Global Climate Targets."
[93] Bowen and Wyche, *Australia's Green Iron Key*.

persistent overcapacity through subsidisation of otherwise unprofitable operations. This provides another pivot point for retirement of emissions-intensive capacity.

Lei et al. found that the pace at which these opportunities are seized could mean the difference between iron and steel being on or off a 1.5°C-aligned pathway. Government interventions have proven ability to quicken the pace of industry action. EU policies and regulations—such as strong carbon pricing, public 'de-risking' of investments, and demand-creating advanced market commitments and life-cycle emissions regulations on steel-using cars—have been critical to the success of projects such as H2 Green Steel.

There is also considerable potential, and likely need, to meaningfully reduce demand for iron and steel, limiting the need for primary production. Materials efficiency, substitution, and circularity in construction and manufacturing could particularly weaken the case for retaining BF-BOF production through CCUS. In the IEA's NZE scenario, strategies to reduce demand—such as increasing scrap use, light weighting vehicles, and extending the lifetime of steel-containing products—are projected to reduce overall steel demand by 20% by 2050.

The claim that iron and steel production as a whole is hard-to-abate is, therefore, misleading. This mainly rests on the incumbency advantages of a particularly fossil fuel-intensive production route, for which there are technologically viable substitutes. There is limited potential to adapt dominant BF-BOF route to a 1.5°C pathway means that CCUS is not a justified solution and entails risk of serving as delaying tactic to avoid stranded assets. Policy options exist for accelerating the retirement and replacement of hard-to-abate capacity and, with it, the overall perception of iron and steel as hard-to-abate.

Case study 2: Cement

Cement, particularly as a component of concrete, is ubiquitous in modern life. Around 4 Gt of cement are consumed each year for producing concrete, mortars, and plasters. The world consumes over 30 Gt of concrete per year, making this the second most widely consumed material after water.[94]

The cement sector contributes 5-8% of global CO_2 emissions.[95] Recent studies have estimated cement production is responsible for 2.1–2.5 $GtCO_2$/year.[96]

Globally, cement production has increased nearly fourfold since 1990, outpacing growth in fossil energy production over the last two decades. China accounted for more than 74% of global growth since 1990.[97] China continues to produce over half the world's total cement, with some provinces (Shandong, Guangdong) producing around the same amount of cement as all EU member states combined.[98]

Current process

It is again necessary to study the essential characteristics and production processes for cement to assess its decarbonisation potential and hard-to-abate legitimacy.

Cement is the mineral glue which holds together a mix of aggregates such as sand, gravel and stones, to make concrete. An intermediate product, clinker, is the largest cement component. Historically, almost all cement was Portland cement, which is typically 95% clinker. The global average clinker ratio has fallen from approximately 83% in 1990 to 71% today as use of blended cements with lower clinker ratios has become more widespread.[99]

Clinker production is especially emissions-intensive and critical to cement's designation as a hard-to-abate sector. Clinker production accounts for 90% of total CO_2 emissions

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[94] Nature, "Concrete Needs to Lose Its Colossal Carbon Footprint."
[95] Farfan et al., "Trends in the Global Cement Industry and Opportunities for Long-Term Sustainable CCU Potential for Power-to-X."
[96] Andrew, "Global CO2 Emissions from Cement Production"; Cheng et al., "Projecting Future Carbon Emissions from Cement Production in Developing Countries"; World Economic Forum, *Net-Zero Industry Tracker 2023 Edition*; Chen et al., "A Striking Growth of CO2 Emissions from the Global Cement Industry Driven by New Facilities in Emerging Countries."
[97] Andrew, "Global CO2 Emissions from Cement Production, 1928–2018."
[98] Liao et al., "China's Provincial Process CO2 Emissions from Cement Production during 1993–2019."
[99] Andrew, "Global CO2 Emissions from Cement Production, 1928–2018."

from cement. The remainder are indirect emissions from electricity used for crushing, grinding and blending, and from transportation fuels.[100] Clinker is produced by heating ground limestone and other cementitious materials, such as clay, in a rotary kiln to about 1450°C. The energy used to heat the kiln to high temperatures is typically provided by fossil fuels, mostly coal, and accounts for around 40% of clinker production emissions.[101] The other 60% comes from direct process emissions from limestone ($CaCO_3$) decomposition into calcium oxide (CaO) and CO_2, also known as 'decarbonation' or 'calcination' of limestone.

To produce cement, clinker is ground and combined with supplementary cementitious materials (SCMs) and gypsum.

Cement also absorbs CO_2 over its decades-long lifetime, in a process known as 'carbonation', creating a carbon sink. Total cement carbonation is a function of global cement stock and is therefore dictated by both current and previous cement production. Cement carbonation is calculated to have increased from an average of 67 $MtCO_2$/yr in the 1960s to an average of 721 $MtCO_2$/yr in the decade to 2022.[102]

Reducing process emission from cement

Direct process CO_2 emissions are integral to the chemical transformation that produces clinker, i.e. limestone decarbonation, and cannot be reduced through efficiency measures or fuel switching. Reducing at-source process CO_2 emissions from cement requires reducing demand for clinker through a combination of material efficiency, material substitution, or alternative chemistries.

The ratio of clinker in cement can be reduced by using a greater share of SCMs such as blast furnace slag from coal-based steelmaking, coal fly ash from coal power, or natural pozzolanic materials.[103] SCMs can already theoretically make up 30-50% of blended cement by weight and options for higher concentrations are being investigated. But, due to factors including limited availability of raw materials, concentrations of 25% are typical today.[104] Availability of fossil-derived derived SCMs is likely to further decrease as coal-based steelmaking and power generation are phased out.

Combining calcined clay with fine limestone (also known as LC3) is another option for replacing traditional clinker. Use is in early commercial operation today and is expected

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[100] Pamenter and Myers, "Decarbonizing the Cementitious Materials Cycle," 2021.
[101] Bashmakov et al., "Industry."
[102] Friedlingstein et al., "Global Carbon Budget 2023."
[103] Bashmakov et al., "Industry."
[104] Habert et al., "Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries."

to play an increasing role as the availability of fossil-based SCMs declines.[105] LC3 substituting for clinker could reduce emissions by 15-30%.[106]

The current known technical minimum clinker content in bended cements for most cement applications is 50%.[107] Cementitious substitution is limited by both availability of raw materials and cementitious reactivity.[108] Since the global average clinker ratio has already fallen to 71%, the mitigation potential from reaching the maximum content of SCMs or LC3 remains limited. [109]

Investigations into alternative binders based on materials other than limestone are ongoing, with great variation in mitigation potential and technical maturity. Deep decarbonisation is possible with alkali-activated binders (geopolymers) and magnesium oxides derived from magnesium silicates (MOMS).

Alkali-activated binders are commonly derived from industrial wastes such as coal fly ash and blast furnace slag and are in early commercial operation today. Alkali-activated binders have the potential to reduce process emissions by up to 80-90% relative to Portland clinker, depending on materials and processes used.[110] MOMS-based cements can, in theory, produce a carbon negative outcome by absorbing more CO_2 while curing than that released during the production process. However, MOMS development has been stuck in early R&D stages for many years.[111]

Other alternative binders including carbonatable calcium silicate clinkers, calcium sulfoaluminate cement, and belite ye'elimite-ferrite, could reduce process emissions by 7-48% relative to OPC clinker.[112]

US-based startup Brimstone claims to have produced net zero emissions cement, at laboratory-scale, which is chemically and physically equivalent to Portland cement.[113] In place of limestone, its process relies on the chemical decomposition of calcium silicate, e.g. from basalt, to produce calcium oxide (CaO) and magnesium byproducts. Brimstone claims the magnesium byproducts reattach free CO_2 from the air. This could produce carbon negative cement if it realised at commercial scale. The US Department of Energy

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[105] IEA, *Energy Technology Perspectives 2023*.
[106] Habert et al., "Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries."
[107] IEA, *Energy Technology Perspectives 2023*.
[108] Pamenter and Myers, "Decarbonizing the Cementitious Materials Cycle," 2021.
[109] Andrew, "Global CO2 Emissions from Cement Production, 1928–2018."
[110] Lehne and Preston, *Making Concrete Change: Innovation in Low-Carbon Cement and Concrete*.
[111] IEA, "ETP Clean Energy Technology Guide."
[112] Lehne and Preston, *Making Concrete Change: Innovation in Low-Carbon Cement and Concrete*.
[113] IEA, *Energy Technology Perspectives 2023*.

recently provided Brimstone with USD 189 million in federal investment to build a pilot facility with a production capacity up to 140 kt of cement.[114]

The cement sector differs from iron and steel in that there are less obvious technologically feasible replacements for fossil fuel-based process emissions. There are, however, certainly options to significantly reduce clinker-related emissions through materials efficiency, materials substitution, and alternative chemistries.

Unfortunately, however, the current policy landscape does not incentivise accelerated pursuit of these options. The EU's Emissions Trading Scheme, for example, provides free allowances covering up to 100% of emissions from cement production, shielding it from carbon pricing due to carbon leakage fears. Emissions reductions benchmarks and building and construction sector codes and standards also remain largely based on Portland clinker production methods, which disincentivises alternative routes, even where resulting products can meet established needs.[115]

Reducing energy emissions from cement

The difficulty of abating process emissions—whether for technological, policy or other reasons—should not overshadow the significant reductions possible in cement's energy-related emissions. These can be mitigated through a combination of energy efficiency measures and fuel switching to low or zero-carbon fuels for process heating. The decarbonisation potential from these strategies is up to 40% that of clinker production emissions,[116] i.e. 100% of energy-related emissions.

Cement sector energy efficiency has already improved in recent decades, notably by switching from wet to dry kilns to eliminate energy-intensive water evaporation. However, cement manufacturing still sees significant heat loss of about 35-40%.[117] Waste heat recovery, increasing the proportion of dry and semi-dry processes, and switching to more efficient grinding, could further improve energy efficiency.[118]

Currently, fossil fuels provide around 91% of total energy demand for clinker production (coal alone provides 82%). Renewable and non-renewable waste streams each contribute around 4% of energy demand.[119] Fossil fuels can be substituted with waste-derived fuels, bioenergy, hydrogen and electricity for generating kiln heat.

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[114] Brimstone, "Industrial Demonstrations Program Selects Brimstone for Transformational $189 Million Federal Investment to Decarbonize Cement Industry."
[115] Bashmakov et al., "Industry."
[116] Bashmakov et al., "Industry."
[117] Fennell et al., "Decarbonizing Cement Production."
[118] Mission Possible Partnership, *Making Net-Zero Concrete and Cement Possible*; Fennell et al., "Decarbonizing Cement Production."
[119] Mission Possible Partnership, *Making Net-Zero Concrete and Cement Possible*; IEA, "Cement."

Waste-derived fuels and biomass are already widely commercially deployed. The EU is a leader in this regard, with waste and forestry residues commonly supplying 40% of the energy to a typical cement kiln.[120] However, this option is limited by competing demands for sustainable biomass within the energy system. One study found that using 90% biomass in cement kilns across Europe would require 19% of the total potential sustainable agricultural and forest residues available in Europe.[121]

Kilns heated via concentrated solar power (CSP) are under development at the full prototype stage. CEMEX and Synhelion successfully produced solar-powered clinker in a 2022 pilot.[122] Direct electric heating, for example via resistance-based heating, is also under development at the large prototype stage but not yet competitive with fuel switching.[123] Hydrogen use for process heat is also under development at a similar level of maturity but is not expected to be able to fully displace fossil fuels alone.

Approaching zero emissions cement

Given the challenges in fully eliminating process emissions, material efficiency strategies to reduce clinker ratios in cement and cement ratios in concrete are an important pillar of cement and concrete decarbonisation.

Reducing overall utilisation of cement could include limiting concrete use to essential applications e.g. where its compressive strength and corrosion-resistance is vital. Cement could otherwise be replaced with building material alternatives, such as wood and stone. Material substitution and reducing overbuilding could reduce cement demand by 20-30%.[124]

Cement demand can also be reduced by making stronger concrete, through multi-sized aggregates and better mixing. This minimises the cement amount required for binding. The application of proper mixing and aggregate sizing can reduce emissions by up to 50% without compromising the strength or fluidity of the concrete.[125]

Habert et al. found the combined effect of incremental improvements in cement production, including clinker substitution, alternative binders, alternative fuels, kiln efficiency, and efficient material use, could reduce cement emission by around 50%.[126] Similarly, the IPCC estimates around 55% of cement emissions can be reduced through

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[120] Lehne and Preston, *Making Concrete Change: Innovation in Low-Carbon Cement and Concrete*.
[121] Cavalett et al., "Paving the Way for Sustainable Decarbonization of the European Cement Industry."
[122] IEA, "ETP Clean Energy Technology Guide."
[123] IEA, "ETP Clean Energy Technology Guide."
[124] Bashmakov et al., "Industry."
[125] Habert et al., "Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries."
[126] Habert et al., "Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries."

a combination of material and energy efficiency, clinker substitution, novel cements, fuel switching and electrification.[127] The IEA's NZE scenario would see a 46% reduction in CO_2 emissions between 2022 and 2050 before considering CCUS, taking into account increased demand reduction and decarbonised production measures.[128]

Towards a whole-of-system approach

Traditional supply-side interventions, such as reducing clinker ratios, improving kiln efficiency, and switching to alternative fuels, while essential, are not sufficient on their own to achieve a 1.5°C-aligned cement sector. A whole-of-system approach that targets more ambitious production breakthroughs, alongside extensive demand reduction, could make far more progress. This can be achieved without considerable dependence on CCUS applied to kiln flues.

The importance of reducing cement demand in a rapid but targeted manner appears critical in light of two facts:

- Cement production generates the highest CO_2 emissions per unit of revenue of any industry. When combined with challenges in overhauling production processes, this severely limits industry support for supply side transformation[129]
- Somewhat counterintuitively, cement-based materials such as concrete have a carbon intensity per tonne "much lower than almost all alternative" building and construction materials, while cement itself has middle-range carbon intensity. This means cement's overall carbon footprint mostly results from the enormous quantities in which it is used, including as a share of end use products.[130]

Some trends already in motion are promising in this context. Primarily, China's cement output is in steep decline in response to slowing economic growth and structural adjustment away from materials-intensive development. A middle-of-the-road projection is that, absent policy interventions, Chinese cement production could reach 900 Mt/year in 2050, down from about 2 Gt/at present.[131] However, this will still be off the net zero pace, and cement demand is still likely to rise in other emerging economies.

Cao et al. present a more ambitious perspective on China and two other major cement markets' future emissions, USA and India. It finds that satisfying demand in line with a net zero emissions pathway is possible in China, India and the USA (comprising ~67% of global demand), with only 18% of production capacity needing CCUS in 2060. Besides representing two-thirds of global cement demand, these countries also span a very wide

[127] Refer Figure 11.13 in Bashmakov et al., "Industry."
[128] IEA, "Net Zero Roadmap."
[129] Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, *Laying the Foundation for Zero-Carbon Cement*.
[130] {Citation}
[131] "Global Cement Volume Forecast Report (GCVFR)."

range of national income levels, so that there is reason to assume that the identified feasible mitigation measures in these countries would apply for most of the rest of the world as well.

The study combines aggressive pursuit of conventional and innovative abatement routes in production, with far-reaching demand-side strategies, including material-efficient design, material substitution, extended lifetime of structure and reuse of concrete components. In this 'whole-systems' scenario, emissions would be reduced by 72% by 2050, without cement plant CCUS, compared to 2018.

This compares with the study's scenario with more emphasis on production-side measures, where 100% of cement plants would require CCUS and emissions would only fall by 28% by 2050 from non-CCUS measures alone.[132] More research is needed to explore the applicability of this approach of increased adoption of demand-side intervention to reduce residual emissions in this sector without much relying on CCUS.

Cao et al.'s whole-systems scenario does include CO_2 curing and mineralisation (a form of CO_2 utilisation) captured from sources such as power or cement plants themselves. This approach may still not fully align with broader economy-wide net-zero ambitions, as it remains uncertain whether all captured CO_2 will be utilised for curing and mineralisation, or where it will be deployed if not. This study shows that with CO_2 curing and mineralisation, emissions would be reduced by 98% by 2050, without any direct CCS at the cement plant, compared to 2018.

Applying the same assumptions for adoption of demand-side strategies in countries as economically and culturally distinct as the USA, China, and India could also obscure important differences. While a common framework might provide a high-level picture, more research is needed to adjust assumptions to reflect each country's unique context, construction practices, and policy environment.

Watari et al. also highlights the importance of demand-side strategies in cement decarbonisation, using a Japanese context. This includes a finding that if demand-side strategies are implemented at 80% of their technical potential, the need for CCUS in decarbonising the Japanese cement sector can be completely avoided. This shifts the narrative from a heavy dependence on emerging CCUS technologies to a more holistic approach that emphasises the efficient use of materials and cross-sectoral collaboration.

Watari et al.'s assumption of a drastic reduction in cement demand, while ambitious, may be challenging in other economies, particularly rapidly growing and urbanising regions. Japan's mature infrastructure and demographic trends support the plausibility of declining demand domestically, which can be assumed to be applicable to many other high-income countries with low population growth as well. Therefore, while the study

[132] Cao et al., *Decarbonizing Concrete: Deep Decarbonization Pathways for the Cement and Concrete Cycle in the United States, India, and China*.

offers valuable insights for Japan, it may benefit from further exploration of how these strategies can be adapted to fit the diverse economic and developmental contexts of other countries.

CCUS in the cement industry

Process-related CO_2 emissions are integral to producing clinker. Reducing these emissions will require transformative change in both cement production and consumption. But, rather than considering these, cement decarbonisation strategies tend to rely heavily on the future rollout of CCUS at scale. As with iron and steel, assessments of CCUS potential for cement must be grounded in current observations.

It is first important to note that CCUS will be the most expensive component of net zero-compliant cement production. The IEA estimates cement-linked CCS has an abatement cost of USD 60-120/tCO_2.[133] By contrast, the Council of Engineers for the Energy Transition estimates four existing cement decarbonisation levers (efficient design, construction, and concrete production; decarbonised cement and binders; fuel switching; and energy efficiency) could deliver up to 70% of cement emissions savings, at a combined abatement cost of less than USD 20/tCO_2.[134]

There are no currently operating commercial-scale CCUS projects in the cement industry, though 48 were planned or under construction as of 2024. These have a combined announced capacity of 36 $MtCO_2$/year.[135] This compares with 2.4 $GtCO_2$/year total cement sector energy and process emissions in 2022,[136] and the 1.3 $GtCO_2$/year capture in 2050 for the cement sector in the IEA's NZE scenario.[137]

Heidelberg Materials has taken final investment decisions on two CCUS projects. The first is a retrofit of its existing cement plant in Brevik, Norway, which is expected to come online in 2025. Heidelberg Materials aims to capture 400 $ktCO_2$ /year,[138] halving emissions from the cement plant. The captured CO_2 is intended to be permanently stored in an aquifer in the North Sea as part of the Northern Lights project.

Heidelberg Materials also took a final investment decision on the Leilac-2 project in early 2022, but construction is yet to commence. Leilac-2 is planned as a retrofit to Heidelberg Material's existing facility in Ennigerloh, Germany, and is currently slated to commence operations in 2026.[139] It follows the Leilac-1 project in Belgium, both of which employ a novel method of limestone calcination. In the Leilac process, limestone

[133] IEA, *Is Carbon Capture Too Expensive?*
[134] Council of Engineers for the Energy Transition, *Decarbonizing the Cement and Concrete Sector*.
[135] IEA, "CCUS Projects Database."
[136] IEA, *World Energy Outlook 2023*.
[137] IEA, *World Energy Outlook 2023*.
[138] IEA, "CCUS Projects Database."
[139] Heidelberg Materials, "CCUS: More Future with Less CO_2."

calcination occurs in a steel vessel that is heated indirectly using fossil gas. It produces a relatively pure CO_2 waste stream, reducing the energy required for CO_2 capture and purification. According to industry claims, the Leilac process combined with CCUS could reduce emissions by up to 85% compared to traditional cement production, though these figures should be approached with caution until independently verified.[140]

The Leilac-1 and Leilac-2 projects have received a combined €28m in funding from the EU's Horizon 2020 programme.[141] The Leilac-2 facility has an announced capacity of 100 ktCO_2 /year but there are "no current plans to actually store or use the CO_2 from Leilac-2".[142]

Despite the lack of commercially viable and operationalised CCUS facilities for cement, many industry members remain confident of its potential. In its 2050 industry roadmap, for example, the European Cement Association projects that by 2050, the "total use of the different carbon capture techniques will reduce CO_2 emissions by 42%."[143] However, such claims require careful scrutiny, as they are based on projections from industry bodies whose interests are often tied to the continued promotion of CCUS technologies.

Assessing cement's hard-to-abate claims

Relatively limited progress has been made to date in decarbonising the cement sector. The difficulty in eradicating process emissions associated with clinker production suggests the sector has earned the hard-to-abate moniker. Once again, however, this tells an incomplete story and risks serving as justification for delay.

Clinker production accounts for 60-70% of cement emissions, yet the 40% of this linked to energy use can theoretically be eliminated. Numerous strategies also exist for reducing clinker usage and its remaining unavoidable process emissions. This includes comparatively straightforward material efficiency measures, e.g. targeted material use and improved aggregate sizing in concrete.

However, there is currently little momentum behind these measures. Cement is a cheap, profitably produced, and widely available material and eliminating its emissions will be more expensive than for most sectors. Sector strategies to decarbonise cement production lean heavily on CCUS as a primary mitigation strategy, with little near-term action. This, in turn, reinforces the hard-to-abate narrative.

There is strong industry reluctance to transition away from a successful business model. In the absence of a strong carbon-pricing signal or other regulatory sticks and carrots,

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[140] Bashmakov et al., "Industry."
[141] Leilac, "Leilac-2"; Leilac, "Leilac-1."
[142] Leilac, "Leilac-2."
[143] CEMBUREAU, "Cementing the European Green Deal."

there is little short-term incentive to make changes. Alternative binders have been under development for many years but are yet to be commercially realised. Some project proponents cite a lack of research and development funding as contributing to this.[144]

Replacing more clinker with SCMs or pursing alternative cement chemistries face genuine barriers to commercialisation, including ingrained building standards, regulatory barriers, more limited material availability, and lack of profitability.

But similar claims might be made of CCUS, which remains the industry-preferred climate solution. Deploying CCUS at the scale and reliability required by some scenarios will be exceedingly difficult. Waiting for breakthroughs that may never arrive can disincentivise short-term investment and investigation of nascent technologies.

The cement sector is, therefore, emblematic of how the hard-to-abate label interacts with impressions of the indispensability of certain economic activities. There are valid reasons why global consumption of cement-containing concrete is second only to water. Yet this does not imply that cement and concrete, at least not in the way they are currently produced, are anywhere near as vital to humanity as water. It does not imply industry members and policymakers can ignore options for transformative change.

Addressing cement decarbonisation requires a comprehensive approach that moves beyond the conventional hard-to-abate view. While improving production efficiencies is crucial, it is equally or even more important to examine the entire lifecycle of cement, including the impact of demand management, end-use applications, and material substitution. A holistic perspective enables the identification of innovative solutions, such as circular economy principles and sustainable construction practices, which can significantly reduce cement's carbon footprint without overly relying on CCUS.

By integrating demand-side strategies and considering broader socio-economic and environmental impacts, stakeholders can foster a more resilient and sustainable cement industry that aligns with global climate goals. This multifaceted approach could not only enhance the effectiveness of decarbonisation but also contribute to economic growth and social wellbeing across various regions, challenging the notion that cement production must remain a significant source of emissions. Ultimately, moving beyond a narrow focus on production to embrace a more comprehensive strategy is essential for achieving meaningful progress in cement sector decarbonisation.

[144] IEA, "ETP Clean Energy Technology Guide."

Avoiding strategies of delay

Sectors such as iron and steel and cement face challenges rapidly reducing emissions relative to others. But, as outlined above, applying the hard-to-abate term to these sectors is misleading at best. Both can make significant short-term emissions reductions. Iron and steel can effectively reach zero CO_2 emissions by 2050. Cement emissions can also be dramatically reduced if transformative action were taken across the sector.

The hard-to-abate label obscures viable options for significant emissions reduction that already exist or would be “technically and scientifically feasible” to deploy by mid-century with appropriate policy support.

Comparative analysis of iron and steel with cement also reveals how the hard-to-abate term can obscure sector-specific challenges and opportunities.

There are identified technological pathways for zero emissions iron and steelmaking. There are obstacles to implementing these, but they could be overcome. There is primarily a need to accelerate deployment of new, and retirement of old, assets, in particular blast furnaces.

Technology and policy options for substantially reducing cement sector emissions by 2050 are more complicated. This likely cannot be done by simply overhauling the cement production process itself. It must instead involve a suite of transformative measures outlined above. Nevertheless, it is clear even cement can achieve significant reductions in the next decade and relatively small residual emissions by 2050.

Comparative analysis of iron and steel and cement also suggests how policy support can help shift the impression of sectors from being hard-to-abate to easy-to-abate. EU support has, for example, been critical to zero emissions iron and steel advancing most quickly in Sweden and elsewhere in Europe. The EU has, however, applied noticeably less pressure and provided less incentive to cement sector decarbonisation, which, idiosyncratic challenges notwithstanding, has significantly lagged.

These are important lessons when assessing where industries or companies might sustain mid-century residual emissions and require compensation with CDR. It is possible for steel and iron to largely avoid this need, and to minimise it for cement.

Importantly, these pathways are based on achieving real emissions reductions, rather than relying on managing emissions through CCUS or offsets. Continued industry recourse to these might thus be considered strategies of delay.

Carbon capture, utilisation and storage

Some of the specific challenges of over-relying on CCUS in the iron and steel and cement sectors have already been covered. It is, however, worth considering some of the issues and challenges facing CCUS in more detail. CCUS has been presented as key to eradicating 'hard-to-abate' emissions across a wide range of economic sectors.

Outlook

The IEA has now released three revisions to its NZE scenario, first published in 2021.[145] Each subsequent revision has downgraded projections for CCUS in 2050. The latest NZE scenario includes total CO_2 captured of 1.0 $GtCO_2$/year in 2030 and 5.9 $GtCO_2$/year in 2050.[146] This is a 39% and 22% reduction in the outlook for CCUS in 2030 and 2050, respectively, compared to the first NZE scenario, published just three years earlier.

The IEA has also reduced the specific role it expects CCUS to play in both the cement and steel sectors. Between the 2021 and 2023 NZE reports, the projection for CO_2 captured in steel in 2050 decreased 40%, to 399 $MtCO_2e$/year.[147] This corresponds to a reduction in primary steel production equipped with CCUS in 2050 from 53% to 37%. The IEA has simultaneously revised its outlook for hydrogen-based DRI-EAF production in 2050 from 29% to 44%. The outlook for CCS in the steel industry in 2030 was cut even more sharply, by 61%.

The IEA retained a similar projection for the CCS role in the cement industry in its latest NZE report, at 1.3 $GtCO_2$/year in 2050. Yet it revised down its near-term outlook for CO_2 captured in 2030 by 32%, down to 170 $MtCO_2e$/year.[148]

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[145] IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector."
[146] IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[147] IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector"; IEA, "Net Zero Roadmap."
[148] IEA, "Net Zero Roadmap."

The IEA has revised the outlook for CCS downward in each NZE scenario

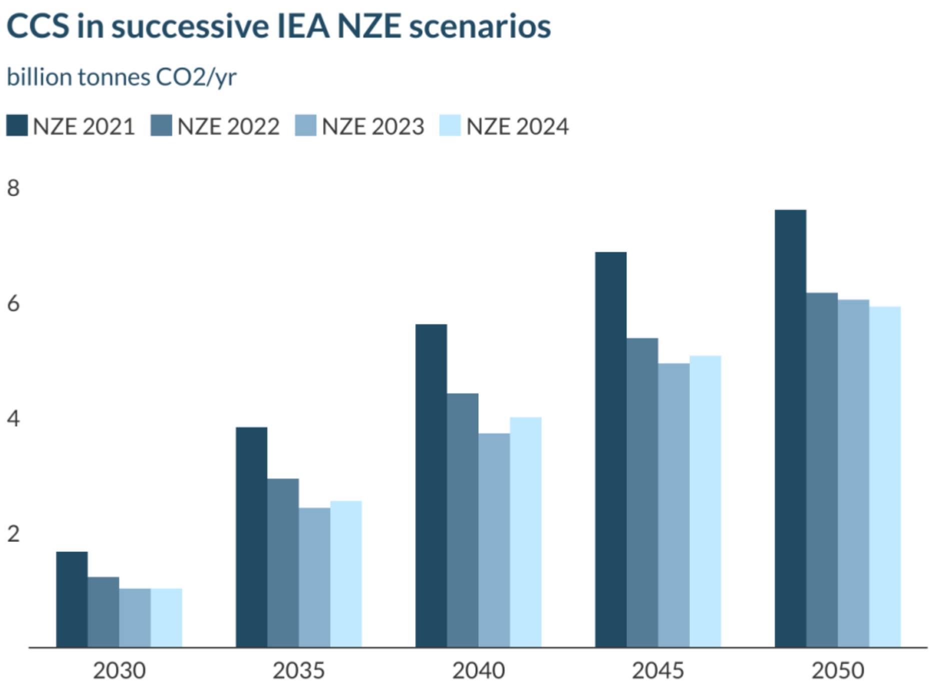


Figure 5: Projections for total CO_2 captured in the IEA's Net Zero Emissions (NZE) scenarios, published in successive World Energy Outlooks from 2021 to 2024.[149]

Project pipeline

The IPCC notes that "implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers," and that, globally, the rate of CCS deployment is "far below" those in 1.5°C compatible pathways.[150] Likewise, the IEA assesses CCUS as being "not on track" in its *Tracking Clean Energy Progress*, stating it has "trailed behind expectations" and noting that the pipeline of CCS projects remains "well below what is required in the Net Zero Scenario."[151]

The IEA's database of CCUS projects[152] demonstrates there is significant global interest in making this technology work. But the database also highlights the key issue with CCS as a mitigation technology: of 844 CCUS projects logged as of 2024, just 51 - across all sectors - are operational, and five have failed. The rest are planned or under construction.

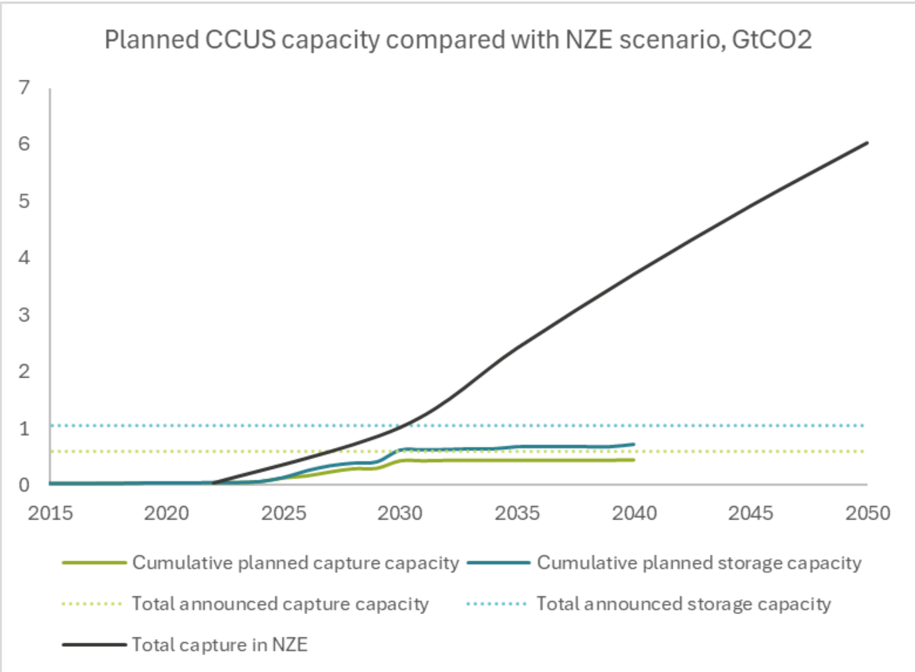
[149] IEA, *World Energy Outlook 2021*; IEA, *World Energy Outlook 2022*; IEA, *World Energy Outlook 2023*; IEA, *World Energy Outlook 2024* (International Energy Agency, 2024).
[150] IPCC, "Summary for Policymakers."
[151] IEA, "Carbon Capture, Utilisation and Storage."
[152] IEA, "CCUS Projects Database."

Additionally, the vast majority (79% by capacity) of globally operating CO_2 storage facilities use captured CO_2 for enhanced oil recovery.[153] In CO_2-EOR projects, CO_2 is injected into a depleted oil reservoir to extract more fossil fuels, which may not otherwise be economically recoverable. Although some CO_2 is diverted from the atmosphere, these projects ultimately increase overall emissions by increasing or prolonging oil production.

While the number of planned CCUS has grown in the last 5-10 years, this has not translated into committed projects. The pipeline of projects under development that are targeting operation by 2030 would capture a combined 436 $MtCO_2$/year.[154] This falls 589 $MtCO_2$/year short of total CO_2 capture in the NZE scenario in 2030. By 2035, this gap widens to 1.98 $GtCO_2$/year.

The challenges facing CCUS should be put in context of this technology first being deployed three decades ago. Novel technologies in sectors that are considered hard-to-abate, including iron and steel and cement, face considerable pressure to rapidly scale up in line with net zero pathways. Yet some, such as green hydrogen-based DRI-EAF steel production are already technologically proven. Diverting finite policy support to applications that can feasibly stop emissions being generated, rather than those that might prolong emissions generation, appears a far less risky strategy.

The pipeline of CCUS projects falls well short of the IEA's NZE scenario



[153] IEA, "Operating and Planned CO2 Storage Facilities by Storage Type as of 2023."
[154] There is currently greater storage capacity under development than capture capacity. Of projects targeting operation by 2030, the combined capture capacity is 436 $MtCO_2$/year, and the combined storage capacity is 616 $MtCO_2$/year.

Figure 6: Cumulative capture and storage capacity, by planned operation year, and total announced capture and storage capacity for all projects, as of 2024, compared with total CO_2 capture in the NZE scenario. Source: IEA CCUS projects database[155] and WEO.[156]

Unabated

There is also ambiguity about the expected performance of CCUS. This was exemplified at COP28, where it was agreed to transition "away from fossil fuels in energy systems" and to accelerate "efforts towards the phase-down of unabated coal power".[157]

There is no agreed definition or threshold for what qualifies as 'unabated'. This leaves the door open for underperforming fossil CCS projects to claim alignment with the Paris Agreement goals regardless of their actual mitigation potential. To date, failed or underperforming CCUS projects considerably outnumber successful projects.[158]

The IPCC Working Group III contribution to the AR6 loosely defined 'unabated fossil fuels' as those "produced and used without interventions that substantially reduce the amount of GHG emitted throughout the lifecycle; for example, capturing 90% or more CO_2 from power plants, or 50-80% of fugitive methane emissions from energy supply".[159] A more recent study from IPCC lead authors argues for the term 'abated' to be reserved for cases where ongoing fossil fuel use emissions are reduced 90-95%+.[160]

A recent analysis quantified the risk of relying on large-scale CCS combined with underperformance of CCS technology. The authors considered a high-CCS 1.5°C compatible pathway from the IPCC AR6 and found that if CO_2 capture rates were reduced from an optimistic level (95%) to the levels seen in projects operating today (50%), this would risk an additional 86 $GtCO_2e$ being released to the atmosphere cumulatively between 2020 and 2050.[161]

There is also the question of cost. An assessment of the relative costs of high-CCS and low-CCS 1.5°C compatible pathways developed for the IPCC's AR6 found that taking a high-CCS pathway to net zero emissions would cost at least USD 30 trillion more than a low-CCS route.[162] In this study, high-CCS pathways mitigate about half of today's emissions in 2050 with CCS, whereas low-CCS pathways mitigate around one-tenth of today's emissions in 2050 with CCS.

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155 IEA, "CCUS Projects Database."
156 IEA, *World Energy Outlook 2023*.
157 UN Climate Change, "COP28 Agreement Signals 'Beginning of the End' of the Fossil Fuel Era."
158 Robertson and Mousavian, *The Carbon Capture Crux*.
159 IPCC, "Summary for Policymakers."
160 Bataille et al., "A Paris Agreement Compliant Definition for 'Abated Fossil Fuels.'"
161 Climate Analytics, "Unabated. The Carbon Capture and Storage 86 Billion Tonne Carbon Bomb Aimed at Derailing a Fossil Phase Out."
162 Bacilieri et al., *Assessing the Relative Costs of High-CCS and Low-CCS Pathways to 1.5 Degrees*.

Offsets

Governments and corporations have also leaned heavily on offsets in net zero plans. For proponents, offsets allow for channelling finance from those directly or indirectly responsible for and/or profiting from high-emitting behaviour to worthy projects in need of economic support. However, there is now widespread recognition that global offset schemes are deeply flawed.[163] They rarely deliver real emissions reductions, and cause other real harms, such as displacement of indigenous people and unsustainable land management practices.[164]

Offsets play a significant role for members of sectors labelled "hard-to-abate" to manage emissions, but their effectiveness remains highly contested. The key distinction is that offsets do not reduce emissions at source. Even at their theoretical best, offsets merely compensate for emissions by supporting removals elsewhere, often without addressing the root causes. As such, their role should be considered supplementary, not central, to climate strategies.[165]

There are several important issues to consider around offset accounting, including additionality, permanence, leakage, and potential double-counting. Given that CO_2 is a long-lived greenhouse gas and can remain in the atmosphere for thousands of years after emitted, credible offsets must ensure permanence on a similar timescale. After 100-200 years, around 60% of CO_2 is taken up by the land biosphere and ocean, while about 40% remains in the atmosphere.[166] After 1000 years, approximately 20-25% remains in the atmosphere, and after 10,000 years, 7.5-20% could remain. To genuinely offset emissions, carbon must be stored for centuries to millennia. Therefore, for offsets to be a credible counterbalance to greenhouse gases emitted elsewhere, they must be essentially permanent.

Land-based offsets, e.g. reforestation, avoided deforestation and improving soil carbon, have permanence timescales of decades to a century and are inherently more susceptible to risk of reversal than geological storage. For example, trees are susceptible to drought, fire, disease, and weather events, which can result in stored carbon being released back to the atmosphere. Climate change will exacerbate issues with soil and forest carbon impermanence though increasing risk of forest fires and other extreme weather events.[167]

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163 Probst et al., "Systematic Review of the Actual Emissions Reductions of Carbon Offset Projects across All Major Sectors."
164 Finley-Brook and Thomas, "Renewable Energy and Human Rights Violations."
165 Aldy and Halem, "The Evolving Role of Greenhouse Gas Emission Offsets in Combating Climate Change"; Calvin et al., "Global Climate, Energy, and Economic Implications of International Energy Offsets Programs."
166 Climate Analytics, *Why Offsets Are Not a Viable Alternative to Cutting Emissions*.
167 IPCC, "Summary for Policymakers," ed. Shukla et al.

For offsets to be additional they must be in addition to what would have occurred in the absence of the activity. That is, they must reduce or remove emissions in a way that would not have happened anyway. For example, a project that would have happened without financial assistance from developed countries, because it was already profitable or required by law, is not considered additional.[168]

Article 6 of the Paris Agreement allows countries to pursue "voluntary cooperation" to achieve their emissions reduction commitments. A new international carbon market was initiated under Article 6.4. Many countries have signalled their intention to use Article 6 in their nationally determined contributions (NDCs) and long-term low emissions development strategies (LT-LEDS) under the Paris Agreement.

Offsets should ultimately be reserved for use once a country or organisation has done everything practicable to reduce their emissions. They should not be used as a front-line climate action strategy. There is a fundamental difference between making direct emissions reductions at the source and offsetting those emissions elsewhere. This, once again, incentivises support to efforts that, rather than tolerate residual emissions, might turn hard-to-abate sectors into easy-to-abate sectors.

[168] Josh Gabbatiss et al., "In-Depth Q&A: Can 'Carbon Offsets' Help to Tackle Climate Change?"

Conclusion

The persistent classification of iron and steel and cement as “hard-to-abate” sectors has shaped both policy and industrial responses in ways that risk undermining the urgency and effectiveness of global climate mitigation efforts.

While the technical and process-related challenges in these sectors are non-trivial, the evidence presented in this report demonstrates that their decarbonisation is not only possible but highly achievable with existing and emerging technologies—especially when guided by integrated, whole-of-system approaches and supported by robust policy frameworks.

A narrow focus on production-side constraints—such as process emissions in clinker production or the fossil fuel dependence of BF-BOF steelmaking—has encouraged decarbonization strategies put forward by the industry to rely heavily on CCUS and offsetting as core mitigation strategies. This framing assumes that a substantial portion of sectoral emissions are unavoidable, which justifies delayed action and continued operation of high-emissions infrastructure. However, our analysis shows that much of what is labelled “residual” or “unavoidable” emissions can, in fact, be abated at source through a combination of clean technology deployment, material efficiency, and demand-side reductions.

In the iron and steel sector, commercially available technologies—particularly electric arc furnaces (EAFs) coupled with high scrap availability and direct reduced iron (DRI) using green hydrogen—can replace the BF-BOF pathway. While steel production capacity is long-lived and capital-intensive, studies show that aligning investment timelines with early retrofit and decommissioning schedules could reduce cumulative emissions by up to 66% over 2020–2050, compared to just 47% if low-carbon measures are delayed by five years.

Moreover, future demand growth projections must be critically assessed. A rising scrap share (from 33% in 2022 to 48% by 2050 in the IEA NZE scenario) and material efficiency strategies—including extending product lifetimes, vehicle light-weighting, and improved manufacturing yields—could reduce steel demand by approximately 20% compared to current policy pathways.

Similarly, the cement sector’s decarbonisation potential is frequently underestimated. While process emissions from calcination are inherently difficult to avoid, energy-related emissions (accounting for ~40% of the total) can be eliminated through electrification, fuel switching, and improved thermal efficiency.

More critically, the remaining, non-energy-related emissions can be addressed through clinker substitution, the development of alternative binders, and demand-side strategies. IPCC in its AR6 concludes that emissions reductions of 55% by 2050 are possible through production-side measures alone—even without reliance on CCUS—

compared to the IEA NZE scenario's 46% reduction with heavy CCUS use. When demand-side levers are added, a whole-of-system approach could reduce emissions by up to 72% by mid-century, with much lower dependence on negative emissions technologies.

It is increasingly clear that demand reduction and circularity are central to achieving deep decarbonisation in these sectors. The Ellen MacArthur Foundation estimates that circular economy strategies—such as reducing steel overspecification in construction, promoting modular and reusable design, and increasing recycling rates—could avoid 500 Mt of primary steel production and more than 1 $GtCO_2$ emissions annually by 2050. Such strategies also alleviate pressure on raw material supply chains and reduce the need for large-scale infrastructure deployment for CCUS or negative emissions technologies.

CCUS can play a marginal role in managing genuinely residual emissions in the cement sector. However, our analysis reinforces that reliance on CCUS poses multiple risks. Capture rates are typically below 90%, deployment is geographically limited, and the IEA's 2023 NZE update downgraded expected CO_2 capture by 39% for 2030 and 22% for 2050 compared to its 2021 projections. Moreover, offset mechanisms—widely used in both sectors—suffer from credibility issues, with concerns over additionality, permanence, and verifiability. These instruments, rather than enabling real abatement, often function as "strategies of delay."

The underlying issue is that the hard-to-abate label is more reflective of political economy dynamics than of physical or technological limits. In both sectors, high-emissions incumbents have significant structural power, supported by government subsidies, regulatory gaps, and the perception of economic indispensability. These dynamics suppress ambition and innovation and delay transformative change.

Reframing these sectors as "transformable" rather than "hard-to-abate" requires a holistic policy approach. Key elements include:

- **Mandating early retirement of high-emissions assets** and setting clear timelines for phasing out BF-BOF and high-clinker technologies
- **Scaling up public and private investment** in low-carbon technologies, especially green hydrogen production, alternative binders, and recycling infrastructure
- **Incentivising material efficiency and demand reduction** through updated building codes, public procurement criteria, and product standards
- **Addressing geographical disparities** in decarbonisation potential by supporting technology transfer and infrastructure development in emerging economies
- **Shifting the focus of modelling and planning** from top-down CCUS-reliant scenarios to bottom-up pathways that prioritise emissions elimination

There is no single pathway to decarbonising cement and steel, but the continued framing of these sectors as inherently “hard to abate” is both scientifically inaccurate and politically counterproductive. The evidence is clear: many of the most impactful abatement measures are available today, and their deployment is limited primarily by policy, investment, and institutional inertia.

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