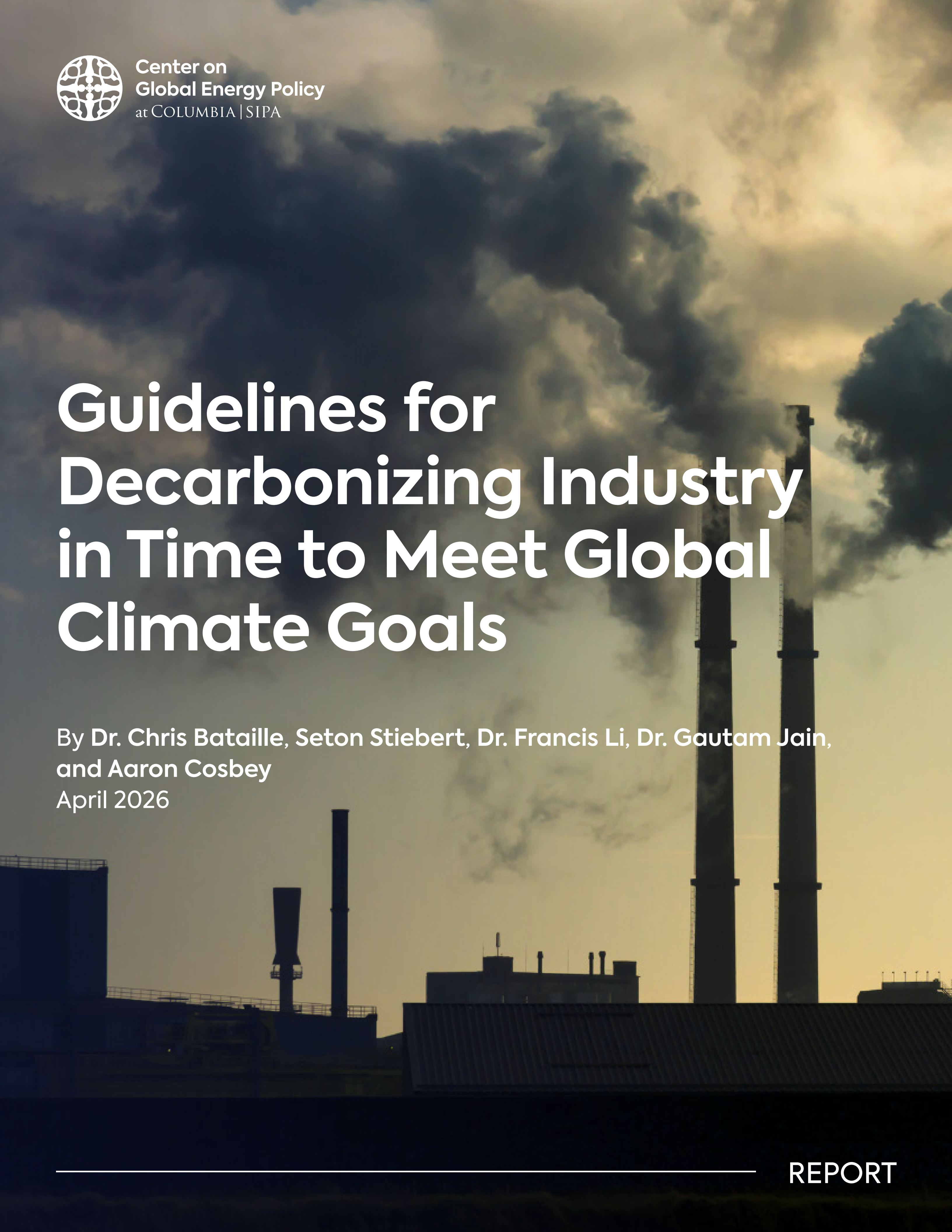

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Guidelines for Decarbonizing Industry in Time to Meet Global Climate Goals

By **Dr. Chris Bataille, Seton Stiebert, Dr. Francis Li, Dr. Gautam Jain, and Aaron Cosbey**

April 2026

REPORT

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Acknowledgements

Dr. Bataille gratefully acknowledges generous support from the Pooled Fund on International Energy (PIE), which was provided to the author in an individual capacity. The research and views expressed in this report are solely those of the authors and do not necessarily reflect the views of the PIE, the Center on Global Energy Policy, or Columbia University. The piece may be subject to further revision.

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Dr. Francis Li is a quantitative research scientist and founder of Subtext Systems, an independent modeling practice focused on industrial transition, trade, and infrastructure realism. He has over 20 years of experience designing and applying large-scale economic and engineering models to support long-horizon policy, investment, and risk decisions in energy- and resource-intensive sectors. Francis specializes in facility-level and supply-chain modeling that explicitly incorporates uncertainty, market dynamics, and policy constraints. Prior to founding Subtext Systems, Dr. Li was a principal research scientist at YarCom and a senior research fellow at University College London Energy Institute. He has published extensively in leading journals including *Energy Policy, Nature Energy, and Applied Energy*, and he has advised organizations such as the Inter-American Development Bank, International Renewable Energy Agency, ClimateWorks, and the United Nations Framework Convention on Climate Change.

Dr. Gautam Jain is a Senior Research Scholar at the Center on Global Energy Policy (CGEP) of Columbia University's School of International and Public Affairs (SIPA). He focuses on the role of financial markets and instruments—including thematic bonds, blended finance structures, and carbon markets—in the energy transition, with an emphasis on emerging economies.

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Executive Summary

Near-term guidance for decarbonizing global industry is needed to ensure it happens on pace to meet Paris Agreement climate goals. Such insights would help industry and financial decision-makers as well as inform government policies meant to support the transition toward lower-carbon energy sources.

This report combines a review of country diplomatic commitments, policies, and industrial roadmaps with decarbonization scenarios and new global modeling to suggest timelines, carbon prices, regulations, and lead markets for clean products, to replace unabated fossil fuel–powered industrial facilities and equipment with near-zero carbon emissions alternatives. It also estimates the capital and operating expenditures required, and provides policy options to support these efforts.

Key findings include the following:

- To meet the Paris Agreement climate goals, the speed of global industrial decarbonization must triple from current global average rates of about 2 percent per year to at least 6.1 percent per year, depending on the level of direct carbon dioxide removal from the atmosphere available to mop up residual emissions.
- To achieve these rates of decarbonization requires all new heavy industry facilities in high income countries, including China, to be near-zero emitting (NZE) by 2030 and for existing higher greenhouse gas (GHG) intensity facilities to be phased out by 2050. In emerging market and developing economies (EMDEs), the same requirements apply by 2040 and 2060.
- Lower cost partial mitigation options are already available (e.g., material efficiency and substitution; more metals recycling and direct reduction of iron; cementitious material substitution; chemical feedstock substitution; and electric heating). But full decarbonization requires commercialization of technically feasible but underdeveloped NZE processes for each sector (e.g., low-carbon feedstocks; process electrification; hydrogen reductants and fuels; and carbon capture, use, and storage).
- To implement needed industrial transformation, the authors' modeling scenarios indicate about $88 billion per year in extra direct capital expenditure will be needed across the globe (representing 2.7 percent of the 2024 energy investment of $3.3 trillion). Another $171 billion per year will be needed for extra operational expenses, mainly for clean electricity and hydrogen and CCUS.

Recommended policy pathways for governments around the world to address these findings include the following:

- Focus policies for already commercialized but underutilized low-carbon technologies on removing market barriers (e.g., changing building codes and new cement and concrete approval processes to allow more cementitious material substitution, and enhancing building supply chains for heat pumps and heat batteries) and addressing relatively lower fossil fuel to electricity pricing. To accomplish the latter, this report's modeling indicates policy stringency (or strength) equivalent to approximately US$250 per ton of carbon dioxide equivalent in high income countries and China, and $125 per ton in EMDEs. Reaching this level of carbon pricing will be very difficult in most countries and may require a combination of regulatory measures (e.g., building GHG or steam electrification standards) and subsidies such as tax and production credits.

- Focus policies for transformative but underdeveloped technologies on supporting the building of the first NZE plants for each sector wherever possible globally to reduce perceived risk and trigger innovation and cost declines. The first NZE plant and following clean facilities will require lead markets paying a premium to support demand, with costs distributed across the sector and passed through to end users. Policies to enable this could include green procurement; sectoral clean subsidy and cost recovery recharge schemes (where the sector as a whole funds NZE production and recovers the revenues from all sales); or tradable low-emissions production requirements, as used to drive development of zero-emissions vehicles.

- Adapt border GHG standards or carbon adjustments to specific industrial climate policies to subject importers to the same policies as domestic producers to protect more expensive domestic clean investments.

- Support the characterization and standardization of thematic green bonds to help close the upfront additional capital gap, as well as production or investment tax credits, zero-emissions material standards, and carbon pricing to close the operating cost gap.

- Set GHG standards for all major inputs into industrial processes to ensure overall emissions don't worsen in the short to medium term versus using unabated fossil fuels. Many of the processes in this analysis depend on the use of low GHG intensity electricity and hydrogen or the use of CCUS (with specific capture rates, permanence of storage, and limits to upstream fossil fuel fugitive methane).

Introduction

To meet the Paris Agreement goal of limiting the rise in global temperatures to below 2°C[1] to avoid the worst effects of climate change, all new energy-using investments and renovations, including for industry, need to be near-zero carbon dioxide (CO_2) emitting as soon as possible. Global temperatures will continue to rise until net-zero greenhouse gas (GHG) emissions are reached. Offsetting and net-negative carbon dioxide removal will be required to reach zero and eventually negative emissions.[2] This is an enormous challenge, especially in light of recent political developments in the United States, including reduction or cancellation of most financial support for industrial decarbonization (e.g., from the Office of Clean Energy Demonstrations), clean energy to supply near-zero emitting (NZE) facilities (e.g., sections 45Y and 48E of the Inflation Reduction Act), and clean procurement (e.g., from executive orders).

While the US steps back, China is accelerating its efforts toward industrial decarbonization in its upcoming 15th Five-Year Plan, with a dedicated funding facility announced in October 2025.[3] And while broad tariffs by the United States make needed trade in clean energy inputs and goods more difficult, they may actually make technologies like solar and batteries cheaper for developing countries as Chinese production is diverted to these markets.[4]

But the challenge is global in nature and must be assessed from this perspective. Understanding the current and potential rates of clean investment in heavy industry sectors is critical to aligning their emissions trajectories with the Paris Agreement's climate goals. The heavy industrial sectors—encompassing steel, cement, chemicals, and other energy-intensive industries—have long been perceived as challenging to decarbonize due to their reliance on high temperature processes, carbon-intensive inputs, long process and facility lives, and complex supply chains. Historically overshadowed by a focus on energy and transport, these sectors have received limited attention in global climate strategies, with most countries adopting economy-wide emissions targets that lack detailed pathways for subsectors. However, emerging technologies, coupled with increasing global attention on industrial emissions, indicate there are pathways to accelerate decarbonization within these sectors.

And time is of the essence. A mid-2025 analysis of the state of the climate system[5] estimates a 130 gigaton (Gt) of carbon dioxide equivalent (CO_2e) carbon budget remains before breaching a 50 percent chance of exceeding a 1.5°C temperature rise, and 1,050 Gt for 2°C. These amounts equate to 3 and 25 years, respectively, at current rates of CO_2 emissions. Remaining below 1.5°C has likely become unattainable at this point without steep declines in energy and combustion CO_2, as well as breakthroughs in CO_2 removal. Staying under 2°C might still be achievable despite recent reversals, considering faster than expected drops in the cost of solar, batteries of all types, and electrolyzers and the emergence of practical large-scale heat batteries—all critical to industrial decarbonization.

The world, however, is not currently moving at anywhere near the speed assessed in this report as required to meet Paris Agreement goals. A range of actors need near-term guidance for long-lived industrial investment to slow climate change, including policymakers, climate negotiators, investors, firms and nongovernmental organizations in the Group of Seven (G7)/Organisation for Economic Co-operation and Development (OECD), China, and EMDEs.

The purpose of this report is to clarify what actions would be most impactful in the industrial sector for countries committed to adhering to the Paris climate targets. The authors review countries' nationally determined contributions (NDCs) for reducing GHG emissions and their industrial roadmaps and perform new global modeling to provide guidance—or rules of thumb—for national policies on industrial decarbonization. The analysis reveals target dates for investment and renovation of industrial facilities, assesses the extra capital and operating expenditures required to meet these dates, and discusses early policies to drive such investment.

The authors begin the paper with a review of how industry is treated in country legislation, broader policy, and NDCs, as well as how industry is portrayed in net-zero studies. Using this information, a stock turnover model encompassing multiple heavy industry sectors and geographies is then used to explore rates of change and implied investment requirements to achieve industrial sector transformation compatible with the Paris Agreement. Based on this analysis, the authors provide investment, operations, and associated policy guidance for policymakers, investors, climate negotiators, and nongovernmental organizations.

A Review of National Commitments, Policy Approaches, and Strategies for Industrial Decarbonization

To assess the state of countries' current commitments and plans, the authors reviewed NDCs and biennial transparency reports (BTRs) (detailed in Appendix A) as well as net-zero pathway studies for major economies comprising more than 80 percent of global manufacturing output and about 70 percent of global emissions (China,[6] India,[7] the United States,[8] the European Union,[9] Russia,[10] Japan,[11] South Korea,[12] South Africa,[13] Australia,[14] Brazil,[15] and Türkiye,[16] in order of absolute industrial emissions). The authors also explored NDCs and BTRs for Argentina, Canada, Indonesia, Mexico, and the United Kingdom (see Appendix A).

Based on explicit and implied rates of industrial decarbonization in commitments made under international climate negotiations, the authors found that to meet Paris Agreement goals, the speed of global industrial decarbonization in terms of annual reductions in GHG intensity needs to triple from current rates to about 6.1 percent per year globally and at least double in all countries as soon as possible. For this to happen, industrial decarbonization must enter national transition planning, negotiations, and policymaking explicitly and immediately.

National Commitments

Analysis of NDCs and BTRs (see Appendix A for country details and full references) reveals significant variability in the scope, specificity, and mechanisms of industrial decarbonization commitments, as well as differences in the legal status and ambition of net-zero targets. Until recent US political changes, all G20 members articulated economy-wide emissions reduction targets aligned with the Paris Agreement, however, approaches to defining these targets varied. For instance, countries like Brazil and China frame their NDCs around emissions ceilings while others such as Japan, Canada, and the European Union express their targets as percentage reductions from a baseline year. Some countries, including Indonesia and Türkiye, define their goals relative to business-as-usual (BAU) scenarios, which, while showing reductions from projected growth, may still represent absolute increases in emissions. Additionally, nations such as China and Türkiye emphasize a "peak emissions year" as part of their strategy, signaling intent to reverse growth trends at a defined point. Notably, while China committed to peaking in 2030, it may have already peaked.[17]

Net-zero targets also show disparities in the degree of commitment. Jurisdictions such as Japan,[18] the United Kingdom,[19] and the European Union[20] have legislated net-zero goals, providing a binding framework for long-term decarbonization. In contrast, nations like Australia, Brazil, and Indonesia present net-zero as aspirational policy commitments in their NDCs and BTRs, lacking formal legislative underpinning at the time of review.

Quantification of industrial sector-specific decarbonization targets is relatively uncommon across the G20, with notable exceptions. Japan's BTR explicitly outlines a 35 percent reduction in industrial emissions by 2030 compared to 2013 levels (implying a 2.5 percent reduction per annum) while the European Union's BTR shows an industrial decarbonization trajectory from 2005 to 2050 of 1.5–1.8 percent per annum. Brazil offers a target of reducing emissions intensity in industry per unit of value added by 30 percent through its industrial transformation plan, Nova Indústria Brasil.[21] In contrast, other nations either lack quantified targets or provide reductions framed against BAU scenarios, as seen in Indonesia, where projected emissions from industrial growth are reduced but remain above current levels. India, China, and Russia currently offer no quantifiable industrial goals, reflecting a reliance on broader economic or directional policy commitments.

Policy Approaches

Several different general policy approaches to industrial decarbonization reveal widely varying means, coverage, and ambition.

The oldest and most widely studied and used industrial decarbonization policy is carbon pricing through emissions trading, where an absolute or intensity-based cap in emissions is established, permits are allocated via some mix of historical emissions and auctioning, and firms buy and sell permits to cover their emissions. The European Union operates one of the world's oldest and largest schemes, the EU Emissions Trading Scheme (EU ETS),[22] under which the emissions cap across covered sectors—including energy-intensive industry—is mandated to fall by 62 percent relative to 2005 levels by 2030. Free allowances have historically been provided to large emitters under the EU ETS, but to phase these out while reducing the cap, the EU is moving toward a border carbon adjustment mechanism, where imports must carry the same portion of emissions permits as domestic production. Notably, China, working with the EU ETS as a template, has since 2021 applied an emissions cap on its electricity generation system. This cap and trade system is gradually being expanded to also include steel, cement, and aluminum, with full coverage by 2027.[23]

Variants of industrial cap and trade systems exist globally. Australia's Safeguard Mechanism,[24] a facility-specific cap and trade system covering major emitters, exemplifies a market-based cap and trade approach with declining facility caps to align with Australia's national NDC. Canada's facility-specific but sectorally benchmarked output-based allocation systems is another.[25]

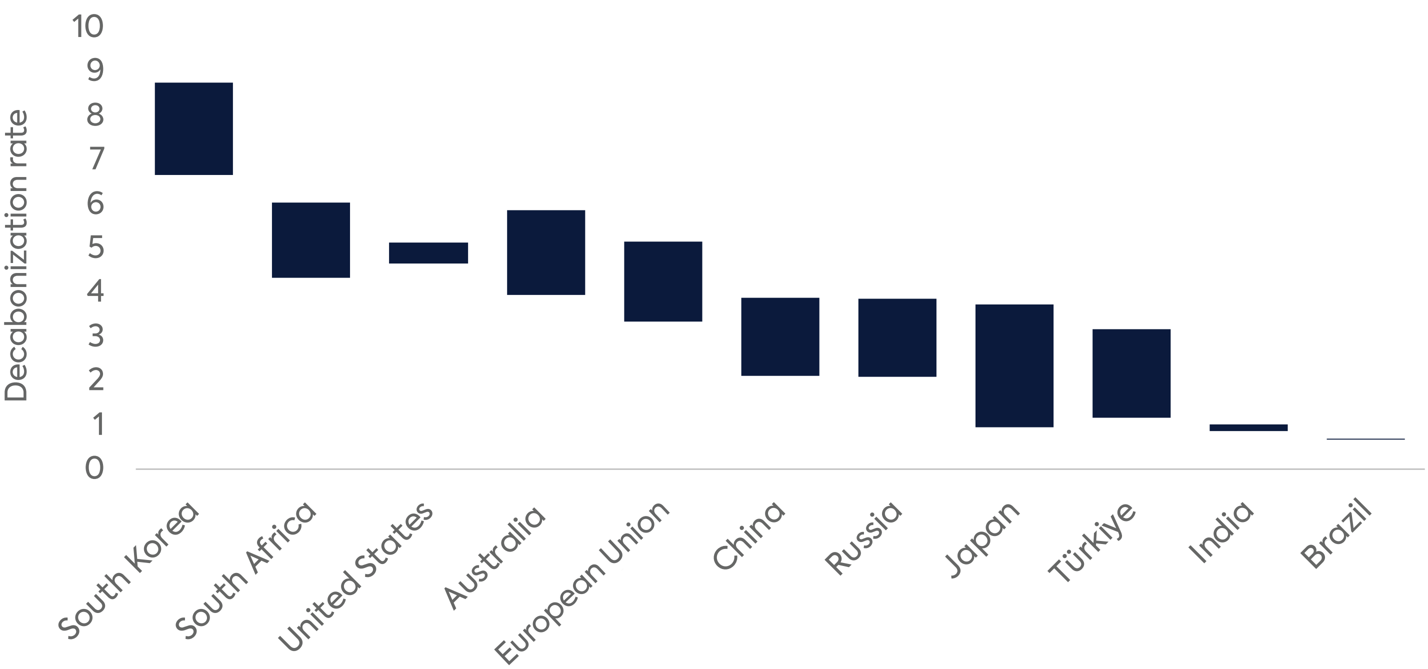
As an alternative, until recently the US had a broad and evolving suite of production and investment tax credits for clean electricity, energy storage, CCUS, and hydrogen that effectively acted the same as a carbon price in changing investment, but by subsidizing clean technologies instead of penalizing fossil fuel technologies. China also added state financial support similar to the US Inflation Reduction Action subsidies for green hydrogen and other industrial decarbonization efforts in October 2025.[26]

South Korea[27] and Indonesia[28] provide examples of more technological-prescriptive policies, such as inducements for adoption of electric arc furnaces in steelmaking, biofuels for petrochemical processes, and the use of alternative cementitious materials.

However, for many nations, industrial decarbonization remains embedded within broader economy-wide policies without dedicated sectoral strategies.

Explicit and implied decarbonization rates are summarized in Figure 1 across the reviewed NDCs, BTRs, and net-zero analyses.

Figure 1: Implied industrial decarbonization rates per year in quantified national analyses



Note: NDCs, BTRs, and net-zero analyses by country and their assumed rates of industrial decarbonization represented by ranges across country studies. An expanded analysis of the associated NDCs and BTRs is provided as Appendix A.

Explicit and implied decarbonization rates are summarized in Figure 1 across the reviewed NDCs, Figure 1 should be interpreted as illustrating the industrial decarbonization rates implied by countries' stated targets and pathways as reflected in reviewed NDCs, BTRs, and published net-zero analyses rather than as an indicator of current policy ambition or effectiveness. Higher implied decarbonization rates generally reflect larger gaps between current industrial emissions trajectories and those implied by these stated goals, regardless of whether the underlying targets are sufficient to align with 1.5°C or 2°C outcomes. As a result, countries such as South Korea and South Africa exhibit high implied rates despite being independently assessed as having insufficient current climate efforts to meet Paris Agreement goals, underscoring the scale of industrial adjustment implied by their stated pathways rather than existing progress or policy strength.

Strategies for Industrial Decarbonization

Industrial decarbonization roadmaps across major emitting economies share a consistent set of strategies.[29] Across the 59 NDCs, BTRs, and net-zero studies analyzed for this report, recurring themes include:

- **Circular economy and material efficiency** reduce emissions by cutting raw material demand, particularly steel and aluminum recycling, minimizing steel and cement use in building design, and substituting cementitious materials.
- **Energy efficiency improvements** are foundational in every roadmap, with actions like waste heat recovery and process optimization prioritized globally.
- **Low GHG electrification of industrial processes** is central to most roadmaps, especially for low and medium temperature heat applications.
- **Hydrogen** is seen as a key solution for carbon-intense reductants and feedstocks in steel, chemicals, refining, and possibly for high temperature heat.
- **Carbon capture, utilization, and storage (CCUS)** is seen as critical for addressing residual process emissions in sectors like cement and chemicals.
- **Sector-specific pathways** appear in many roadmap exercises and analyses, with some common elements appearing in different industrial subsectors. In the steel sector, gas to hydrogen and CCUS-based direct reduction of iron (DRI) and scrap-based electric arc furnaces (EAF) are emphasized. The cement sector prioritizes clinker ratio reduction, CCUS for process emissions, and new low-carbon chemistries. The chemicals sector emphasizes green hydrogen, bio-based feedstocks, and advanced recycling technologies. Finally, in the aluminum sector, there is hope for inert anode deployment (e.g., with the Rio Tinto/Alcoa Corporation ELYSIS

project in Québec[30]).

- **Policy and enabling environments** and how to create or structure them for industrial transformation are discussed in many analyses. There has been a long-term transition from focusing purely on carbon pricing to sector- and innovation-specific policies.
- **Research, innovation, and emerging technologies** are included in almost all studies, emphasizing the long-term development of next-generation technologies like aqueous or molten oxide electrolysis for reduction of iron to make steel, new CO_2-free cement technologies, or bio-based polymers for chemicals.
- **Critical energy, feedstock supply, and infrastructure development** are common elements, particularly coordinated investment in shared industrial transformation infrastructure such as plentiful and low-cost clean electricity, hydrogen, and CCUS pipelines and hubs.

These strategies reflect a converging global consensus on the technical pathways needed to reduce industrial emissions. However, their effectiveness depends on their alignment with national circumstances, policy frameworks, and financial support.

Modeling of the Paris Agreement Goals in Industry

To experiment with industrial investment and operations dates for pathways compliant with the Paris Agreement goal for less than 2°C, the authors constructed a regionally detailed model of projected global demand and supply for a group of GHG-intense, homogenous industrial commodities and heat needs, representing 9.1 $GtCO_2e$, or 80 percent of global industrial emissions as archetype plants. The seven key industrial products or commodities modeled—steel, cement, ammonia, lime, ethylene, methanol, and aluminum—were chosen because of their process homogeneity and representativeness of total emissions. In addition, industrial heat demand associated with other sectors and products is distributed in archetype aggregate units.

The methodology focuses on the emitting processes of the commodity production (Scope 1 emissions from production sites). For example, in the case of steel, iron ore reduction and crude steelmaking are included, but emissions related to secondary steel product manufacturing or upstream mining of iron ore are not included, as these relate to other sectors.

The Global Industrial Transformation Model (GITM) is a technology stock turnover model that considers the evolution of production of key emission-intensive industrial outputs in response to carbon policy (see Appendix B for details). GITM is a simple optimization model implemented in Microsoft Excel that deploys the lowest cost technology in each year from a suite of existing and new low-carbon production options (see Table 1). Comparative costs for each archetype plant are assessed based on capital and operating costs, GHG compliance costs (modeled as a carbon price on all tons), and the amortized value of stranded capital for the existing production unit if it has not reached its estimated end of life.

Table 1: Primary technology options by sector

Commodity	Technology options	Source (of capital expenditure, operational expenditure, and availability data)
Steel	Increased low-contamination recycling enabled by product design and reduced rusting loss; syngas driven direct reduced iron (DRI) with CCS followed by an electric arc furnace (EAF); hydrogen driven DRI-EAF; direct electrolysis	Bataille, Stiebert, and Li 2024.[31]
Cement	Advanced supplementary cementitious materials, CCUS, advanced chemistries (e.g., geopolymers, electrocatalytic calcium silicates)	IEA 2018.[32] Marmier 2023.[33] UN Environment 2018.[34] Additional estimates for CCS from Bataille et al. 2024.[35] Gardarsdottir et al.[36] 2019.
Lime	Advanced materials, CCS, electrocatalytic separation $CaCO_3$	European Lime Association 2014.[37] Simoni et al. 2022[38]
Ammonia	Electrolysis, CCUS, methane pyrolysis for hydrogen supply	IEA 2021.[39] Bataille et al. 2024.[40]
Ethylene/ cracker products	Electrochemical cracking, hydrogen heat, CCUS	Existing: Chen et al. 2024.[41] Low carbon options: Lenzio et al. 2023.[42]
Methanol	Bio-methanol, CCUS, e-methanol	Methanex 2024.[43] IRENA 2013.[44] IRENA and Methanol Institute 2021.[45]
Aluminum	Increased low-contamination recycling, inert anodes, electricity decarbonization	Low carbon technology costs.[46] Existing costs.[47]
High, medium, and low temp heat	Heat pumps, heat batteries, green hydrogen, synthetic hydrocarbon fuels	Gilbert et al. 2023.[48] IEA 2022.[49]

Note: The GITM model includes the best available technology fossil fuel version for producing each commodity as the base option when existing capital stock wears out. When moving from the baseline, business-as-usual case to the net zero–aligned scenario, end-use material input efficiency options are always applied first for all commodities.

Source: Bashmakov et al., "Industry," chap. 11 in IPCC Sixth Assessment Report, Working Group III: Mitigation of Climate Change (Intergovernmental Panel on Climate Change, 2022), https://www.ipcc.ch/report/ar6/wg3/, unless otherwise noted.

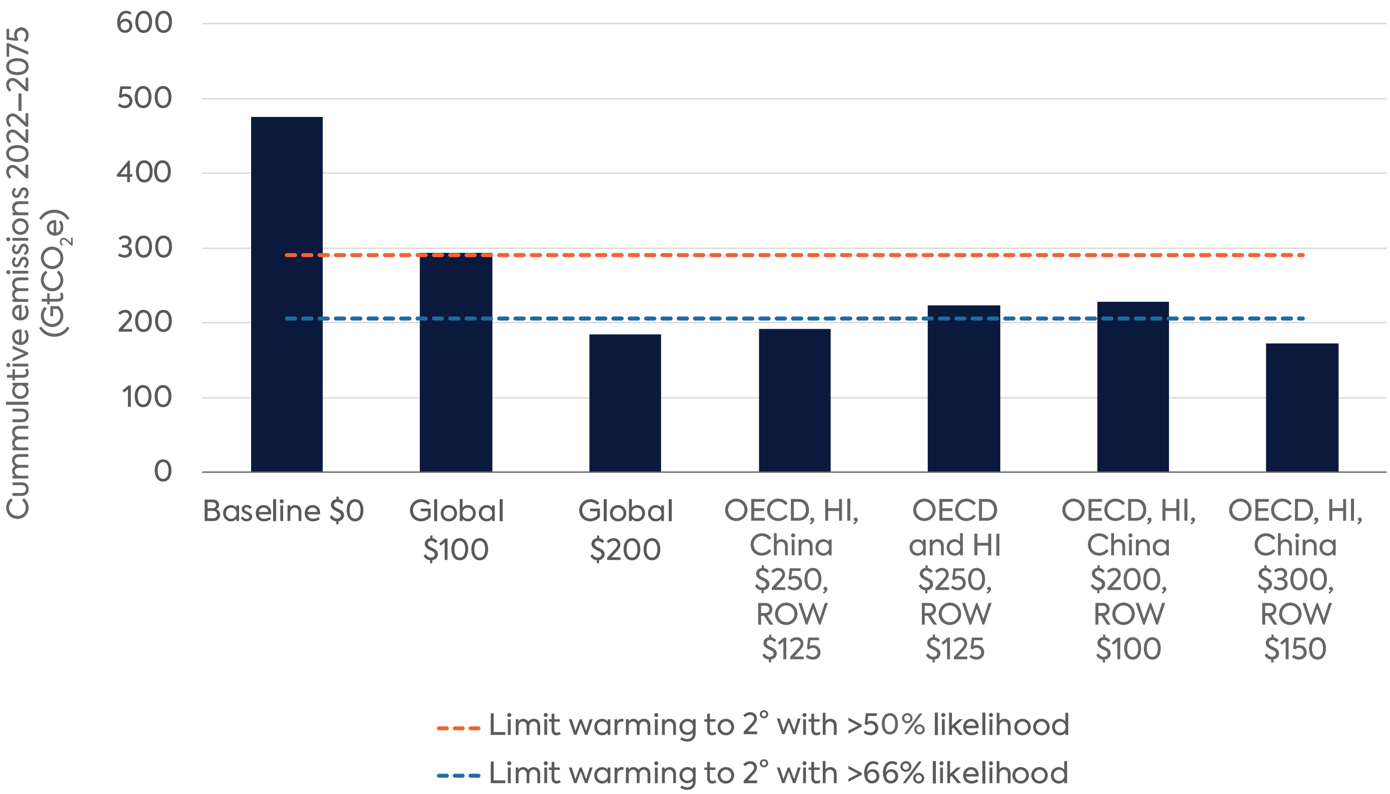
GITM does not explicitly model regional energy prices over time. Operational costs that include energy prices are developed by region in the model for different technologies and commodities. It is assumed that energy prices for fossil fuels including coal, natural gas, and refined petroleum products do not change from current cost estimates. A regional carbon policy compliance cost is included for climate policy scenarios. New low-carbon technologies using renewable electricity, renewable fuels, or green hydrogen have a cost decline function identified over time for total operational costs for each technology in the model. These cost decline functions for operational costs are based on the authors' literature review and indirectly include changes in the expected future costs for renewable energy.

To drive and constrain the model, the authors assigned industrial sector carbon budgets for a 50 percent (about 300 $GtCO_2e$) and 66 percent (about 200 $GtCO_2e$) chance of staying under 2°C, based on a 2022 IPCC working group report,[50] with the industry portion extrapolated from the Science Based Target Initiative.[51]

Figure 2 displays cumulative emissions for the covered sectors under several policy stringency scenarios. Policy stringency in this report refers to the strength of climate policy applied to sectors and is measured by a carbon pricing value. The policy itself, however, does not need to be carbon pricing (i.e., by carbon taxation or emissions permit cap and trade). It could instead be command and control or performance-based regulations (e.g., energy efficiency regulations on vehicles, appliances, and buildings), production and investment tax credits, etc., which would have the same effect as a specific carbon price.

The bars in Figure 2 represent total cumulative emissions 2025–2075, with lines representing a 50 percent or 66 percent chance of staying under 2°C. Global policies representing a cost of US$100 per ton CO_2e in today's dollars would maintain a 50 percent chance, while US$200 is required to maintain a more than 66 percent chance. Alternatively, for a 66 percent chance, the cost could be between about US$200–$300 for OECD, high income countries, and China, and $125 for the rest of the world.

Figure 2: Modeled baseline industrial emissions at various carbon prices, with a 50% and 66% chance of remaining below 2°C global temperature increase



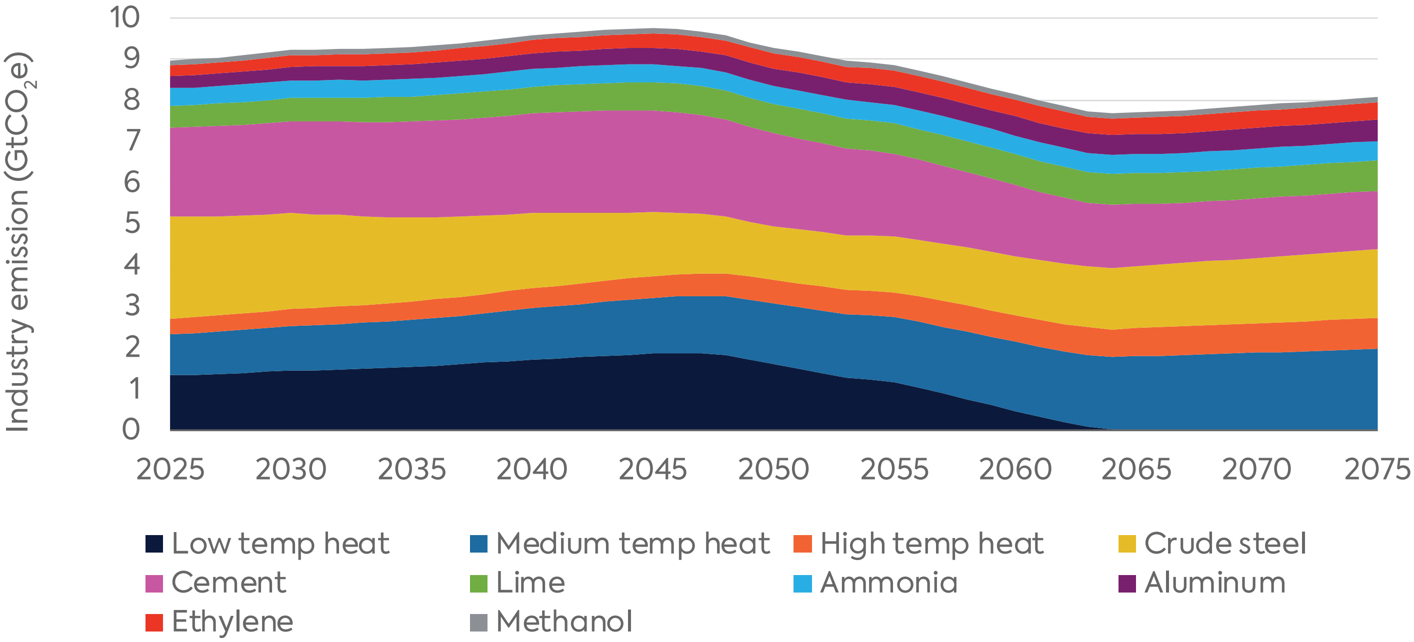
Note: High-income countries (HI) include those with more than US$14,000 in gross national income per capita. ROW = rest of the world (also referred to in this paper as EMDEs).

The authors then increased the carbon price path in the investment stock turnover model from 2025 until the carbon budgets were met (see Figure 3). Energy combustion and process emissions were charged accordingly, and reductions in demand based on end-use material efficiency policies were applied where justified by the literature. The carbon prices here only represent stringency of effort and should not be taken as an explicit policy; a combination of induced innovation policies for first and nth-of-a-kind facilities, as well as market uptake requirement policies (e.g., fixed and flexible regulations, standards, and carbon pricing), would be required to simulate carbon pricing of this stringency.

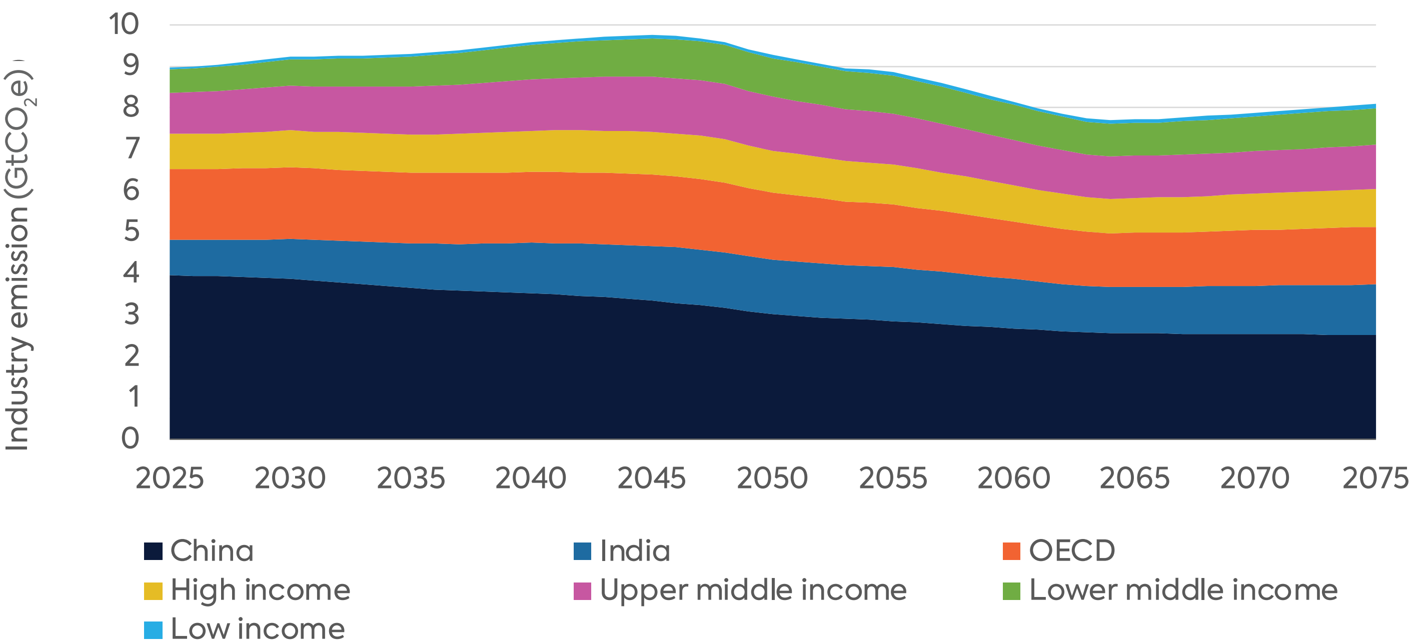
Figure 3 expresses global industrial emissions for the no-policy, business-as-usual baseline as well as for policy stringency rising to $250 per ton CO_2e for the OECD, China, and high income countries, and to $125 for EMDEs (broken into three different income levels), showing results both by sector and by region (country or country category).

Figure 3: Global industrial emissions to 2075 by commodity and heat service or region, with and without 2°C-compliant climate policy

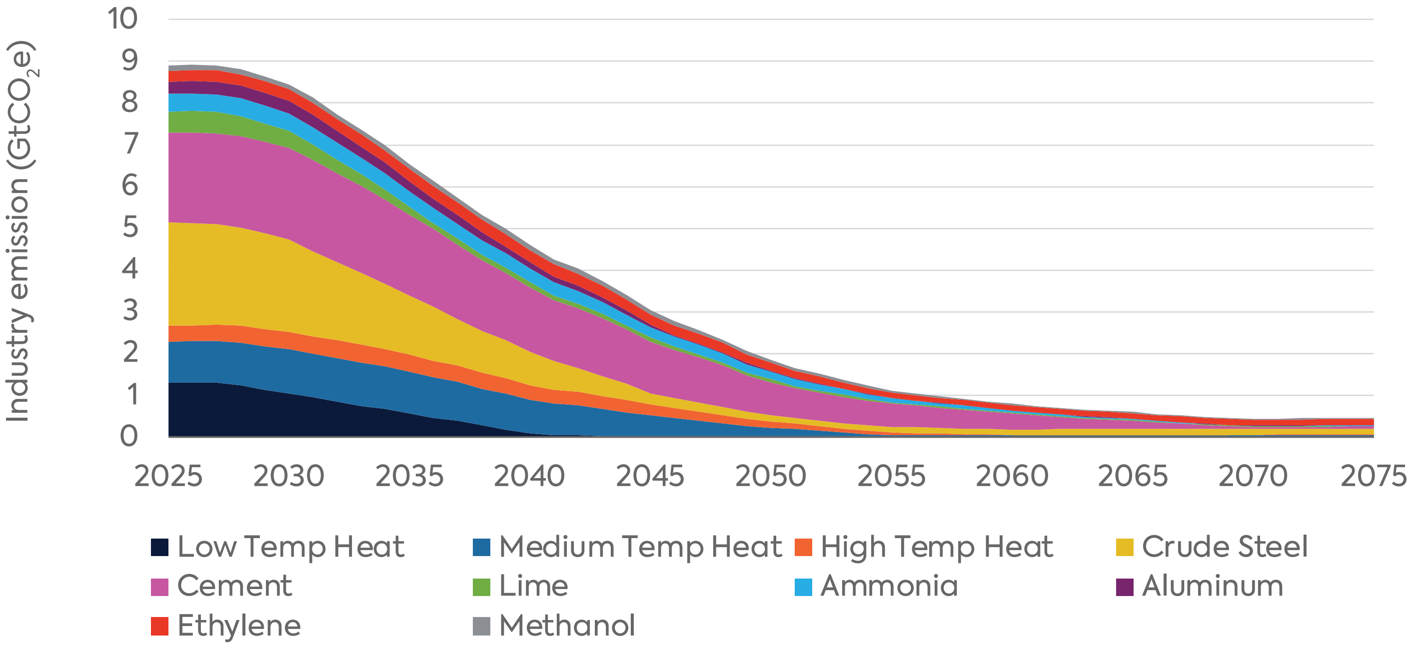
a. Baseline, business-as-usual industrial emissions by commodity and heat service with no climate policy



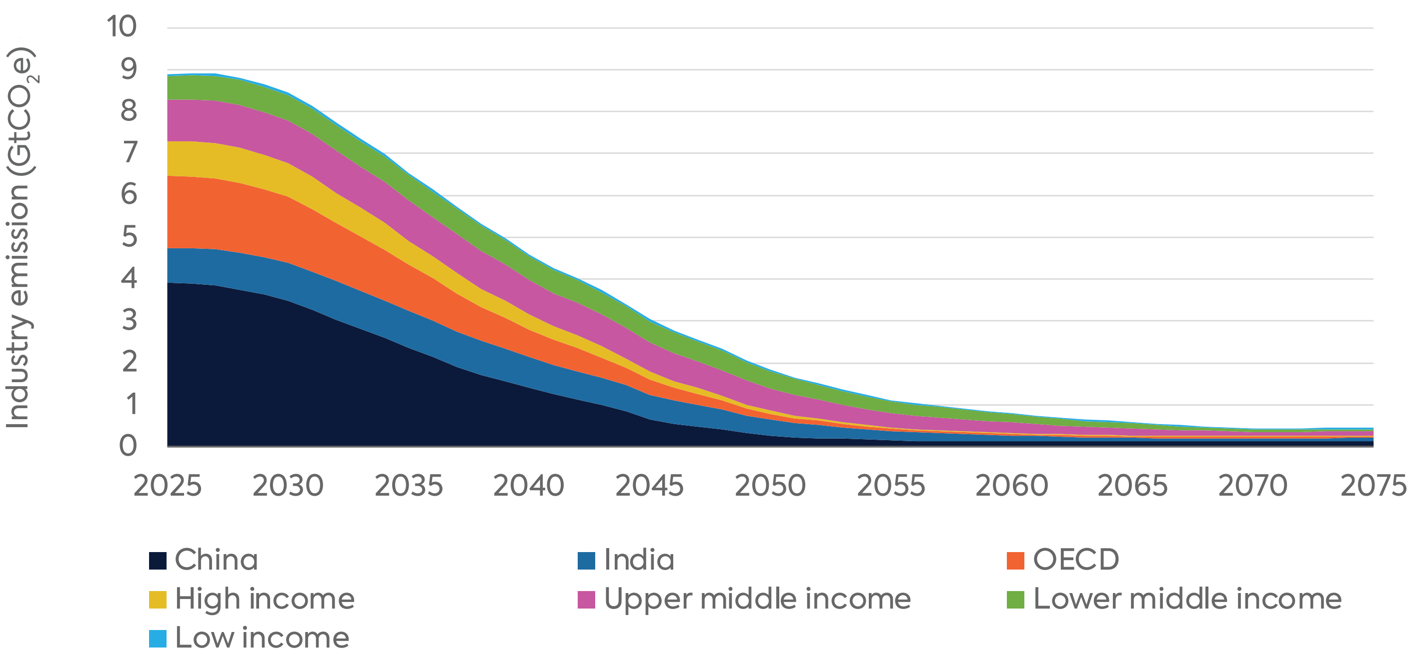
b. Baseline, business-as-usual industrial emissions by region with no climate policy



c. Net-zero-aligned industrial emissions by commodity and heat service with climate policy and induced innovation



d. Net-zero-aligned industrial emissions by region with climate policy and induced innovation



Note: Portrays global industrial sectors' and regions' industrial GHG emissions with baseline, business-as-usual conditions as well as with OECD, Chinese, and high-income country (those with more than US$14,000 in gross national income per capita) climate policy rising to the equivalent of $250/t CO_2e from 2025–2075, with the rest of the world (EMDEs) rising to $125. See Appendix B for details.

Business-as-usual industrial emissions, subject to stock turnover, standard innovation, and demographic effects, without strong climate policy, gently rise to 9.7 Gt in 2045, fall through 2065, and then rise again later this century if not controlled based on underlying regional population and development dynamics. Most of the stabilization and fall is low temperature heat naturally electrifying through the century, with global steel and cement demand also slowly falling as development needs mature.

The model projects that in the baseline, business-as usual-scenario, the share of global industrial emissions from the OECD, China, and high income countries falls in the future while overall emissions stay roughly stable. The four other regions (India, upper middle income, lower middle income, and low income) increase their share of global industrial emissions from 26 percent to 39 percent by 2050 in the baseline. This is a function of demand for industrial commodities shifting to EMDE countries and baseline energy efficiency improvements.

Full application of Paris-compliant climate policy reduces emission from 8.9 $GtCO_2e$ per year today to 1.8 Gt in 2050, and 0.5 Gt in 2075. The authors discuss the characteristics of this transformation, the conditions needed for it to occur, and its implications in the following section.

Industrial Decarbonization Guidelines

In this section, the authors synthesize key insights for industrial decarbonization investment from the NDC, BTR, and net-zero plan review and the modeling scenarios.

The Rate of Decarbonization Must Triple

To maintain a 66 percent chance of staying under 2°C, sector-wide decarbonization rates of at least 6.1 percent per year are required starting immediately, depending on the availability of carbon dioxide removal to compensate for residuals. This is an ex-post mathematical outcome[52] of the 66 percent chance of 2°C scenario, with $250/$125 carbon pricing, starting at 8.9 Gt tons per year and falling to 1.8 Gt per year by 2050 and 0.5 Gt per year by 2075. Based on the model, this is an estimate of the fastest rate possible without substantial stranding of facilities or missing the 2°C target. There are no free riders in this scenario; if one region goes slower, another must go faster. Slower decarbonization rates will require more carbon dioxide removal or cause more warming.

Industrial Climate Policy Stringency Needs to Increase Dramatically

To make net-zero industrial decarbonization happen, much more active and directed climate policy focused on investment and innovation is necessary. To stay within the roughly 200 GtCO_2e carbon budget for industry for a 66 percent chance of maintaining 2°C, global average prices starting in 2026 and rising linearly to $200 per ton CO_2e by 2050 are required, or $250 for the OECD, high income countries, and China and $100–$125 for EMDEs. Similar responses have been seen in the literature.[53]

China's Participation Is Crucial

China is estimated to be 36 percent of global industrial emissions in the baseline; without including China as part of stringent climate policy, it is simply impossible for rich countries alone to stay under the 2°C warming limit; China would consume 83 percent of the budget alone. For purposes of industrial decarbonization, China should be considered a fully developed and capable nation. Recently announced financial supports for industrial decarbonization in the country's 15th Five-Year Plan indicate that China's leadership is behaving this way.[54]

Policy Stringency Can Vary to Be Equitable

The most cost-effective strategy would be to impose similar climate policy stringency (i.e., cost per ton CO_2e) on every industrial facility in the world. This does not, however, recognize fairness and the improbability that countries will follow similar patterns of carbon policy stringency. To allow differentiated stringency and still meet the global carbon budget, it becomes likely that some nations go first, ideally the wealthier and/or more capable countries.

The countries that went first would have several tasks, motivated by aspirations of being central to future clean supply chains. They would pilot and demonstrate near-zero emissions technologies during the initial high cost per ton period of commercialization.[55] Based on these pilots, they would then build risky full-scale, first-of-a-kind (FOAK) commercial plants, likely in their home markets due to political pressures to keep subsidies domestic, as well as enact policies to support demand (e.g., through clean government procurement and tax benefits for firms that buy clean materials). The faster-moving countries could also import clean commodities from EMDEs over the next decade, especially if some clean commodities or intermediate products can be processed less expensively in EMDEs due to better endowments of potential low-cost renewable electricity (e.g., reduction of green iron in South Africa or Brazil).[56]

New Facilities Must Be Net-Zero

All new heavy industry facilities in the OECD, high income countries, and China should be near-zero emission (at least 95 percent less emitting than they currently are) from 2030. Existing facilities in these countries should be retrofitted with NZE technologies or phased out by 2050. The existing pipeline of projects and the time needed to design, permit, finance, order equipment, and build a facility means that all new investments today must be compatible with NZE production by 2030. Additionally, this calls for investing in fully commercial but more expensive technologies (e.g., low-carbon hydrogen DRI for iron ore) that could become more competitive with market-driving and technology-agnostic policies that encourage innovation.

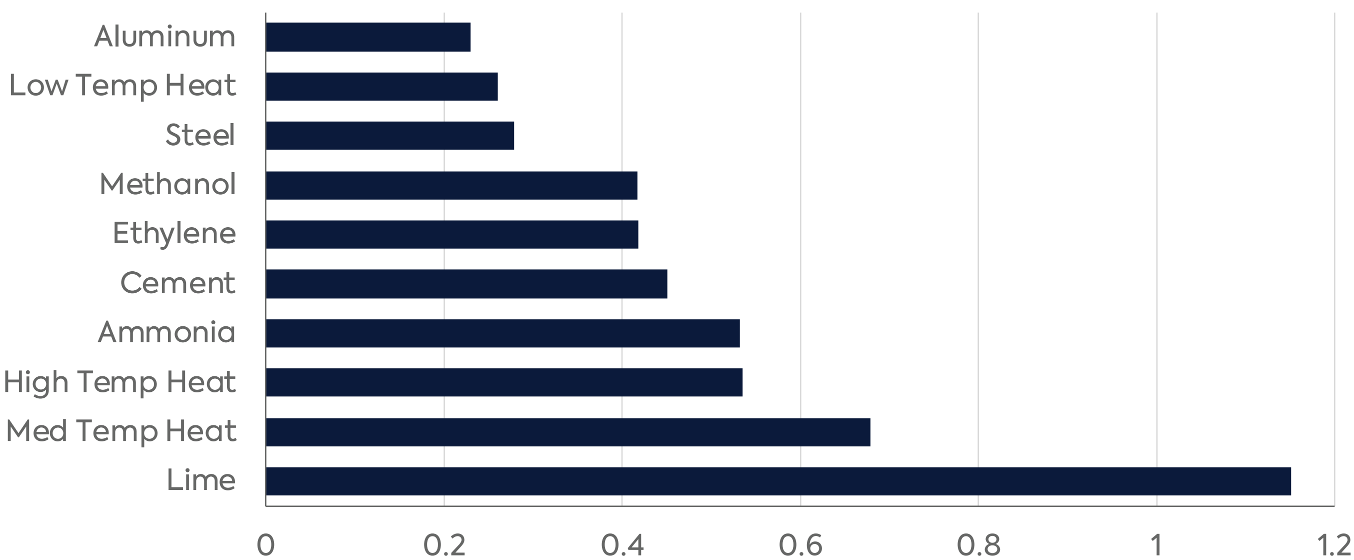
Phase-outs of remaining high emissions facilities will be politically challenging but could be made more palatable if associated with reducing local air pollution, as lower GHG processes almost always do because they eliminate uncontrolled combustion. Any GHG intensity facility standards will need to be clearly communicated several years before they go into effect to send clear investment signals. Where low-emissions processes cannot directly replace high emission processes at the same facility and facilities need to be closed, there will need to be substantial local community and workforce preparation, retraining, and economic diversification policies to reduce impacts on communities and workers.

In EMDEs, all new heavy industry facilities should be NZE from 2040, and all existing facilities should be retrofitted with NZE technologies or phased out by 2060. This timeline can be accelerated, particularly for leading EMDEs, if policy, technology, and financing support is provided by advanced economies. Common equipment and measurement standards, access to sustainably oriented capital, and access to clean lead markets in the OECD would allow EMDEs to participate more fully and quickly.

Governments Will Need to Support FOAK Development

Learning by doing and innovation are critical for industrial decarbonization and remaining below the 2°C warming limit. Incremental investment and operational costs for the first few plants are in most cases much higher than any broad carbon price policy can support (\$100–\$400/tCO_2e) due to perceived and real FOAK investment risks.[57] Figure 4 shows estimated costs for FOAK processes for decarbonizing various commodities as well as heat. While the private sector regularly brings new technology to market, it does so on its own timetable based on perceived profitability. To bring new technology to market with public goods characteristics like reduced GHG and local air pollutant emissions, governments need to "nudge" innovation with research, development, and commercialization support and create markets for the new goods, as is done regularly in the defense sector to meet security needs.

Figure 4: Estimated additional cost of first-of-a-kind processes for full decarbonization in 2025



Source: See Table 1 for references by commodity and heat.

Governments likely need to provide investment or production subsidies of some kind to trigger the building of pilot and then full commercial-scale FOAK plants to reduce additional upfront capital and ongoing production costs. These subsidies can also be offered in a way that induces price discovery, where firms bid for support and the government funds the lowest cost projects that meet their objective. Once enough full-scale low emitting plants are built, they reduce perceived investment and operations risks for future plants, inducing a virtuous spiral of increased demand and falling costs.

The FOAK challenge has important implications for the definition of being near-zero or net-zero capable, such as is used by the International Energy Agency, climate negotiators, and global institutions in the industrial clean production standard setting community.[58] "Near-zero capable" is often construed to mean the abatement technology is fully commercialized but simply costs more than the standard unabated fossil fuel–driven version and can be deployed as a retrofit when policies tighten sufficiently. There are very few technologies of this type, with heat pumps, electric boilers, and direct reduced iron furnaces using autothermal syngas production being key exceptions. Most near-zero emissions technologies, even if based on current technologies, have no real-world experience of production and need to be deployed to trigger learning through experience. The use of near-zero capability as a standard should therefore be accounted for, used judiciously, and be focused on actual operating near-zero emissions facilities because of the benefits of learning by doing.

Costs Can Be Shared Across Countries, Firms

International and cooperative hardware-oriented sectoral strategies, targeted at codeveloping physical processes as opposed to diplomatic or organizational cooperation, are required to share high development costs for near-zero emitting processes, including pooling of development capital to reduce risk and increase impact. While technically feasible, several key processes (e.g., clinker making, iron reduction, bulk steam, glass and ceramic making) do not yet have fully commercialized, widely available decarbonization options that must be fully commercialized at the normal plant size as soon as possible to meet climate goals. Given the development cost of new NZE industrial processes, it is likely that no one or even a few countries and cooperative firms can bear these costs alone, and bespoke coalitions may be required.

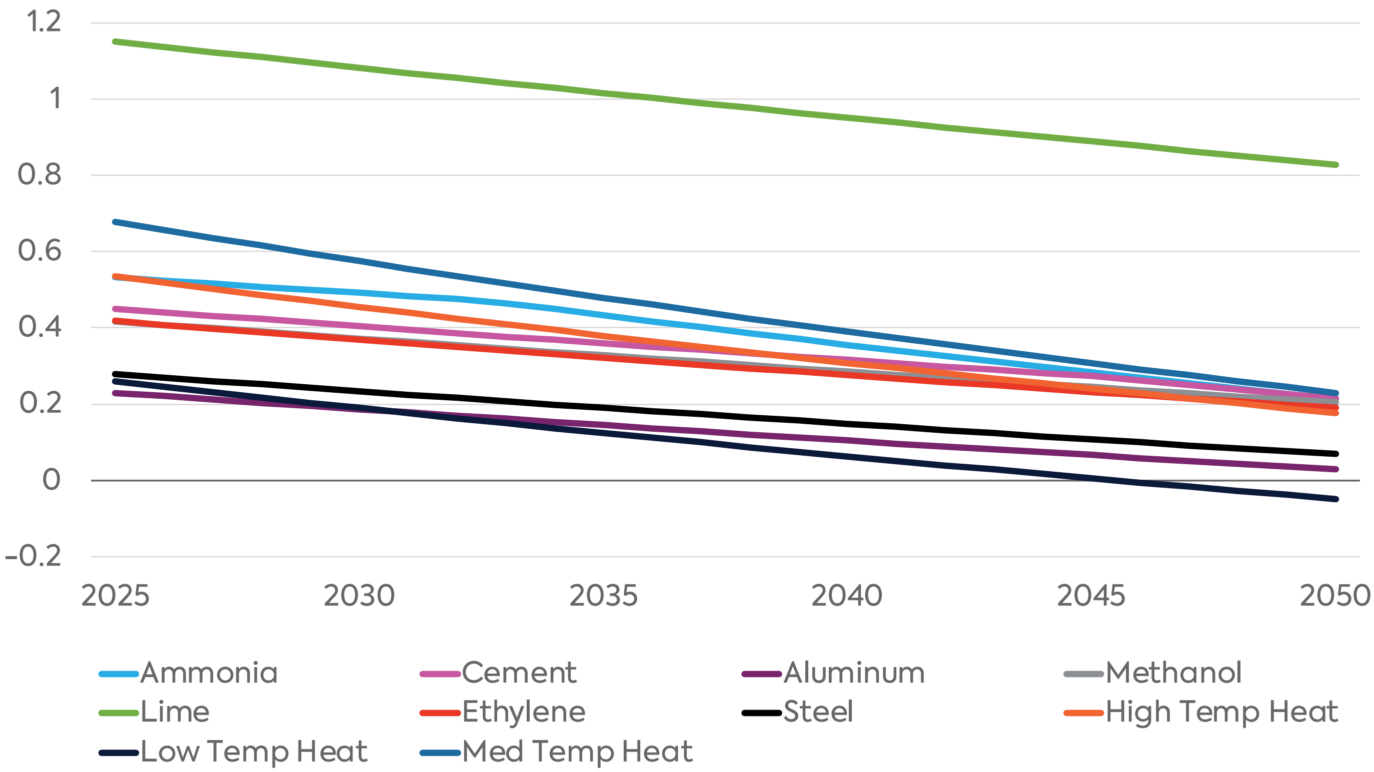
The UK Offshore Wind Accelerator, where the UK government coordinated a goal-oriented commercialization effort for key enabling technologies (e.g., floats and service vessels) with several firms, could serve as a model for larger efforts.[59] While until recently the US was likely to anchor several sector hardware strategies through the Office of Clean Energy Demonstrations, funding has since been removed for most projects.[60] Other OECD members, China, fast developing Southeast Asian industrial countries, and perhaps India, given its demand growth, may need to anchor future efforts.

Mandatory Market-Creation Policies Are Required

While government funding can drive the first few near-zero emitting facilities,[61] market take-up beyond this requires the implementation of mandatory policy to create the markets for progressively more plants, despite their extra per-unit costs. Once commercialized, the first generation of near-zero emitting processes is likely to cost more until "learning by doing" happens, and this may be the case for decades. Higher capital amortization and operating energy and labor costs will have to be recovered from revenues and must eventually be passed through to end-using firms and consumers. Once these facilities are operating, some form of progressively more stringent market uptake mechanism would be required to pass through the higher costs from the narrow set of producers to the much broader set of end users, for whom the costs are minimal and well within normal exchange rate and other price variations.[62] This could occur through green procurement for infrastructure; mandatory product standards; tradable carbon intensity or zero-emissions material production requirements; or subsidy and recharge schemes, where the sector as a whole funds NZE production and recovers the revenues from all sales.[63]

With technological innovation and learning by doing, the model indicates that costs per clean ton produced will fall by 2050 (see Figure 5). In the case of low temperature heat (e.g., steam from heat pumps and renewably charged heat batteries), costs are expected to eventually be lower than conventional technologies, and green steel could fall to near parity with current steel by mid-century. Other commodities are likely to remain between 3 percent to 23 percent higher than conventional production, except for lime, which has a relative cost of production 83 percent higher than current high emissions production because of its substantial process CO_2 emissions. The estimated cost reductions, based on learning rates combined with cumulative use and volumes from the model, are conservative and similar to recent literature estimates,[64] and should be seen as closer to a minimum for each commodity. Some may fall much faster and further than others, as did solar photovoltaic systems and batteries.

Figure 5: Estimated production cost over baseline for lowest cost low carbon technology that achieves more than 90% emission reductions over fossil fuel alternatives



New Financing and Ongoing Policies Are Needed to Cover Additional CAPEX and OPEX

The model estimates about $88 billion extra capital expenditure (CAPEX) and $171 billion extra operational expenditure (OPEX) will be needed per year, including clean energy, for industrial decarbonization to reach Paris Agreement–compliant levels (see Table 2). The additional CAPEX represents a 2.7 percent increase from 2024 energy investment of $3.3 trillion, and the OPEX a 5.1 percent increase on the $3.3 trillion, given it is mostly CAPEX for renewable clean energy supply. These are significant but not macroeconomically large or destabilizing additions.

The CAPEX could come through finance channels such as dedicated thematic green bonds[65] (with key performance indices based on established and verified decarbonization options such as those outlined in this paper) or a product premium or subsidy. Additional OPEX will likely have to come through a premium product price or subsidy, such as a production tax credit. One study suggests the required financing rate for CAPEX will be at least 10 percent higher than standard OECD capital costs, partly because of increased risk and partly because a large portion of the investment will be in developing countries.[66]

Table 2 provides modeled outcomes for additional CAPEX and OPEX by sector and region and for scenarios in which all countries pay the same implicit carbon price, rising to $200 per ton CO_2e, or where the implicit carbon price rises to $250 in the OECD, China, and high income countries and to $125 in the rest of the world. The authors provide these two different scenarios because of Paris Agreement obligations for "common but differentiated responsibilities" (CBDR). In short, CBDR requires that countries that can pay more do so to help the less capable and to address their past cumulation of GHG emissions. This requirement is not just ethical but political and necessary for participation by less developed countries.

The numbers in Table 2 are macroeconomically small (compared to normal finance flows and normal variations, such as due to currency fluctuations), but because they are concentrated in producing industrial firms, dedicated policies and instruments are needed to spread the cost across the broader economy.

Of note in Table 2, capital costs are about 7.3 percent higher in the scenario with different policy stringency for richer and poorer nations, but operational costs are about the same. The OECD and China's capital expenditures are 30–40 percent higher in the differential price scenario than in the common price scenario, whereas India's are less than half.

Table 2: Additional annual CAPEX and OPEX in 2022 USD billions, 2026–2050, for a 66% chance of remaining under 2°C given varying carbon prices, specified at 2022 USD per ton CO_2e

	Additional annual CAPEX		Additional annual OPEX	
	OECD, China, HI rising to $250; ROW to $125	All rising to $200	OECD, China, HI rising to $250; ROW to $125	All rising to $200
Steel	$37.5	$35.3	$35.9	$33.0
Cement	$20.0	$16.8	$39.3	$40.2
Lime	$11.7	$11.6	$30.3	$28.7
Ammonia	$1.2	$1.2	$7.1	$7.2
Ethylene	$4.2	$3.3	$5.8	$4.3
Methanol	$0.6	$0.1	$0.7	$0.1
Aluminum	$2.5	$2.3	$8.4	$7.3
Low temperature heat	$0.0	$0.1	$8.2	$8.5
Medium temperature heat	$6.6	$7.1	$26.0	$27.4
High temperature heat	$3.3	$3.7	$9.2	$10.3
Total	**$87.7**	**$81.4**	**$171.0**	**$167.1**
China	$52.6	$39.7	$91.7	$69.9
India	$3.2	$7.5	$9.1	$19.6
OECD	$19.3	$13.6	$38.5	$28.9
High income	$8.8	$5.9	$20.8	$15.1
Upper middle income	$2.6	$8.9	$7.1	$19.9
Lower middle income	$1.0	$5.1	$3.6	$12.4
Low income	$0.1	$0.6	$0.4	$1.3
Total	**$87.7**	**$81.4**	**$171.0**	**$167.1**

Table 3 provides stranded assets, the portion of facilities and facility lifetimes that need to be retired before fully amortized. If richer nations pay the higher carbon price, total global costs are about 8 percent higher than in the common price scenario, but the stranded costs for India, for example, are over two-thirds lower. It is key to note that these are cumulative global total stranded assets for the entire 2026–2050 period, while the costs in the previous table are annual.

Table 3: Total stranded assets by sector and region with varying carbon prices, 2026–2050 (2022 USD billions)

	OECD, China, HI rising to $250; ROW to $125	All rising to $200
Steel	$130	$104
Cement	$79	$82
Lime	$25	$23
Ammonia	$14	$8
Ethylene	$6	$3
Methanol	$16	$10
Aluminum	$27	$26
Low temperature heat	$118	$117
Medium temperature heat	$83	$92
High temperature heat	$25	$19
Total	**$524**	**$484**
China	$273	$191
India	$21	$67
OECD	$129	$83
High income	$79	$52
Upper middle income	$14	$54
Lower middle income	$8	$36
Low income	$0	$2
Total	**$524**	**$484**

Protective Measures Are Needed for Early Adopter Countries

To protect the investments of early adopters and to augment incentives for others, protective measures such as border carbon adjustments, maximum GHG intensity standards, and exceedance penalties may be required.

Given the increased costs of decarbonizing industrial processes, not all firms, sectors, or nations will decarbonize on the same trajectory, whether because of differing resources, national policies, or preferences. In the long run, policies and measures such as those identified in this report, as well as cost reductions for improving technology, can result in global adoption of near-zero carbon production methods for energy-intensive trade-exposed industrial sectors. In the meantime, there will be significant discrepancies between the emissions and cost per unit of individual producers, depending whether they have begun to decarbonize.

Because the products of these sectors are heavily traded, typically with low profit margins, market share for higher-cost low-carbon producers could be captured by lower cost conventional producers. The effectiveness of climate policies in the implementing countries could be compromised by this differential, transferring production and therefore emissions abroad, a phenomenon known as carbon leakage. There has been no significant carbon leakage measured to date, but policy stringency on industrial sectors has also been so low that little is likely to have been seen until the third reform (early Phase IV) of the EU ETS during 2021–23, which raised average carbon prices from 10–15 euros per metric ton CO_2 to over 80 euros per metric ton.[67]

To incentivize decarbonizing investment, to bolster the political feasibility of domestic industrial decarbonization policies such as carbon pricing, and to help incentivize low-carbon investment globally, first-mover countries will need to adopt protective measures, as noted, such as a border carbon adjustment—which imposes the costs of domestic climate policy on foreign producers at the point of import—or GHG intensity standards, which make low GHG intensity a condition for sale on the domestic market.

GHG Standards Are Required for Electricity, Hydrogen, and CCUS

Many of the low GHG processes used in this analysis depend on the use of low GHG intensity electricity and hydrogen as inputs or the use of CCUS (with standards for permanence of storage as well as capture and upstream fugitive methane rates). But what "low" means must be defined to ensure overall emissions don't worsen in the short to medium term versus using unabated fossil fuels.

Supporting research conducted by the lead author and others[68] have suggested the following target GHG intensities: electricity GHG intensity toward less than 30 grams CO_2 per kWh and hydrogen less than 1.5 CO_2e per kg; CCUS storage longevity to more than 1,000 years; capture rates toward more than 90 percent; and upstream fossil fuel fugitive methane of less than 0.5 percent and toward 0.2 percent gas production equivalent within 10 years.

An alternative path is to specify maximum GHG standards that ratchet up for all GHG-intense intermediate inputs in the economy. While various organizations have proposed this, there is no coherent effort yet underway.

Standards for the GHG intensity of carbon inputs for fuels and chemical feedstocks are needed as well, but these are not yet developed.

Conclusions

This paper examined how quickly and at what scale global heavy industry must decarbonize to remain consistent with stated climate goals, given long-lived capital stock and realistic investment constraints. Using a regionally disaggregated stock turnover model covering major industrial commodities and heat demand, the authors assessed the necessary timing of investment decisions around facility and process decarbonization, associated emissions trajectories, and the implied capital and operating costs of doing so. Several important findings emerged:

- Industrial decarbonization must triple from roughly 2 percent to more than 6.1 percent per year, a radical change in investment practice for the sectors. Across the reviewed national commitments and pathway studies, implied rates of industrial emissions intensity reduction substantially exceed past trends, highlighting the scale of transformation required.
- Near-term investment decisions will determine long-term success. Because industrial facilities are long-lived and capital-intensive, delaying the deployment of near-zero emissions technologies materially increases cumulative emissions and narrows future options, either forcing steeper later reductions or increasing reliance on early retirement of existing assets. Over the next decade, if progress is to be made with decarbonization of heavy industry, producers of currently GHG-intense commodities such as iron, clinker, ammonia, methanol, and aluminum need direct and supporting policy to allow the building of NZE facilities and to eventually phase out remaining non-NZE facilities.
- The timing of industrial facility and process decarbonization differs by region but converges globally. The analysis indicates that new industrial investments in the OECD, China, and high income countries must rapidly shift toward NZE configurations, with emerging market and developing economies following on a slightly delayed but potentially accelerable trajectory if finance, technologies, and lead markets are accessible. Slower progress in any major region increases the required pace elsewhere.
- While the incremental CAPEX and OPEX associated with industrial decarbonization represent a small share of global investment and energy spending, the impact is concentrated on a limited number of heavy industrial sectors. This underscores the need for targeted policy and financing instruments to pass the costs down to the broad set of end users (e.g., buildings and infrastructure) for whom the costs are relatively small, rather than economy-wide price signals alone.
- For most major industrial processes, NZE production routes are technically feasible but not yet deployed at scale. FOAK deployment carries higher costs and risks but is necessary to trigger

cost reductions, operational learning, and broader market adoption. Implementation of the easiest and cheapest options to reduce cumulative emissions (e.g., material efficiency and substitution, and maximization of recycling and cementitious substitutes) will help reduce the overall cost gap with fossil fuel competitors.

Appendix A

Table 4: Analysis of available G20 nationally determined contributions (NDCs) to the Paris Agreement and biennial transparency reports (BTRs) submitted to the United Nations Framework Convention on Climate Change

Country/ Region	Formal decarbonization target(s) in NDC, and any net-zero/carbon neutrality goals	Decarbonization actions specific to industrial sector(s)	Quantified industrial sector decarbonization targets
Argentina[69]	Net emissions celling of 349 $MtCO_2e$ by 2030	No	No
Australia[70]	43% reduction below 2005 levels by 2030, aspirational policy commitment to net-zero by 2050 (not legislated)	Industrial emissions reduced through the Australian Safeguard Mechanism, a facility-specific (219 facilities, 30% of emissions) cap and trade system where the emissions cap for each facility declines over time, covering major emitters (above 100 $ktCO_2e$/annum of Scope 1 emissions).	Not expressed as a sectoral emissions cap or a reduction level, but Safeguard Mechanism uses emission reduction rate of 4.9% per annum until 2030 with rates then adjusted in five-year increments to align with national NDC target(s).
Brazil[71]	2030 emissions ceiling of 1.20 $GtCO_2e$ (53.1% reduction vs. 2005), aspirational policy commitment of net-zero by 2050 (not legislated)	Replacing fossil fuels with biofuels and electrification, industrial process change, and implementing carbon capture where useful.	Mission 5 "bioeconomy, decarbonization, and energy transition and security" of Brazil's industrial transformation plan (Nova Indústria Brasil[72]) to 2033 includes a target to reduce emissions intensity per unit of production value added from industry by 30%.
Canada[73]	40–45% reduction below 2005 levels by 2030, with net-zero by 2050 (target legislated in the Canadian Net-Zero Emissions Accountability Act of 2021)	No. Focus is more on funding mechanisms and carbon pricing.	Specified by individual Canadian province and territory. At the time of writing, the only jurisdiction with a specific industrial decarbonization target is British Columbia (38–43% below 2007 levels by 2030).

Country/ Region	Formal decarbonization target(s) in NDC, and any net-zero/carbon neutrality goals	Decarbonization actions specific to industrial sector(s)	Quantified industrial sector decarbonization targets
China[74]	Emissions peak before 2030, intention to achieve carbon neutrality before 2060 announced at UN General Assembly in 2020 (policy commitment, not legislated)	No. Focus is on directional policies rather than quantified sector-specific targets or detailed technological pathways.	No
European Union[75]	55% reduction in emissions by 2030 compared to 1990 through domestic action (no international offsets), net-zero by 2050 legislated in 2021 European Climate Law	No. Focus is on market design, not prescriptive policies.	NDC target is for a 62% reduction by 2030 vs. 2005 levels for sectors covered by the EU Emissions Trading Scheme (ETS), which includes energy-intensive industries like steel, cement, chemicals, aluminum, etc. with no opt outs. Smaller installations not covered by the EU ETS to be reduced by 40% by 2030 compared to 2005 levels. The European Union's Biennial Transparency Report[76] aggregates energy production for all sectors excluding transport, but one can infer some idea of the decarbonization trajectory for industry from looking at projections for industrial processes and product use. This falls from 429 $MtCO_2e$ in 2005 to 190 $MtCO_2e$ in 2050 for the "with additional measures" scenario (56% reduction) and to 220 $MtCO_2e$ in 2050 for "with existing measures" scenario (49% reduction).

Country/ Region	Formal decarbonization target(s) in NDC, and any net-zero/carbon neutrality goals	Decarbonization actions specific to industrial sector(s)	Quantified industrial sector decarbonization targets
India[77]	Target to reduce emissions intensity of gross domestic product (GDP) by 45% by 2030 from 2005 level, aspirational 2070 net-zero goal mentioned (not legislated)	No	No
Indonesia[78]	Unconditional target of 31.89% reduction against BAU by 2030, conditional target of to 43.20% reduction against BAU with international support. Net-zero by 2060 (policy commitment, not yet legislated)	Specific actions mentioned for cement industry (e.g., the use of alternative cementitious materials to reduce clinker to cement ratio) and ammonia production (e.g., replacing existing plants with more energy efficient plants, CO_2 utilization for making sodium carbonate).	Yes, but these are theoretical reductions against a BAU scenario, so they actually represent an increase in emissions. Unconditional scenario (CM1) shows 7 $MtCO_2e$ reduction vs. BAU from 2010–2030, but emissions growing from 36 $MtCO_2e$ in 2010 to 63 $MtCO_2e$ in 2030, whereas conditional scenario (CM2) shows 9 $MtCO_2e$ reduction vs. BAU from 2010–2030, but this represents growth to 61 $MtCO_2e$ in 2030.
Japan[79]	46% reduction on 2013 levels by 2030 (1,408 to 760 million t-CO_2), net-zero by 2050 (legislated in 2021 Revision to the Act on Promotion of Global Warming Countermeasures)	No	While there are no industry specific targets in Japan's NDC itself, its BTR[80] shows industrial energy and process emissions falling from 512.3 $MtCO_2$ in 2013 to 332.1 $MtCO_2$ in 2030 (35% reduction).

Country/ Region	Formal decarbonization target(s) in NDC, and any net-zero/carbon neutrality goals	Decarbonization actions specific to industrial sector(s)	Quantified industrial sector decarbonization targets
South Korea[81]	40% reduction from 2018 levels by 2030, carbon neutrality by 2050 (legislated in Framework Act on Carbon Neutrality and Green Growth for Climate Crisis Response of 2021)	Specific mention of low-carbon transition in emission-intensive sectors including steelmaking (electric arc furnace use), cement (waste fuel for heat), and petrochemicals (bionaptha for chemical cracking)	No
Mexico[82]	35% reduction in GHG emissions by 2030 compared to 2019 (unconditional), 40% reduction conditional on international support	No	No
Saudi Arabia[83]	"Reducing, avoiding, and removing" GHG emissions by 278 $MtCO_2$-eq annually by 2030, contingent on hydro-carbon export revenue	Transformation of Jubail and Yanbu into global CCUS hubs, production of blue and green hydrogen	No
South Africa[84]	350–420 $MtCO_2$-eq for 2030 (17–32% reduction on 2017 levels)	Discussed in context of "hard-to-mitigate sectors" to be addressed in 2040s	No
Russia[85]	70% reduction from 1990 levels by 2030, conditional on sustainable socioeconomic development	No	No
Türkiye[86]	41% reduction from BAU by 2030 (NDC), peak emissions by 2038, net-zero by 2053 (aspirational, not yet legislated but climate law framework under development)	Increasing use of biofuels and alternative fuels, reducing carbon footprint of industrial products, improving energy and resource efficiency, using "best available techniques," and preparing Green Growth Technology Roadmaps for high emissions industrial subsectors	No

Country/ Region	Formal decarbonization target(s) in NDC, and any net-zero/carbon neutrality goals	Decarbonization actions specific to industrial sector(s)	Quantified industrial sector decarbonization targets
United Kingdom[87]	Economy-wide 68% reduction by 2030 compared to 1990 levels (NDC), net-zero target of 2050 enshrined in law	UK Industrial Decarbonization Strategy[88] recommends development of low-carbon industrial clusters with at least one of these to be net-zero by 2040	No, but recommendation for ore-based steelmaking to reach near-zero emissions by 2035 was "under consideration" at the time the NDC was updated in 2022
United States[89]	Prior to January 2025: Economy-wide 50–52% reduction below 2005 levels by 2030 (NDC), aspirational net-zero target posited as longer-term goal (not legislated)	Support for research and development of low-carbon industrial processes, carbon capture, new hydrogen sources	No

Appendix B

Global Industrial Transformation Model

The Global Industrial Transformation Model (GITM) is a technology stock turnover model that considers the evolution of a global fleet of archetype industrial plants. The model considers the evolution of existing production of key emission-intensive industrial outputs in seven global regions in response to carbon policy until 2075. The model was implemented in a Microsoft Excel spreadsheet. The seven regions were identified to represent key producing economic regions today and in the future that are likely to have similar climate policy stringency and cooperate on climate policy.

Not all emission-intensive industrial production globally is represented. Instead, the aim is to model the largest and most important industrial commodities that contribute to most of the world's GHG industrial emissions. In total, seven key industrial products or commodities are included: crude steel, cement, ammonia, lime, ethylene, methanol, and aluminum. These seven industrial commodities alone contribute to an estimated 6.4 $GtCO_2e$ in industrial emissions in 2022, or 54 percent of total global industrial emissions (i.e., 11.4 $GtCO_2e$).

In addition to the production of these seven industrial commodities, the model considers additional emissions associated with heat demand in other sectors not related to the production of the seven commodities. This total heat demand is estimated to account for an additional 2.7 $GtCO_2e$ of industrial emissions, bringing the coverage of the model to 80 percent of 2022 industrial CO_2e emissions. This remaining industrial heat demand is from disparate sources in many different sectors. Instead of modeling archetype production facilities, we model overall heat consumption related to low (less than 150°C), medium (150°C–400°C), and high (greater than 400°C) temperature heat demand.

The model is an optimization model, deploying the lowest cost technologies from available options based on their total unit cost. All archetype plants and heat equipment have a typical capital lifespan within which it is assumed that their capital costs are amortized. In this way, when a plant or equipment reaches its end of life, the lowest cost technology is deployed. It is also possible to retire plants or equipment early if it is cheaper to do so (i.e., costs of new technology are lower than continuing to operate the equipment). New technologies include low carbon production options that have significantly lower emissions as well as a baseline technology that represents the lowest emission intensity technology that is currently globally commercially deployed.

The model keeps track of average unit capital and operating costs and emissions intensity for each relevant technology and region, with accumulated global learning and cost reductions. The model also allows the user to introduce a carbon price for each unit of emissions to represent policy or financial levers that regions have or could adopt to reduce industrial emissions.

As output, the model provides total annual emissions and amortized operating and capital costs by technology, region, commodity, and carbon cost scenario.

More detailed methodologies are available below in relevant sections.

Selection of Industrial Demand Products

The goal of the modeling exercise was to cover most industrial emissions by including the minimum number of commodities and heat energy uses that contribute to the most global emissions today. Table 5 includes the estimate of 2022 global emissions and the share of total industrial emissions for each commodity and for heat. The year 2022 was used because it is the latest year for which all the necessary sectoral data was available.

Table 5: Global emissions from select commodities and industrial heat energy

Industrial commodity		Global emissions 2022 ($MtCO_2e$)	Estimated share of total industrial emissions
Crude steel		2,546	22.3%
Cement		2,126	19.4%
Lime		529	4.6%
Ammonia		432	3.8%
Aluminum		271	2.4%
Ethylene		256	11.6%
Methanol		127	1.1%
Aluminum		271	2.4%
Heat energy not otherwise included in commodities above	Low temperature	1,330	11.6%
	Medium temperature	962	8.4%
	High temperature	375	3.3%
Total modeled		**9,042**	**79.2%**
Industrial process emissions not modeled from various sectors		**2,378**	**20.8%**

Source: Total industrial emissions is based on Friedlingstein et al., "Global Carbon Budget 2023," Earth System Science Data 15, no. 12 (December 5, 2023): 5301–69, https://doi.org/10.5194/essd-15-5301-2023; ECJRC and IEA, GHG Emissions of All World Countries (Publications Office of the European Union, 2024), https://data.europa.eu/doi/10.2760/4002897. See Table 6 for the source of individual commodity emissions.

Sources of Data for Global Emissions, Production, and Facilities

Global production and emissions data for key commodities comes from several sources. Table 6 summarizes the production and emissions data references for each commodity.

Table 6: Sources of production and emissions data by commodity, heat

Commodity	Regional production	Regional emissions
Steel	Worldsteel 2023[90]	Bataille et al. 2024[91]
Cement	USGS 2024.[92] Tkachenko et al. 2023[93]	IEA 2023,[94] Climate TRACE 2023[95]
Lime	USGS 2024[96]	UNFCCC 2024,[97] Resources for the Future 2022[98]
Ammonia	USGS 2024,[99] Lorenzo and Gabrielli 2022,[100] International Fertilizer Association 2024[101]	IEA 2021,[102] UNFCCC 2024[103]
Methanol	Methanex 2024[104]	UNFCCC 2024,[105] Jong et al. 2022[106]
Ethylene/Olefins	Chen et al. 2024,[107] IHS Markit 2016[108]	S&P Global 2022,[109] IPCC 2006[110]
Aluminum	International Aluminum 2024,[111] USGS 2024[112]	International Aluminum 2024.[113] Does not include indirect electricity emissions, which are assumed to decarbonize.
Heat (low, medium, and high)	IEA 2024.[114] Overall global heat demand by temperature is based on IEA 2017.[115] Industrial heat demand for steel, cement, lime and ammonia is counted as high temperature heat. Methanol and ethylene are assessed as medium temperature heat.	IEA 2024[116]

Industrial Production Demand Forecasts

Projecting global demand for the seven commodities for the next 50 years is challenging and uncertain. Short-term market forecasts published by industry associations are not typically more than 5 to 10 years into the future and focus on announced project additions and macroeconomic assumptions about the growth of demand sectors for these products. While forecast economic growth is a strong indicator of potential demand, there are other factors to be considered. Most importantly:

1. **Material efficiency.** Less product is used to achieve the same level of economic growth.
2. **Development stage of economy.** For many products such as cement and steel that are important in infrastructure, regions and countries that have been highly industrialized for some time such as North America and Europe exhibit lower material demand than in the past despite continued economic growth. Rapidly industrializing economies such as India exhibit higher rates of material demand as they build up infrastructure.
3. **Product substitution and new technologies.** Economic alternatives to emission-intensive industrial products are deployed or industrial production is supplanted or no longer required by new technologies and processes. For example, lower emission intensity wood products could be used to substitute steel or cement demand.
4. **Circular economy and recycling.** Methods to recycle and reuse industrial products can be significantly less emission intensive. For example, secondary steel production from scrap steel is much less emission intensive and, depending on scrap costs, typically cheaper than primary steel production.

Studies conducted for cement and steel demand have consistently shown that once an economy is industrialized, demand per capita and per unit of GDP falls significantly and is no longer correlated to overall economic growth.[117] In addition, short-term industry association forecasts tend to be overly optimistic about market opportunity, projecting stronger demand than actually occurs.

In this study, we accept that there is very large uncertainty associated with long-term demand forecasts. However, due to all the factors listed, we can expect in the long term that industrial demand growth for these products, and associated heat demand, will be significantly lower than overall projected global and regional economic growth. Primary steel demand projections to 2075 are based on long-term relationships between $GDP/capita and historical steel demand at varying levels of development.[118] These projections also consider increased material efficiency and increased secondary steel production from recycling of scrap steel.

Cement demand is derived from published long-term regional global demand estimates based on long-term estimates of per capita demand.[119] For other industrial commodities, no reliable long-term regional forecasts of production were identified. In these cases, we calculate the annual change in industrial demand regionally as the product of the following four variables:

$$\lambda Demand = \lambda Pop \times \lambda Econ \times \lambda Dev \times \lambda Eff$$

Where:

Variable	Description	Data sources
λPop	Population growth factor $\lambda Pop = (1+R_{POP})$ where R_{POP} is the annual rate of change in regional population per year to 2075	United Nations, Department of Economic and Social Affairs, Population Division 2024.[120]
λEcon	Economic growth factor $\lambda Econ = (1+R_{GDP})$ where R_{GDP} is the annual rate of change in GDP per capita in constant prices and based on purchasing-power parity (PPP) per year to 2075	OECD 2024.[121] For years beyond 2060 and lower middle income and low income countries not identified in the OECD data, we develop $GDP/capita growth rates based on historical and nearer term growth rates from IMF 2024.[122] Based on a review of this data, we establish a correlation between per capita GDP growth rates (y) and the level of GDP per capita (x). For low income and lower middle income economies to a level of $15,000 GDP per capita (constant 2015), $y= 0.0054\ln(x)-0.0212$. Above this level of GDP per capita for all other regions, $y = 11x^{-0.61}$. These functions mean that low income and lower middle income economies grow to a maximum rate of 3.3% at a level of $15,000 GDP per capita. Beyond this level, rates fall from 3.3% to finally level out at about 1% around $75,000 GDP per capita. Ammonia demand saturates beyond a minimum level and then rises at 50% of GDP per capita.
λDev	Development growth factor $\lambda Dev = (1+R_{DEV})$ where R_{DEV} is the annual rate of change expected due to the stage of economic development to 2075	Development growth factors are based on the authors' previous work and literature review conducted for industrial sectors (Wei et al. 2019, Van Ruijven et al. 2016, and Xinrui et al. 2019).[123] This literature suggests a relationship between per capita demand for industrial and chemical products and the level of per capita GDP, demonstrating that at low levels of GDP, countries will have low but rising consumption and that as the country consumption grows with GDP, at a certain point of development, consumption is saturated and peaks, declining with further economic development until it stabilizes. Evidence from this literature is used to define an inverted demand U curve for commodities and used in modeling demand. Assumed annual rates by region are provided in supplementary materials posted on ResearchGate.[124]

Variable	Description	Data sources
λEff	Material efficiency growth factor $\lambda Eff = (1+R_{MEF})$ where R_{MEF} is the annual rate of change due to material efficiency and product substitution to 2075	The International Energy Agency has done extensive research on material efficiency for steel, cement, and aluminum, estimating that a 24% decrease in baseline demand for cement, 26% for steel, and 17% for aluminum are possible (IEA 2020, IEA 2019, and IEA 2021).[125] Less attention has been paid to other commodities, but similar impacts can be expected, especially with contributions from product circularity for chemicals and heat recovery. The modeling assumes a material efficiency of −0.5% annually for major commodities (a negative value here denotes an improvement in material efficiency, resulting in lower overall demand). Production substitution is assumed limited. Assumed annual rates by region are provided in the supplementary materials.[126]

Model Regions

China is the largest global emitter of industrial emissions today and will be for the foreseeable future. India just surpassed the US as the second largest industrial emitter and will similarly remain so for the foreseeable future; because of their dominant position and distinct sovereign politics, they are modeled separately. The third region includes all 38 OECD countries that represent nearly 50 of total world economic activity as measured by GDP. The final four regions are based on World Bank categories of national income in 2022 but exclude China, India, and OECD countries, as these are included in their own model regions. A summary of the seven regions is provided in Table 7.

Table 7: Model regions' represented countries and their portion of global GDP and gross national income (GNI) per capita in 2022

Model regions	Countries	Percentage of global GDP	GNI per capita
China	1	19%	$18,025
India	1	7%	$6,951
OECD	38	46%	$15,014–$87,468
High income	52	8%	>$14,005
Upper middle income	49	12%	$4,516–$14,005
Lower middle income	50	8%	$1,146–$4,515
Low income	27	1%	<$1,145
Total	**218**	**100%**	

Source: GDP and GNI per capita from World Bank, "World Development Indicators," 2022, https://data.worldbank.org/indicator/NY.GDP.PCAP.CD.

Capital Lifetime Assumptions for Archetype Plants and Equipment

The model requires an assumption of the age at which facilities need to make large new capital investments to continue operations, i.e., the capital stock turnover rate. Much of this is tied to the idea of the estimated physical depreciation of facility assets (equipment and machinery) and the economic useful life of the asset, which is the estimated time that the assets can be used profitably for production before it needs to be fully replaced.

When considering the average capital lifetime (i.e., the point that it makes financial sense to replace the equipment) for different facilities that produce emission-intensive commodities, it may not be relevant to focus on all assets and equipment but only on those that are relevant to emission intensive processes that suffer wear and tear. For example, for cement plants, new low emission intensive plants likely need to replace the cement kiln and heat processes, but other capital equipment, such as buildings, grinding, and conveying, do not need to be considered, as they would be similar for the new low-carbon technology. The data source of average capital lifetime assumed for facilities in this study by commodity are identified in Table 7.

Table 8: Average capital lifetime of equipment used in production of different industrial commodities

Commodity	Affected equipment and data source	Average capital lifetime (years)
Steel	Specific to blast furnace and relining[127]	17
Cement	Cement kilns and heat processes	20
Lime	Specific to lime kilns and heat processes	18
Ammonia	Haber process, reactor, coolers, reformer (IEA 2021)[128]	22.5
Ethylene	Steam crackers and distillation	17
Methanol	Steam reforming, synthesis, and distillation process	20
Aluminum	Anode baking assets, including crucibles and furnaces (ATO 2023)[129]	20
High temperature heat	Ladle, pit heaters providing high temperature heat	20
Medium temperature heat	Large boilers providing medium heat	17.5
Low temperature heat	Heaters and boilers providing low temperature heat	15

Source: American Society of Appraisers, "Estimated Normal Useful Life Study," version 1/24, 2024, https://www.appraisers.org/docs/default-source/16---member.-resources/mtsc-normal-useful-life-study-update-2024.pdf?sfvrsn=2c943b33_1, unless otherwise noted.

Identifying Archetype Facilities by Region

Archetype industrial plants are representations of average total global production until 2075, by which point almost all industrial facilities are assumed to have decarbonized. The first model year is selected as 2022 and represents the latest year for which production and emission data is readily available for modeling. The level of production at each archetype plant for the seven commodities is an estimate of the approximate number of active global plants today, as listed in Table 8. Heat energy is not allocated by archetype plant but simply by 1,000 total aggregations of total heat demand, allocated across all regions from many disparate sources (see Table 9).

Table 9: Heat aggregate demand groups and average production

Industrial heat energy (not including the seven commodities)	Number of aggregated demand groups modeled globally	Average heat demand rate in 2022 per aggregate
High temperature heat	1,000	5,943 TJ
Medium temperature heat	1,000	15,025 TJ
Low temperature heat	1,000	20,797 TJ

We use the estimated average production in each region for the entire modeling period to allocate archetype plants of the same production level. For regions where production grows faster than the global average, this means that allocated archetype facilities have lower than average production to start but higher average production in the future. For regions where production grows slower than the global average, the inverse is true. The global fleet is split between regions based on the proportion of global production of that region. The plants are then given a profile of age that matches what is known about the age of the industrial fleet.

It is assumed that the age of the fleet is related to the average emission intensity of the fleet. The oldest facilities that haven't been updated, retrofitted, or received time-limited capital investments to maintain long-term operations are assumed to be the most emission-intensive plants of the regional fleet. The newest facilities that have had recent investment are assumed to be the least emission intensive. This assumption captures the characteristic of continual improvement and increased efficiency with time but is an approximation.

The spread of emission intensity of the regional fleet is based on a linear triangular distribution of the expected highest emission intensity for the oldest facility, an average emission intensity for the 50th percentile age, and the lowest emission intensity for the newest facility. Average emission intensities are calculated based on known regional emissions and production, while lower and higher bounds of emission intensity are based on reported ranges in the literature.

Different production technologies, fuel types, energy efficiencies, and emissions of existing regional fleets are captured by the bounds of emission intensity modeled, such that existing archetype facilities only differ in age and emission intensity and have the same production level as well as CAPEX and OPEX costs. This is a simplification that will miss CAPEX and OPEX differences due to differing technology choices within the same age class.

Technology Options and Costs

Every region starts with an allocation of existing plants with a distribution of emission intensity by age. At the end of the useful economic capital life of the plant, this existing plant is replaced by one of the technologies defined in the model. All regions have access to the same technology options for each commodity.

Unit production costs of technology options in the model reflect full CAPEX, OPEX, and financing costs. These costs are not equal to market costs, which include profit margins for producers. Production costs have been converted to 2022 USD based on US Consumer Price Index[130] but may not represent actual price conditions outside the United States.

Production costs for low-carbon technologies in the model are meant to represent actual costs and do not include existing subsidies, tax credits, or carbon pricing.

In each model year, costs are calculated as the total of unit CAPEX, OPEX and carbon pricing policy costs identified in the model scenario for the corresponding regional facility. Unit CAPEX costs represent the average amortized unit capital costs over a specified lifetime. The age of a facility closely corresponds to the concept of expected capital lifetime of major equipment before retrofit. For example, if the age of a facility is 15 years since a retrofit, and the capital lifetime of the facility is estimated to be 20 years, then the expected capital lifetime before retrofit is 5 years.

Replacement technologies are identified in the model and are accessible to all regions with the same fixed CAPEX and OPEX costs. However, unit CAPEX costs are adjusted by region for different weighted average costs of capital, where typically wealthy regions (OECD, high income, as well as big producers China and India) have lower costs of capital, and lower income countries have higher weighted average costs of capital. CAPEX may also be adjusted for some technologies in future years to represent innovation. For example, Wright's Law states that technologies get cheaper at a consistent rate as the cumulative production of that technology increases. This lowering cost innovation is currently represented in the model by either a linear decline rate (same percent decline per year) or a learning curve rate that fits an exponential function to lifetime and expected emission reduction.

OPEX costs are differentiated by region based on a labor adjustment. This relationship is based on the World Bank estimates of output per worker in 2024 ($GDP per worker) and the proportion of average labor to total OPEX costs. OPEX may also be adjusted for some technologies in future years to represent innovation and Wright's Law. This lowering cost innovation is currently represented by a simple annual rate of decline function.

The model can then predict the year for every region at which a new technology is cheaper than an existing technology that has reached the end of its economic life at different carbon pricing assumptions. When the model reaches this predicted year in the time step, the model adopts the new lowest cost technology. The model allows for early retirement if the lowest cost replacement technology is cheaper, even including the full stranded capital costs for the remaining lifetime years.

Technology costs of low-carbon abatement options for each of the commodities and heat energy from the literature have significant variance and uncertainty. Some of the reasons for this include the age of the study (estimates of technology costs change with time), the currency and year that costs are expressed in (prices and currencies fluctuate in time), whether all the costs and benefits of existing carbon pricing policies and incentives are included, changing energy prices, and whether investment and project risks in first-of-a-kind low-carbon plants are included in the cost estimates. Risks for FOAK projects that increase the cost of projects include additional financial risk, technical and performance risk, policy and regulatory risk, and market risks that are generally not priced into technology cost estimates.

Based on all these factors, cost estimates for technologies are based on average values from different available sources in the literature, but generally we use the highest cost estimates to represent near-term costs of building facilities to represent FOAK risk premiums and the lower cost estimates to represent future cost declines that can be expected due to technical innovation and learning by doing. Table 1 identifies the data sources of CAPEX and OPEX costs for different commodities and technologies.

Main Equations in the Model for Selecting Competing Technologies for a Given Commodity and Country

In the model, the technology adopted in any year or region for any given archetype facility is the one available with the lowest calculated unit production cost, considering the cost of stranding an asset if the lifetime of the existing archetype facility has not been reached. In this way, the model works as a least cost model until the point that limits on the number of new facilities that can be built in a given year is reached.

$$Unit\_Production\_Cost_{T,R,Y} = CAPEX_{T,R,Y} + OPEX_{T,Y,R} + Carbon\_Price_{Y,R} + Stranded\ Asset_{T,R,Y}$$

Where **T** is the competing technology available, **R** is the model country or region, and **Y** is the year.

$$CAPEX_{T,R,Y} = CAPEX_{T,2022} \times Capex\ Decline\ Function_{Y,T} \times Regional\ WACC\ Function_{R}$$

Where the **CAPEX Decline Function** accounts for the change in estimated CAPEX costs of new technologies in time and the **Regional Weighted Average Cost of Capital (WACC) Function** accounts for the effect on CAPEX of different weighted average costs of capital rates for different regions.

$$OPEX_{T,R,Y} = OPEX_{T,2022} \times Opex\ Decline\ Function_{Y,T} \times Regional\ Cost\ of\ Labor\ Function_{R}$$

Where the **OPEX Decline Function** accounts for the change in estimated OPEX costs of new technologies in time and the **Regional Cost of Labor function** accounts for the effect on OPEX of different labor costs for different regions.

$$\text{Stranded\_Asset}_{T,R,Y} = \text{CAPEX}_{T,R,Y} \times \left(\frac{\text{Remaining}_{\text{Lifetime}_{T,R,Y}}}{\text{Expected}_{\text{Lifetime}_{T,R,Y}}} \right)$$

The stranded asset cost is the calculated CAPEX cost of the existing technology adjusted proportionately for the remaining years of lifetime to total expected lifetime. Carbon prices are identified for a scenario for each region and year.

Limitations of the Model

The GITM model is intended to provide a broad view of a regional level transition to net-zero through the gradual stock turnover of facilities worldwide. It aims to illustrate the potential timing and costs of this transition, given the existing distribution of facilities globally, forecasts of the future demand for industrial production, and available options for net-zero production. The modeling scope is large and involves significant uncertainties and limitations.

Demand

Demand forecasts for commodities and heat energy in the model account for variables such as population growth, economic growth, development stage, and material efficiency. However, they are limited to a single demand scenario extending to 2075. Changes in global trade patterns are not considered, with the assumption that each region will maintain similar shares of future exports and imports. Because the model does not simulate changes in trade flows, the discussion of carbon leakage and border measures is interpretive, drawing on the modeled cost differentials and established trade literature rather than endogenous trade outcomes. Future modeling could incorporate uncertainty analysis and explore the effects of alternative demand scenarios.

Archetype Facility Lifetime

Assumptions of the age and average operational lifetime of facilities before they are significantly retrofitted or replaced is a key variable of the modeling. These assumptions define the time frame for when it is likely that new and lower emitting production options are considered. The model assumes that the age distribution of archetype facilities in each region is linear. This is unlikely to reflect reality, as it depends on when existing facilities were most recently built or retrofitted. Collecting more detailed age distributions of facilities in different regions could improve the modeling. In addition, new low-carbon production options are assigned the same facility lifetime as existing facilities, which may not be the case for different processes and equipment.

Existing Technology Costs and Emission Intensities

Archetype facilities in each region represent the average capital and operating costs and emission intensities of all production. In many cases, commodities are produced by different technologies that have significantly different levels of cost and emission intensities. For example, in steel production, the coal-based blast furnace–basic oxygen furnace route has very different emission intensities than production with an electric arc furnace. While a distribution of emission intensities is considered for facilities, it does not simulate facilities with significantly different production routes. For greater model accuracy, existing archetype facilities could be divided by specific production routes that reflect different processes or fuels.

In addition, all archetype facilities in a region are modeled as the same size. Facility size distribution is likely to have some cost implication, as generally smaller facilities have higher average production costs than larger facilities.

Learning Curve Assumptions

Both CAPEX and OPEX costs of new low-carbon production technologies are governed by cost decline functions. The underlying assumption is that the cost of production for new low-carbon technologies will likely fall over time with increased deployment. Future modeling could incorporate uncertainty in cost decline functions.

Regional CAPEX and OPEX Costs

Regional CAPEX and OPEX costs of production are likely to vary for many reasons. For CAPEX, key factors include local labor rates, material costs, availability of suppliers, land and permitting costs, and costs of capital. The GITM currently accounts only for the impact of the cost of capital, assigning different rates of WACC to different regions. For OPEX, key factors include local labor rates, raw material and feedstock costs, energy costs, transportation costs, and regulatory and environmental costs. The GITM currently accounts only for the impact of differentiated labor costs by region. While WACC and labor are likely two of the most important factors in differentiated costs by region for CAPEX and OPEX respectively, future modeling could incorporate additional regional factors.

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