CLIMATE POLICY LAB

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INDUSTRIAL STRATEGIES FOR DECARBONIZATION AND GREEN GROWTH IN THE BRAZILIAN STEEL AND CEMENT INDUSTRIES

This report provides an overview of traditional and low-carbon technology options for decarbonizing the Brazilian steel and cement industries. The report offers insights that can be used to advance Brazil's green industrial strategy, by identifying (i) short term technology options and opportunities, and (ii) long term technological solutions aligned with Brazil's Nationally Determined Contribution and innovation ambitions. Finally, the report provides a menu of specific policy options that could catalyze green industrialization in the two sectors.

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CENTER FOR INTERNATIONAL ENVIRONMENT & RESOURCE POLICY

The graduate school of global affairs at Tufts University

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1. Executive Summary

Emissions associated with industrial processes amount to approximately one-third of total global CO_2 emissions. In recent decades, these emissions have increased in volume and as a proportion of total emissions.[1] In this context, Brazil has the potential to meet the climate challenge and emerge as a world leader in low-carbon steel and cement products. Through exports of low-carbon steel and cement, Brazil could also help other countries to decarbonize, while fostering prosperity at the national level. To transition to a low-carbon economy, new technological solutions for energy-intensive steel and cement industries are already being deployed in Brazil and around the world. Low-carbon technologies deployed or tested in the green transition of the steel industry include ***electrification*** (*i.e.*, the use of electricity to power electrode boilers, heat pumps and steam recompression) and the ***use of biomass*** and ***hydrogen*** based on local availability and transportation options. Other technologies include ***direct reduction technologies*** using gas reduction (*e.g.*, hydrogen or carbon monoxide), ***chemical processes*** that use electricity to heat up water and produce iron, and ***recycling technologies*** that transform materials into secondary raw materials to produce new products with equal quality as those made from fossil resources. ***Carbon capture utilization and storage*** (CCSU) technology improves carbon dioxide capture processes in steel and cement manufacturing and can be used for permanent sequestration (storage), and/or for additional use and recycling to generate new products. Measures to improve energy efficiency and ***clinker substitutions*** such as calcined clays are also means to support low-carbon Brazilian cement.

[1] Åsa Löfgren et al., 'Green Industrial Policy for Climate Action in the Basic Materials Industry', *Climatic Change* 177, no. 9 (2024): 147, https://doi.org/10.1007/s10584-024-03801-7.

This report provides insights as to how Brazil can leverage its clean electricity grid and competitive advantages in clean production to expand green steel and cement manufacturing and exports. Importantly, in alignment with the goal of achieving a net-zero economy, Brazil's commitment to phase out unabated coal-fired power generation would support the transformation of steel production facilities to green steel. This transition is anticipated to shift job composition but not necessarily result in employment losses—upskilling and training of the workforce will be critical to support specific tasks during the transition, including construction and maintenance of more efficient furnaces, operations of renewable energy plants and hydrogen production facilities, to name just a few.

With respect to both the steel and cement sectors, the report is organized into the following sections: (a) traditional manufacturing methods in the respective sectors; (b) cleaner production options for decarbonization; (c) an introduction to the Brazilian industry including production, exports, and emissions; (d) Brazilian firms in the sector; (e) international firms and clean technology uptake and innovation by them; and finally, (f) analyses and implications for policy and industrial strategy.

2. Introduction

The global mean surface air temperature in 2024 exceeded 1.5 C above the preindustrial average for the first time ever,[2] highlighting the urgent need for action in light of the Paris Agreement goal to limit global warming to 1.5 C and well below 2.0 C. It is also necessary to accelerate efforts to address poverty, hunger, and inequity to achieve the Sustainable Development Goals.[3] The dominant models of economic growth and development have placed the world on an unsustainable path; thus, new economic development pathways that reconcile economic growth with ambitious climate action are required.[4] Green industrial strategies, based on Nationally Determined Contributions, can drive green growth and just transitions. Critical technologies that will enable green transitions include advanced sustainable materials, chemistry and biotechnology, recycling and circular bioeconomy including circular business models, and energy (*i.e.*, energy savings, clean production, renewable energy such as solar and wind power, geothermal, hydropower, and biomass). In the chemical industry specifically, the integrated production of hydrogen with a low-carbon footprint provides a near-term investment opportunity followed by electrification and use of non-conventional energy sources in industrial processes (including carbon capture utilization and storage).

The ‘hard to abate’ basic materials industry, encompassing iron and steel, cement, and chemicals, is responsible for about 60% of industrial emissions or 20% of emissions globally.[5] Steel production accounted for a quarter of Brazilian industrial emissions in

[2] World Meteorological Organization, ‘State of the Climate 2024 Update for COP29’ (Geneva: World Meteorological Organization, 2024), https://wmo.int/publication-series/state-of-climate-2024-update-cop29.

[3] Federative Republic of Brazil, ‘Second Nationally Determined Contribution’, 2024, UNFCCC NDC Registry.

[4] G20 TF-CLIMA Group of Experts, ‘A Green and Just Planet’, 2024.

[5] Otto Hebeda et al., ‘Pathways for Deep Decarbonization of the Brazilian Iron and Steel Industry’, *Journal of Cleaner Production* 401 (2023): 136675, https://doi.org/10.1016/j.jclepro.2023.136675.

2020[6] and 4% of total national emissions, while cement accounted for 2.6% of total national emissions in 2016.[7] These are essential sectors for economic development, not just in Brazil, but for all emerging economies. In terms of technology investment, the green transition is dominated by investments in renewable energy technologies, followed by advanced materials and recycling technologies. As nations invest in infrastructure and housing, global demand for steel and cement materials is expected to increase. Mechanisms such as the *European Carbon Border Adjustment* are creating significant opportunities for Brazil to leverage its clean electricity grid and competitive advantages in clean production. In this way, Brazil can expand green steel and cement manufacturing, while also ramping up exports.

[6] Hebeda et al.

[7] Joao Henrique da Silva Rego et al., 'Carbon Dioxide Uptake by Brazilian Cement-Based Materials', *Applied Sciences* 13, no. 18 (2023): 10386, https://doi.org/10.3390/app131810386.

3. Steel: Industry and Technology

3.1. INTRODUCTION

The Brazilian steel industry is the ninth largest in the world and the largest in Latin America. Producers rely primarily on the *blast furnace and basic oxygen furnace* (BF-BOF), although steel produced through *electric arc furnaces* (EAF) in the country has a lower emissions intensity. Other lower-carbon production options for decarbonizing primary steel production exist at different levels of technological maturity. *Energy efficiency* improvements and *biofuels* can be employed immediately while *hydrogen-based direct reduction*, *carbon capture utilization and storage* (CCUS) and new *electricity-based production processes* will require substantial investments to support decarbonizing energy-intensive sectors over the medium-to-long term. Brazilian firms have the technological capacity to innovate and several firms in particular are well positioned to lead the global green transition. Robust alignment of policy measures would serve to coordinate investment in and improve the innovation and deployment of existing and emerging technologies.

3.2. TRADITIONAL STEEL PRODUCTION METHODS

The blast furnace and basic oxygen furnace (BF - BOF) is currently the primary method of producing virgin steel, accounting for 70% of all steel produced globally and 74% of steel produced in Brazil.[8] Ore is placed in a blast furnace with a reducing agent (usually carbon in the form of coke) to remove the oxygen from the ore Fe2O3 (magnetite)/ Fe3O4 (hematite). This produces CO_2 and pig iron, a brittle form of iron mixed with carbon. About 80 to 90% of the CO_2 from the process of making virgin steel occurs at this

[8] Hebeda et al., 'Pathways for Deep Decarbonization of the Brazilian Iron and Steel Industry'.

stage, through the process and from the fuel used to heat the furnace.[9] The pig iron is then run through the basic oxygen furnace which removes excess carbon by heating the pig iron and a small amount of scrap steel with pure oxygen, this process also produces CO_2.

<u>Electric arc furnaces</u> <u>(EAF)</u> account for 25 to 30% of global steel production and 24% of Brazilian steel production.[10] Steel is completely recyclable and recycling steel uses, on average, require 74% less energy than creating virgin steel from iron ore. Scrap iron, along with small amounts of other materials to help remove impurities, is put in the EAF. Electricity is then run through electrodes that are lowered into the scrap iron, heating it to produce molten steel. The process does not produce CO_2 as long as coal is not put into the furnace to add carbon to the steel. The only emissions come from producing the electricity that is required to power the furnace, which can be largely curtailed by using renewable energy sources.

3.3. CLEANER STEEL PRODUCTION OPTIONS

<u>Expansion of EAFs and 100% recycling of scrap metal.</u> The process of producing secondary steel in an electric arc furnace is a tried and tested technology for production of low-carbon steel, provided that energy is sourced from renewables. Although global demand for steel will almost certainly rise year on year, which requires an expansion in production of virgin steel using green methods, a substantial proportion of total demand can be met by recycling scrap iron.

[9] Nirmal Madhavan et al., 'Contribution of CO_2 Emissions from Basic Oxygen Steelmaking Process', *Metals* 12, no. 5 (2022): 797, https://doi.org/10.3390/met12050797.
[10] Hebeda et al., 'Pathways for Deep Decarbonization of the Brazilian Iron and Steel Industry'.

Energy efficiency. In the traditional BF-BOF production route, energy efficiency improvements can reduce its emissions by 20%.[11] For instance, the injection of pulverized coal or natural gas into the raceway of the blast furnace is one cost-effective measure to increase efficiency.[12] The use of pulverized coal partly replaces costly metallurgical coke and offers flexibility in adjusting the thermal condition, leading to improving furnace efficiency and reducing energy consumption.[13] Decreasing coke usage also contributes to fewer emissions, making pulverized coal injection a less carbon-intensive option. In addition, the recovery of BOF gas can also reduce energy consumption in the steel production process by capturing and utilizing waste gas.

Direct reduction uses a reducing gas such as hydrogen or carbon monoxide produced through natural gas reforming or water electrolysis. The latter, when powered by renewables, is significantly greener. The gas reacts with the iron ore without melting it, producing direct reduced iron in the form of solid pellets instead of the hot liquid produced from a blast furnace. The process requires less energy due to low temperature requirements. DRI manufactured using green hydrogen comes with a green premium, especially where electricity costs are high. Electricity costs make up 32% to 47% of total production cost.

[11] E+ Energy Transition Institute, 'Scoping Paper on the Brazilian Steel Industry Decarbonization' (Rio de Janeiro, Brazil: E+ Energy Transition Institute, 2022).

[12] Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., & Xu, T. 'A bottom-up model to estimate the energy efficiency improvement and CO2 emission reduction potentials in the Chinese iron and steel industry.' Energy, 50, 315–325, 2023.

[13] Liu, L., Kuang, S., Jiao, L., Guo, B., & Yu, A. 'Optimization of pulverized coal injection (PCI) rate in an ironmaking blast furnace by an integrated process model'. Fuel, 315, 122832.

Electricity use is the distinguishing factor in the most modern steel production processes. *Molten oxide electrolysis* uses electricity to directly reduce and melt iron ore. If electricity is produced using renewable energy, then no fossil fuels need be used. Boston Metals is currently piloting a mid-sized demonstration project using this technology. *Chemical processes* use electricity to warm up water laced with acid that dissolves iron ore through a chemical process to produce iron. Electra, a Colorado, U.S., based company is currently running its first pilot project.

Carbon capture utilization and storage. The process captures and stores carbon produced by the BF-BOF. It can lead to significant emissions reduction but not full decarbonization. ArcelorMittal has invested in this process in a few of its facilities in Europe, notably its Carbalyst project in Belgium, where waste carbon will be utilized and turned into low-carbon alternative fuel.

Biocarbon based methods. Biomass can also be used in blast-furnaces as a replacement for coal-based carbon as the reducing agent to produce pig iron. Though its energy consumption is the same as BF-BOF, the use of renewable sources means emissions intensity is lower. Various sources place the emissions reductions between 20 and 90%. Approximately, 10% of Brazilian steel, as of 2021, is produced using charcoal as reducing agent. The drawbacks of this method are that charcoal can only be used in small BFs and that production is limited by the supply of charcoal and carbonization technologies.

3.4. BRAZILIAN INDUSTRY

Brazil is the ninth-largest steel producing country globally and the largest in Latin America. It produced 31.9 million metric tonnes (mt) of crude steel in 2023, down 6.5%

year-on-year (YoY) as domestic mills lost ground to imports, which soared 50% YoY to around 5 million mt. In 2023, domestic sales fell 4.4% to 19.4 million mt. Likewise, export sales fell by 1.8% to 11.7 million mt that year.[14] Brazil is the seventh largest net exporter as of 2020, selling 8.7 million tonnes of steel more than it imports. As of April 2024, Brazil has started to increase protections for steelmakers by imposing an import quota system on eleven types of alloy products—amid an influx of cheap imports led by China which is exporting more steel due to a domestic slowdown. Shipments exceeding quotas will be taxed 25%, compared to the current tariffs of 11%.[15] Domestic steelmakers expect 6 million metric tonnes of imported steel this year, 20% more than last year.

As of 2022, the most important Brazilian steel products based on total value[16] were ***ferroalloys*** (USD 4.2B) – China (31.5%), Netherlands (12.3%), US (8.7%), Japan (8%), South Korea (5.8%), and Belgium (5.8%); ***semi-finished iron*** (USD 3.4B) – US (42.5%), Mexico (17.7%), Canada (7.4%), Argentina (5.7%), and Dominican Republic (5.7%); ***pig iron*** (USD 2.3B) – US (70.2%), Turkey (5.8%), Netherlands (5%), and China (3.8%); and ***hot rolled iron*** (USD 1.2B) – Argentina (16.8%), Portugal (17.5%), Chile (14.2%), Turkey (11.5%), Colombia (6.6%), and France (5.5%).

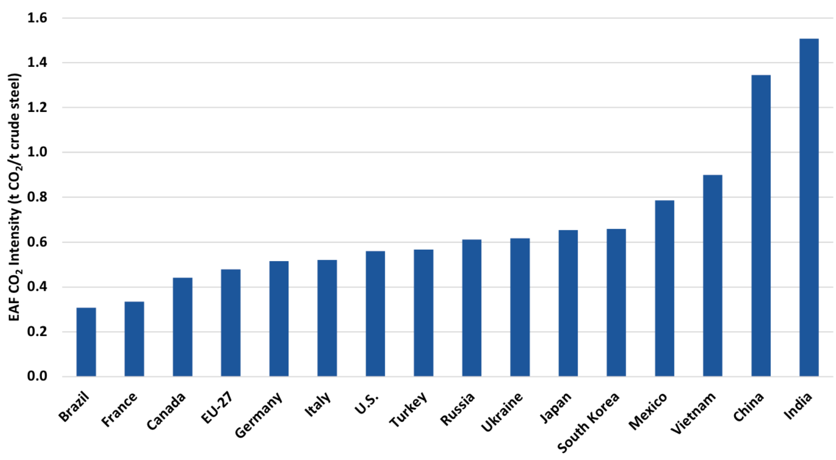
[14] Camila Martinez, Mayara Baggio, and Adriana Carvalho, 'Brazil Ferrous Scrap Exports Reach Record High in 2023 Amid India Steel Boom', *S&P Global* (blog), 2024, https://www.spglobal.com/commodityinsights/pt/market-insights/latest-news/metals/020924-brazil-ferrous-scrap-exports-reach-record-high-in-2023-amid-india-steel-boom.

[15] Mariana Durao and Martha Viotti Beck, 'Brazil Joins Protectionist Wave in Face of Cheap Steel Imports', *Bloomberg*, 2024, https://www.bloomberg.com/news/articles/2024-04-23/brazil-joins-protectionist-wave-in-face-of-cheap-steel-imports.

[16] AJG Simoes and CA Hidalgo, 'Brazil Exports, Imports, and Trade Partners', The Observatory of Economic Complexity, 2021, https://oec.world/en/profile/country/bra.

In Brazil, production is distributed in ten states but concentrated in Minas Gerais (31%), Rio de Janeiro (29%), and Espírito Santo (17%), in the southeast region. Production is divided among twelve business groups, of which 90% of the output comes from six companies—ArcelorMittal (AM), Gerdau, Ternium, CSN, Usiminas, and CSP. ArcelorMittal and Gerdau account for almost 50% of total steel production followed by CSN, Ternium, CSP (recently acquired by AM), and Usiminas. Brazil has a total of twenty-five iron and steel plants as of April 2024[17]; ten EAFs, thirteen integrated BFs, one BF exclusively for ironmaking, and one unclassified.

CO_2 Intensity of EAF Steel Production in Countries/ Regions in 2019

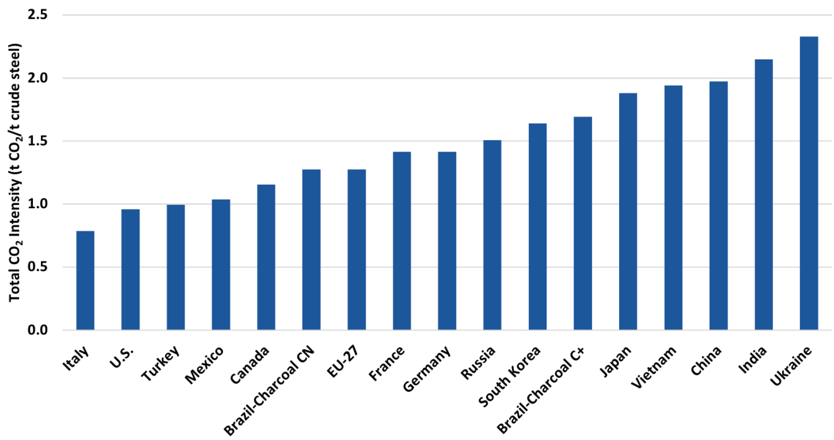


Source: Hasanbeigi, 2022[18]

[17] Caitlin Swalec and Astrid Grigsby-Schulte, 'Pedal to the Metal 2023: Time to Shift Steel Decarbonization into High Gear' (Global Energy Monitor, 2023), https://globalenergymonitor.org/report/pedal-to-the-metal-2023-time-to-shift-steel-decarbonization-into-high-gear/.

[18] Ali Hasanbeigi, 'Steel Climate Impact, An International Benchmarking of Energy and CO_2 Intensities' (Global Efficiency Intelligence, 2022).

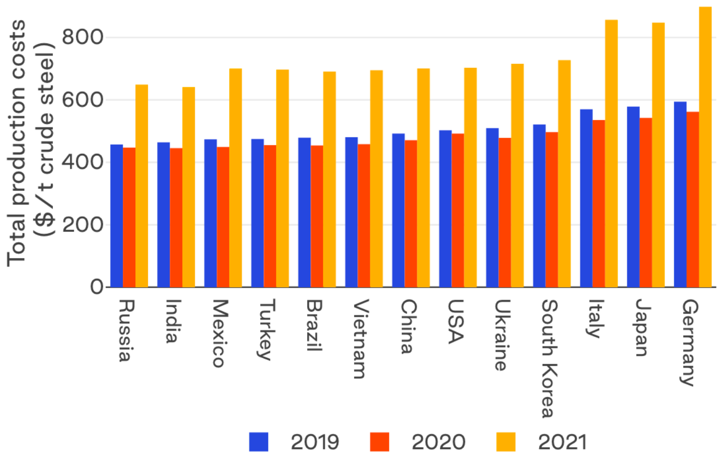
Total CO_2 Emissions Intensity of Steel Industries in 2019



Source: Hasanbeigi, 2022[19]

Note: 'Brazil-charcoal CN' refers to when charcoal is considered carbon neutral; 'Brazil-charcoal C+' refers to when it is not considered carbon neutral

Total Steel Production Costs in Different Countries, 2019 to 2021



Source: TransitionZero and GEI, 2022[20]

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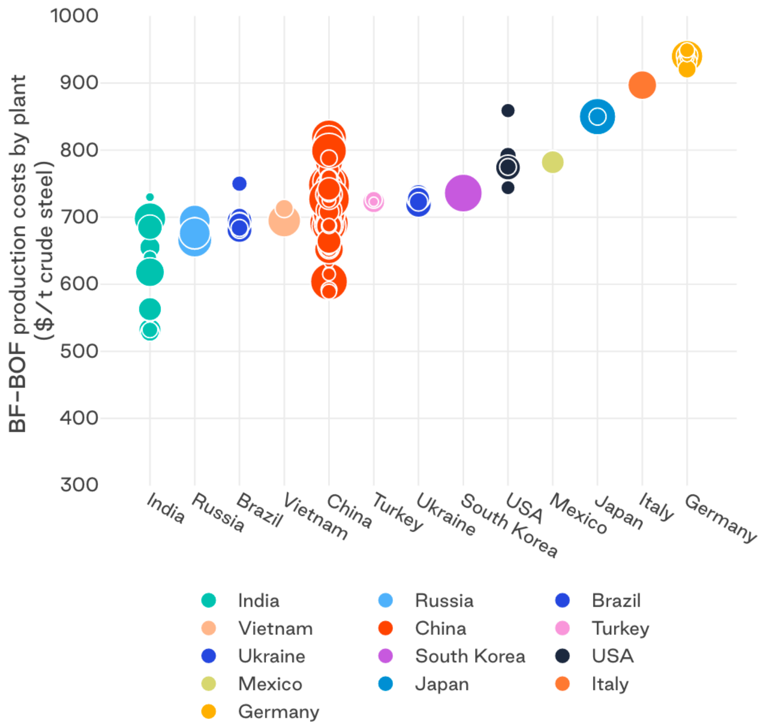
[19] Hasanbeigi.

[20] TransitionZero and GEI, 'Global Steel Production Costs, a Country and Plant-Level Cost Analysis' (TransitionZero & Global Efficiency Intelligence, 2022).

Plant Level BF-BOF Steel Production Costs in Different Countries 2021

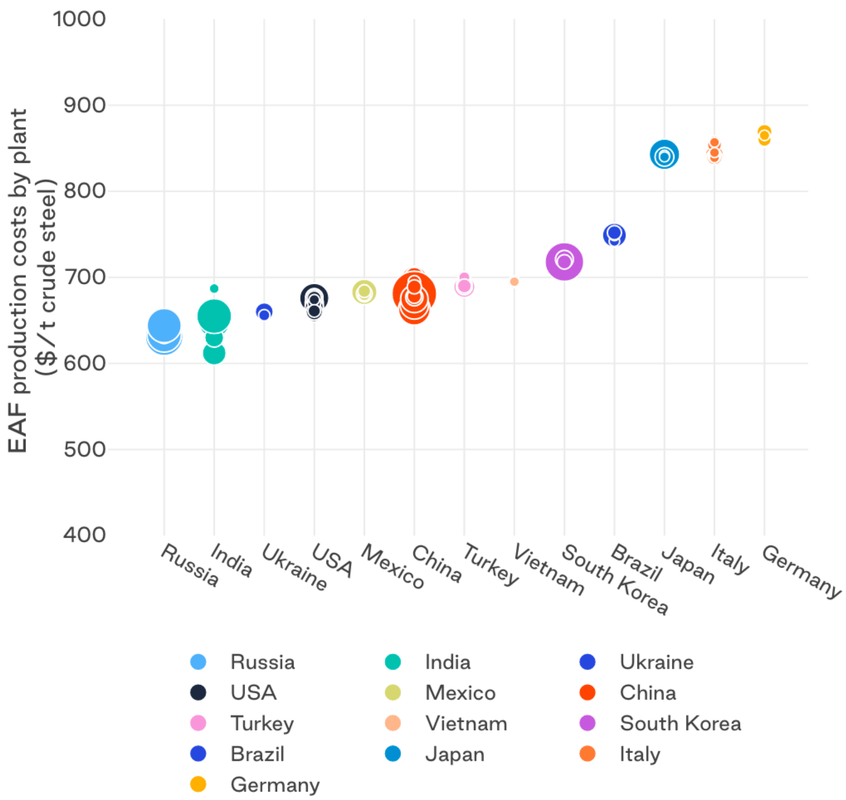


Source: TransitionZero and GEI, 2022[21]

Note: Each dot represents a plant, while the size of the dot is proportional to the plant's installed capacity

[21] TransitionZero and GEI.

Plant Level EAF Steel Production Costs in Different Countries in 2021



Source: TransitionZero and GEI, 2022

Note: Each dot represents a plant, while the size of the dot is proportional to the plant's installed capacity

3.5. COMPANIES MANUFACTURING IN BRAZIL

In Brazil, ArcelorMittal (AM) is responsible for 38% of national production. AM Brazil is owned by ArcelorMittal S.A, a Luxembourg based steel manufacturing corporation formed in 2006 from the merger of Arcelor and Mittal Steel. The parent company is the second largest steel producer in the world. AM Brazil production is largely based on coal, charcoal, and electricity inputs. Worldwide, the company is investing considerably in low-carbon technologies such as DRI. ArcelorMittal Tubarao signed an MOU with EDP, an energy company, in October 2023 to assess the feasibility of a pilot for the production and use of green hydrogen in steelmaking.[22] The plant has started manufacturing and selling 'lower carbon' steel in January 2024 using natural gas in blast furnaces to replace some of the coking coal. The products contain 75% lower emissions than average ArcelorMittal steel products, according to the company.[23] In a July 2022 interview, AM CEO Mittal told analysts that the purchase of steelmaker CSP is part of AM's drive to become a world leader in steel decarbonization. The CSP plant based in the state of Ceara has "great potential due to investments there in renewable energy and plans for a green hydrogen production hub".[24] The company runs nine plants; four in Minas Gerais, one in Ceara, one in Sao Paulo, two in Rio de Janeiro, and one in Espirito Santo.

Gerdau company accounts for 20% of national production. It operates both BF-BOFs and EAFs, and in several plants, uses charcoal in BFs. Gerdau runs steel manufacturing facilities in ten countries across the Americas – Brazil, Argentina, Canada, Colombia, Dominical Republic, Mexico, Peru, U.S., Uruguay, and Venezuela. Among US producers, Gerdau U.S. sells structural steel with the lowest ***embodied carbon*** (in CO_2e/ton) due to the use of EAFs powered by renewables (*i.e.*, 0.527 in the Petersburg plant, 0.686 in Certersville, and 0.713 in the Midlothian plant),[25] compared to the closest competitor

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[22] EDP, S.A., 'EDP and ArcelorMittal Sign Agreement for Green Hydrogen Project for Steel Production in Brazil', edp.com, 2023, https://www.edp.com/en/news/edp-and-arcelormittal-sign-agreement-green-hydrogen-project-steel-production-brazil.

[23] Halina Yermolenko, 'ArcelorMittal Closes First Deal to Sell Green Steel in Brazil', *GMK Center* (blog), 2024, https://gmk.center/en/news/arcelormittal-closes-first-deal-to-sell-green-steel-in-brazil/.

[24] Diana Kinch and Clement Choo, 'ArcelorMittal to Consider Downstream Options for Brazil Steel Slabmaker CSP', *S&P Global Commodity Insights* (blog), 2022, https://www.spglobal.com/commodity-insights/en/news-research/latest-news/metals/072822-arcelormittal-to-consider-downstream-options-for-brazil-steel-slabmaker-csp-ceo.

[25] Gerdau, 'Gerdau Structural Steel: Lowest Embodied Carbon in the U.S.', Gerdau, accessed 12 December 2024, https://www2.gerdau.com/market-applications/construction.

(*i.e.*, 0.816 CO_2e/ton). The firm claims extensive experience in ***scrap steel recycling in EAFs***, and one of the lowest emission averages in the steel industry which is approximately half the global industry average.[26] 73% of Gerdau operations use ferrous scrap as input via EAFs.[27] In Brazil, the company runs seven plants (two in Minas Gerais, two in Sao Paolo, two in Parana, and one in Rio de Janeiro). As part of an effort to increase iron ore production and reduce production emissions, Gerdau recently announced its intention to invest $666 million in 2023 in new production facilities in Minas Gerais by 2026 and continue the construction of solar plants in Brazil and the U.S. to power EAFs. The company's recent climate change strategy sets a target of reducing CO_2 emissions from 0.93 tCO_2e/t of steel (in 2020) to 0.83 tCO_2e/t (in 2031).

Ternium, CSN, and Usiminas are responsible for around 10% of national production each while relying largely on coal for steel manufacturing. In Brazil, the companies run six plants in total (one plant in Rio de Janeiro by Ternium, one plant in Rio de Janeiro by CSN, and two plants by Usiminas—one in Minas Gerais, the other in Sao Paulo). Ternium runs 18 production centers across the Americas and was formed by the merger of an Argentine, Venezuelan, and Mexican company in 2005.[28] Ternium and Vale recently signed an agreement to focus on green technologies for iron reduction. Ternium aims to reduce its emissions by 20% by 2030 through energy efficiency, increasing use of charcoal, CCUS, and increasing use of renewables and scrap metal. In 2021, the company's global embedded carbon was 1.7 tCO_2e/t of steel in 2021.

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[26] Brian Taylor, 'Gerdau Cites Recycling in Decarbonization Summary', *Recycling Today* (blog), 2022, https://www.recyclingtoday.com/news/gerdau-decarbonization-scrap-steel-recycling-brazil-usa/.

[27] Renato Rostás, 'Brazil's Gerdau to Invest $277mln into Solar, Wind Powered Steelmaking', *Fastmarkets* (blog), 2022, http://fastmarkets-prod-01.altis.cloud/insights/brazils-gerdau-solar-wind-powered-steelmaking/.

[28] Green Steel World Editorial Team, 'Ternium Strengthens Its Commitment towards Green Steel', *Green Steel World* (blog), 2022, https://greensteelworld.com/ternium-strengthens-its-commitment-towards-green-steel.

Aco Verde Brazil (AVB) is responsible for only 1.7% of national production but is at the forefront of steel decarbonization in Brazil. It is the first steel company in the world to receive a carbon neutral certification.[29] AVB runs one plant in Maranhao, which uses renewable energy, eucalyptus for sustainable charcoal instead of coal, and reuses process gas from the BF and BOF.

Additional steel producers in Brazil include Mexico-based Grupo Simec, which operates four plants (two in Sao Paulo and two in Espirito Santo). The following companies run one plant each: Vale in the state of Para, Vallourec in Minas Gerais, Grupo Viena in Maranhao, and Aperam SA in Minas Gerais.

3.6. INTERNATIONAL FIRMS AND CLEAN TECHNOLOGIES

Biomass for BF: Expertise in the use of biofuel for steel production is concentrated in a few countries and firms with Brazil leading the way. As of 2021, roughly 11% of Brazilian steel production was based on charcoal derived from biomass.[30] AVB recently received the world's first carbon neutral certification for steel for its eucalyptus charcoal process. Other domestic firms that use charcoal include ArcelorMittal and Rio Tinto. Internationally, Bluescope Steel in Australia is currently exploring the use of biochar as part of its transition to green steel production.

[29] Adriana Carvalho, 'Brazil's AVB Receives Carbon-Neutral Steel Certificate', *S&P Global Commodity Insights* (blog), 2021, https://www.spglobal.com/commodity-insights/en/news-research/latest-news/agriculture/032521-brazils-avb-receives-carbon-neutral-steel-certificate.

[30] Gregor Clark and Caitlin Swalec, 'Forging a Sustainable Future: Brazil's Opportunity to Lead in Steel Decarbonization', 27 August 2024, https://globalenergymonitor.org/report/forging-a-sustainable-future-brazils-opportunity-to-lead-in-steel-decarbonization/.

Electrochemical process. The company Electra, based in the U.S. is piloting a low temperature electro chemical process that can utilize low grade ores and be powered by intermittent renewable energy to produce iron that can be processed by EAFs. A recently launched pilot aims to manufacture 1 sq meter plates. The company will gradually increase its production capacity to validate its modular design which involves connecting the iron plates.[31]

Electrowinning. ArcelorMittal and John Cockerill (company specializing in the development of steel processing facilities and electrolysers) recently announced plans to construct the world's first industrial scale low temperature iron electrolysis plant by 2027 in France. The plant will first produce between 40 and 80 thousand tonnes of iron plates per year and then increase production to between 300,000 and 1 million tonnes. The process is carbon free and uses cold direct electrolysis to extract iron from ore using electricity. It is one of three decarbonization pathways the company is working on. The other two rely on modifying the blast furnace for clean energy such as bioenergy and CCUS and hydrogen based DRI respectively.[32]

Electric smelting reduction. A collaboration between Rio Tinto, BHP, and BlueScope aims to commission a pilot facility by 2027 to produce molten iron using renewables-powered direction-reduced iron technology in Australia.[33] Voestalpine aims to reduce

[31] Akshat Rathi, 'Next-Generation Green Steel Technology Hits a Crucial Milestone', *Bloomberg* (blog), 2024, https://www.bloomberg.com/news/features/2024-03-27/gates-backed-startup-pilots-green-steel-process-plans-factory.

[32] ArcelorMittal, 'ArcelorMittal and John Cockerill Announce Plans to Develop World's First Industrial Scale Low Temperature, Iron Electrolysis Plant', ArcelorMittal, 2023, https://corporate.arcelormittal.com/media/press-releases/arcelormittal-and-john-cockerill-announce-plans-to-develop-world-s-first-industrial-scale-low-temperature-iron-electrolysis-plant/.

[33] Bluescope, 'Australia's Leading Iron Ore Producers Partner with BlueScope on Steel Decarbonisation', 2024, https://www.bluescope.com/news/australia-s-leading-iron-ore-producers-partner-with-bluescope-on.

emissions by 2027 by commissioning EAFs to be powered by renewables at two sites in Austria and shutting down BFs.[34]

Hydrogen direct reduction is one of the most widely explored forms of steel decarbonization, particularly in Europe. ArcelorMittal, Blastr Green Steel, Calix, Fortescue Metals, GravitHy, H2 Green Steel, HBIS Group, Hydnum Steel, Halyron, and Jindal Steel are all investing in the new technology. H2 Green Steel is planning a large-scale plant that will be up and running by 2026.

Molten oxide electrolysis process uses electricity to directly reduce and melt iron ore. If electricity is produced using renewable energy, then no fossil fuels need be used. Boston Metals is currently piloting a mid-sized demonstration project in the U.S.

Natural gas direct reduction to hydrogen direct reduction: ArcelorMittal, Chia Baowu Group, HBIS Group, Liberty Steel Group, Meranti Steel, Salzgitter Group, Techint Group, and Thyssenkrup are exploring this technology.

Wind and hydro power renewable energy sources are used to produce green hydrogen, which is in turn used as a reducing agent in steelmaking process; the technology is being developed by the Swedish company H2 Green Steel.

Recycling technologies related to the steel industry are developed by the German company CleanSort58 focused on technologies for the metal industry that rely on advanced sensors and machine learning to enable efficient sorting and scrap metal

[34] Voestalpine, 'Voestalpine Greentec Steel', Voestalpine, accessed 12 December 2024, https://www.voestalpine.com/greentecsteel/en/.

separation. To distinguish metals and alloys, the Finnish company Magsort has developed magnetic separation technologies.

Advanced manufacturing technologies focus on 3D printing technologies and their applications for steel and metal manufacturing *(i.e.*, Additive Works is developing metal 3D printing software solutions. Lithography-based metal manufacturing (LMM) technologies are developed by MetShape supporting prototyping, high-volume production, sintering services and finishing services.

Artificial intelligence technologies provide support for both the green and digital transition. The company Smart Steel, for example, offers AI-based software solutions helping to improve the quality and the energy demand of steel production while managing CO_2 efficiency.

Digital technologies developed for advanced manufacturing support robotics and automation, artificial intelligence, online platforms, cloud technologies and other software solutions.

Table: Green Iron or Steel Projects (in operation)

Technology	Company	Scale	Year	Location
Bio-charcoal	Aço Verde do Brazil (AVB)	Full scale	2018	Brazil
Bio-charcoal	ArcelorMittal	Demo	2024	Belgium
Electrowinning	ArcelorMittal	Pilot	2023	France
Hydrogen DR	SSAB	Pilot	2021	Sweden
Hydrogen DR	Voestalpine	Pilot	2021	Austria
Hydrogen DR	Hylron	Pilot	2023	Germany
NG and H DR	DRAL	Pilot	2022	Germany

Green hydrogen *as a reducing agent in steelmaking*	H2 Green Steel	Start-up	2020	Sweden
H2 enriched NG DR	HBIS	Pilot	2021	China
Hydrogen DR	Voestalpine	Pilot	2019	Austria
Recycling	CleanSort	Full-scale	2018	Germany
Metal separation	Magsort	Full-scale	2014	Finland
Metal 3D printing *software solutions*	Additive Works	Start-up	2015	Germany
Prototyping and high-volume production	MetShape	Start-up	2019	Germany
Smart Steel	AI-based software solutions	Early-stage VC	2019	Germany

3.7. ANALYSES & IMPLICATIONS FOR POLICY AND INDUSTRIAL STRATEGY

A. Expansion of EAF-based Steel Production and Steel Scrap Recycling

While Brazil's Electric Arc Furnace (EAF)-based secondary steel production is demonstrated as a low-carbon option, the current adoption of EAF technology is low, and steel scrap recycling remains limited. In 2020, only 8 million tonnes of steel scrap were recycled.[35] To drive the transition towards a more sustainable and circular steel sector, policies are critical to incentivize broader EAF deployment and improve steel scrap recycling practices. Economic incentives and other benefits such as tax credits and grants are policy options that can encourage EAF technology use and motivate the phase-out of

[35] Instituto Aço Brasil, 2021.

energy-intensive and inefficient BF-BOF production assets for steel manufacturers in Brazil. As EAF steel production is considerably less carbon-intensive, in comparison with BF-BOF steel production, when most or all of EAF feedstock is recycled steel scrap, Brazil may consider implementing programs aimed at raising steel recycling rates. This could involve creating a certification system for recycled steel to ensure quality and traceability, as well as fostering collaboration with municipalities and waste management companies to improve the collection, sorting, and redistribution of steel scrap. Public-private partnerships in Brazil can also support necessary infrastructure for steel recycling, particularly in untapped sources such as landfills and other waste sites.

B. Investment in Clean Technological Innovations: Hydrogen Direct Reduction and Bio-Charcoal

Hydrogen direct reduction and bio-charcoal are innovative pathways for decarbonizing Brazil's steel sector, while their full potential has yet to be realized. As ArcelorMittal and other leading steel manufacturers in Europe set up hydrogen direct reduction facilities to meet carbon neutrality goal, the Brazilian government can support the scaling of these technologies by creating frameworks in deployment and market formation. This would help build confidence in hydrogen and biomass technologies as a viable and sustainable input for steel production. The government can actively support related research and development through competitive grants, tax credits, and low-interest loans for research institutions, steel manufacturers, and technology developers. In particular, Aco Verde Brazil (AVB) has demonstrated success in carbon-neutral steel production using eucalyptus charcoal and reached negative 0.04 mt of CO_2 per ton of steel in 2020. Incentives in basic and applied research can increase absorptive capacity, allowing domestic firms to take advantage of positive spillovers. Collaborations and partnerships should be encouraged to facilitate technology transfer and knowledge sharing, positioning Brazil as a sector leader in low-carbon steel technologies.

However, technological innovation alone is not sufficient to materialize these innovative solutions. Complementary high-skilled workforce is essential. The government can consider investing in large-scale upskilling and retraining programs focused on low-carbon steel technological skills such as material sciences, energy efficiency, and digital manufacturing technologies, which are critical to achieve the low-carbon transition. These workforce development programs should be designed in collaboration with industry stakeholders and educational institutions to ensure adequate alignment with emerging industry needs. To further stimulate knowledge sharing, Brazil may consider develop specialized innovation hubs or research clusters that focus on green steel technologies, including biofuels, hydrogen, and digital manufacturing. These hubs could foster interactions between steel producers, academic researchers, and technology developers, accelerating the development and commercialization of innovative low-carbon steelmaking processes.

C. Feasibility Assessment of Carbon Capture, Utilization, and Storage (CCUS)

While CCUS technology can play a role in reducing emissions from the steel sector, current deployment has not reached the capacity to decarbonize steel production fully. If new steel production facilities in Brazil are designed with the expectation of relying solely on CCUS for emissions reductions, there are risks of stranded assets. Therefore, the capacity and feasibility in which CCUS technology reduces emissions from blast furnaces should be examined. Existing infrastructure in regions such as the southeast of Brazil, where connections to the depleted Campos Basin are feasible, may allow for affordable transportation of captured carbon. Clear guidelines for the role of CCUS in Brazil's long-term decarbonization strategy can ensure that the technology is used as a practical measure in the net-zero pathway.

D. Integration of Renewable Energy with Steel Production

One of the most significant barriers to reducing emissions in Brazil's steel sector is the high cost of electricity. Additionally, scaling up Electric Arc Furnace can further create considerable stress to Brazil's existing electric power grid. To achieve sustainable decarbonization, electricity supplied to steel manufacturing should prioritize the utilization of renewable sources. To that end, the government can focus on integrating renewable energy sources such as wind, solar, and hydropower abundant in Brazil into the steelmaking value chain. Energy storage and transmission facilities can support low cost and reliable renewable electricity. Thus, policy options should be introduced to incentivize the development of renewable energy infrastructure near steel manufacturing hubs, including offering tax credits and other economic benefits for renewable energy developers. Moreover, long-term contracts and price stability guarantees for renewable energy should be established to mitigate uncertainty for steel producers. Furthermore, government programs to reduce the costs of green hydrogen production can be explored, as hydrogen in Brazil has great potential to significantly reduce emissions from steel production when integrated.

E. Government Procurement and Financing for Green Steel

The Brazilian government has a strong tradition of using public procurement to stimulate development. This mechanism can be harnessed to accelerate the adoption of green steel technologies. By committing to the use of green steel materials in public infrastructure projects, such as government buildings, transportation systems, and other large-scale public facilities, the government can create demand for sustainable steel and nurture the domestic green steel market. Demand-side policy options such as Advance Market Commitments (AMCs), contractual agreements that guarantee future purchase of green industrial products under development, and Contracts for Difference (CfDs), price guarantee for manufacturers, have seen success for green industrial products in the U.S., Germany, and France. Thus, a reliable market for green steel producers is integral to promote green Brazilian steel and also to motivate the private sector to invest the sector. In addition, the government can consider coordinating funding from major national initiatives such as Novo PAC, Nova Indústria Brasil, and the Ecological Transition Plan to send strong market signals for existing or pre-commercialized low-carbon technologies. If designed and implemented effectively, government-led procurement and funding can help catalyze the takeoff of low-carbon solutions in Brazil's steel sector and facilitate green industrial strategies going forward using standards, resources and tools developed.

4. Cement: Industry and Technology

4.1. INTRODUCTION

Brazil has a large and diverse cement industry with one of the lowest global carbon footprints due to previously implemented efficiency measures and the relative greenness of the national grid. The rapid decarbonization of the industry requires a combination of energy efficiency measures, fuel switching, clinker substitution, process changes, and carbon capture utilization and storage (CCUS). Cement poses a unique problem in industrial decarbonization because the production process itself releases CO_2; CCUS is therefore particularly important for the decarbonization of the sector. New production processes are currently in the demonstration phase, some of which sidestep carbon capture, such as the use of silicate rocks and electrolytic technology.

It is important to note, however, that exports are currently extremely low, while the vast majority of cement produced in Brazil is used domestically. The CBAM provides a unique opportunity to create new markets for cement exports if production is expanded. There are several short- to medium-term abatement technology options that can already be deployed. Simultaneously, these options can be treated as opportunities for Brazil not only to invest in but also to capitalize on over the longer term. Accordingly, industrial strategy and policy roll-out for the steel and cement sectors should reflect temporal policy coordination over the short-, mid-, and long-term.

4.2. TRADITIONAL PRODUCTION METHOD

Cement manufacture is a three-stage process consisting of (i) raw materials preparation, (ii) clinker production, and (iii) clinker grinding with other components to produce cement. Naturally occurring calcareous deposits are extracted by heavy duty machines from quarries which are often located close to the cement plant to obtain calcium carbonate. Small amounts of other materials, such as iron ore, bauxite, shale, clay or sand, may also be excavated from deposits to provide the extra iron oxide, alumina and silica needed in the chemical composition of the raw mix. The quarried materials are crushed, typically to less than ten centimeters in size, and are transported to the cement plant. The raw materials are mixed to achieve the required chemical composition in a process called "prehomogenisation". The crushed material is then milled to produce a fine powder called "raw meal".[36]

The raw meal is then heating in the kiln at temperatures of over 900 C. Simultaneously calcination (*i.e.*, the decomposition of limestone into lime) takes places in a combustion chamber. The chemical decomposition of limestone into lime and CO_2 typically emits 60-70% of the total CO_2 emissions, whereas fuel combustion generates the rest of the carbon emissions. Approximately 65% of all fuel is burnt in this step of the process. The pre-calcinated meal is then mixed with the lime and heated in the kiln to complete the calcination of limestone and melt the meal into the clinker, which is then cooled and mixed with other mineral components and inter-ground with gypsum to produce cement. Cement related emissions comprise process emissions and emissions from thermal and electrical input. Cement production is responsible for about 88% of the CO_2 emissions associated with concrete production.[37]

[36] International Energy Agency, 'Technology Roadmap: Low-Carbon Transition in the Cement Industry' (International Energy Agency, 2018).

[37] Ali Hasanbeigi and Adam Sibal, 'What Are Green Cement and Concrete? Definitions from Standards, Initiatives, and Policies around the World' (Florida, United States: Global Efficiency Intelligence, 2023).

4.3. CLEANER PRODUCTION OPTIONS

Methods for reducing cement production related emission include (a) *energy efficiency improvements*, (b) *the use of alternate fuels*, (c) *clinker-to-cement ratio reductions*, and (d) *carbon capture utilization and storage*.

Energy efficiency improvements involve the deployment of technologies in new cement plants and retrofitting of existing facilities to improve energy performance levels.

Switching to alternate fuels such as biomass and waste materials in cement kilns would offset the consumption of carbon-intensive fossil fuels. Wastes include biogenic and non-biogenic waste sources, which would otherwise be sent to a landfill site, burnt in incinerators, or improperly destroyed.

Reducing the clinker-to-cement ratio involves increasing the use of supplementary cementing materials (SCMs), to decrease the amount of high emissions clinker required per ton of cement. The most commonly used SCMs today are *fly ash* from coal plants and *slag* from steel mills — two materials that are limited in supply, expensive to transport and expected to decrease in availability as the power and steel sectors decarbonize. Next generation substitutes such as calcinated clay are rapidly maturing and hold potential to bridge the gap in solutions. *Calcined clay* is produced by heating sources of kaolin clay (*e.g.*, paper sludge) to temperatures between 650°C and 750°C. The resulting material can be added to cement as a substitute for clinker. Alternative low or zero carbon chemistries involving non carbonate sources, magnesium silicates, raw clay, and carbonation of calcium silicates also provide a possible avenue for further clinker-related emissions reductions, though these technologies are in an early stage of development.[38]

Carbon capture utilization and storage integrates carbon capture technology into the cement manufacturing process for long-lasting storage or sequestration.

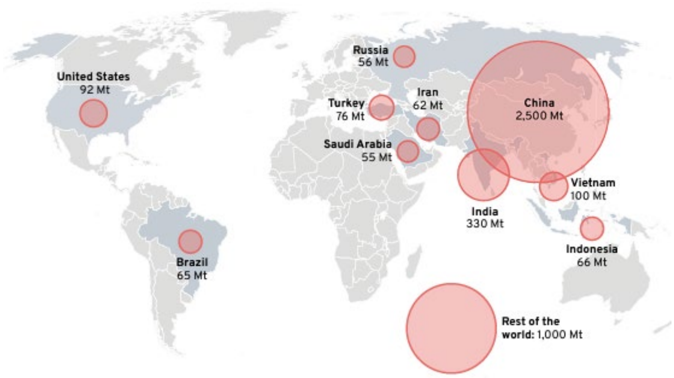
4.4. BRAZILIAN INDUSTRY

As of 2022, Brazil registered 91 cement manufacturing plants controlled by 23 industrial groups, with an annual cement production capacity of 94 million tons. Cement production, sales, and consumption stood at 65.8, 64.7, and 64.3 million tons in 2021, respectively. In 2022, cement exports amounted to USD 32 million, making it the 65th largest exporter of cement in the world.[39] Infrastructure, housing construction, and real-estate development contributed to a 6.6% increase in consumption year-on-year since 2020. In contrast, cement sales have been decreasing 3% year-to-year to 63.1 million tons in 2022, according to the Brazilian National Cement Industry Association (SNIC). Simultaneously, exports have declined to 0.40 million tons in 2022 (from 0.47 million tons in 2021).

[38] Mission Possible Partnership, 'Making Net-Zero Concrete and Cement Possible: An Industry Backed, 1.5C Aligned Transition Strategy' (Mission Possible Partnership, 2023).

[39] Simoes and Hidalgo, 'Brazil Exports, Imports, and Trade Partners'.

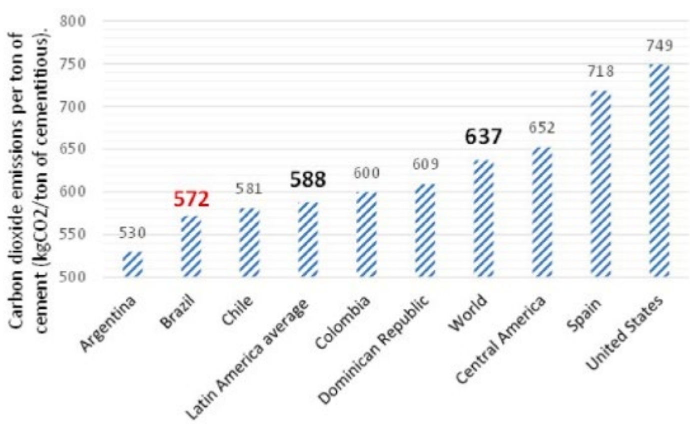
Ten Largest Cement Producing Countries in 2021



Source: U.S. Geological Survey

At the same time, as a global cement producer, the Brazilian cement sector has several advantages. Firstly, it has one of the lowest global carbon footprints due to measures adopted over the past few decades such as the use of limestone and calcinated clay to replace clinker. The additional low-carbon footprints are associated with Brazil's unique electricity matrix which provides access to relatively clean electricity through the grid.[40]

Comparison of CO_2 Emissions Per Ton of Cement Across Selected Countries in 2015



Source: Rego, 2023

[40] Rego et al., 'Carbon Dioxide Uptake by Brazilian Cement-Based Materials'.

4.5. COMPANIES MANUFACTURING IN BRAZIL

In 2019, 10 of the 23 largest industrial groups in the cement business including Cimento Tupi, CSN Cimentos, InterCement and Votorantim signed an agreement committing to a 34% reduction in emissions by 2050. Other members of the SNIC (Sindicato Nacional da Indústria do Cimento) include companies Apodi, Cimar, Strong Cement, National Cement, Pajeu Cement, Green Cement From Brazil, Vittoria Cement, Zombie Cement, CIPLAN, CSN, ICIBRA, Itambe, Joao Santos, Carmocal Mining, Mizu, Pozosul, Revemar, Secil, Tupi, Valobras.[41]

4.6. INTERNATIONAL FIRMS AND CLEAN TECHNOLOGIES

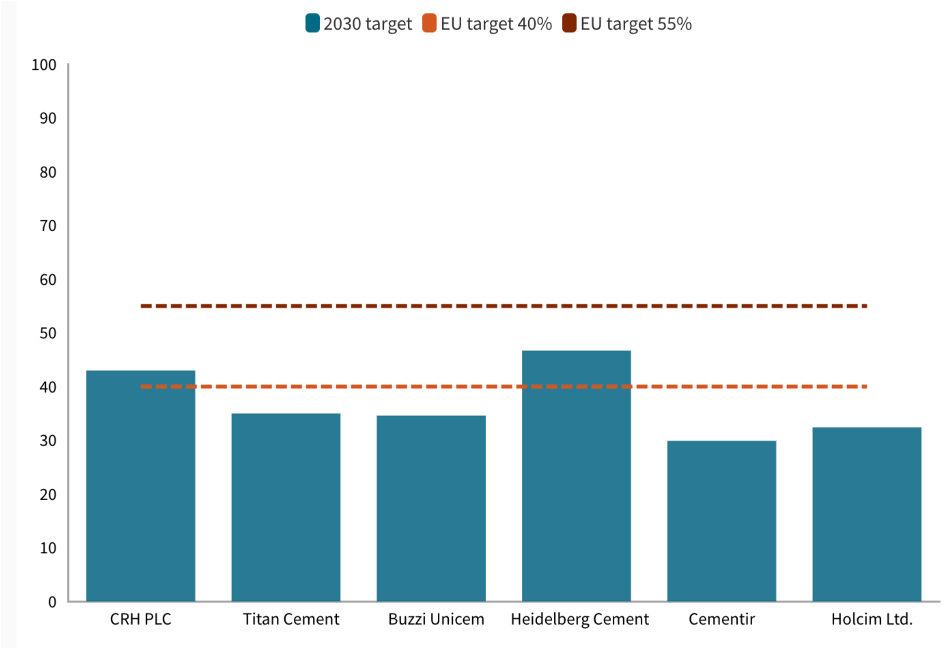
Carbon capture utilization and storage: Heidelberg Materials is expected to receive a $500 million grant from the U.S Department of Energy for a project that aims to capture and store 95% of the CO_2 emitted by its Indiana-based cement plant. It is currently the only company to have full scale CCS based plants under construction in Canada, Norway, and Belgium. Holcim is undertaking one of the biggest U.S. cement CCUS projects at its plants in Colorado and Missouri. Between 2021 to 2022, the company has achieved a 21% CO_2 emissions reduction through reduced clinker use in direct production. Recently, it has received a $100-million investment to increase production capacity by 600,000 tons per year, with reduced annual CO_2 emissions by 400,000 tons in its biggest U.S. based cement plant. Other companies with CCS plants under development are in Germany, Spain, Austria, Poland, Belgium, and Croatia. Aalborg Portland (Denmark),

[41] Sindicato Nacional da Indústria do Cimento, 'Locations', accessed 3 December 2024, http://snic.org.br/fabricas-localizacoes.php.

Aggregate Industries (UK), EQIOM (France), and Titan Cement (Greece) all have full-scale CCS plants under early development.

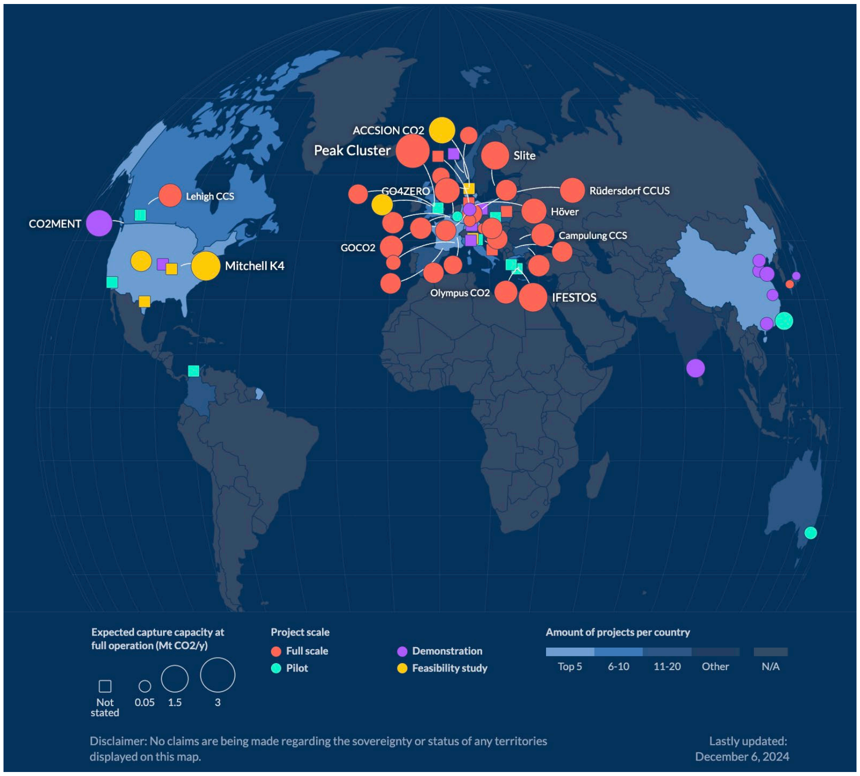
Selected cement companies' Scope 1 carbon reduction 2030 targets vs EU target

(*Percentage reduction compared with 1990 figures*)



Source: S&P Global, 2022

International CCS Cement Projects



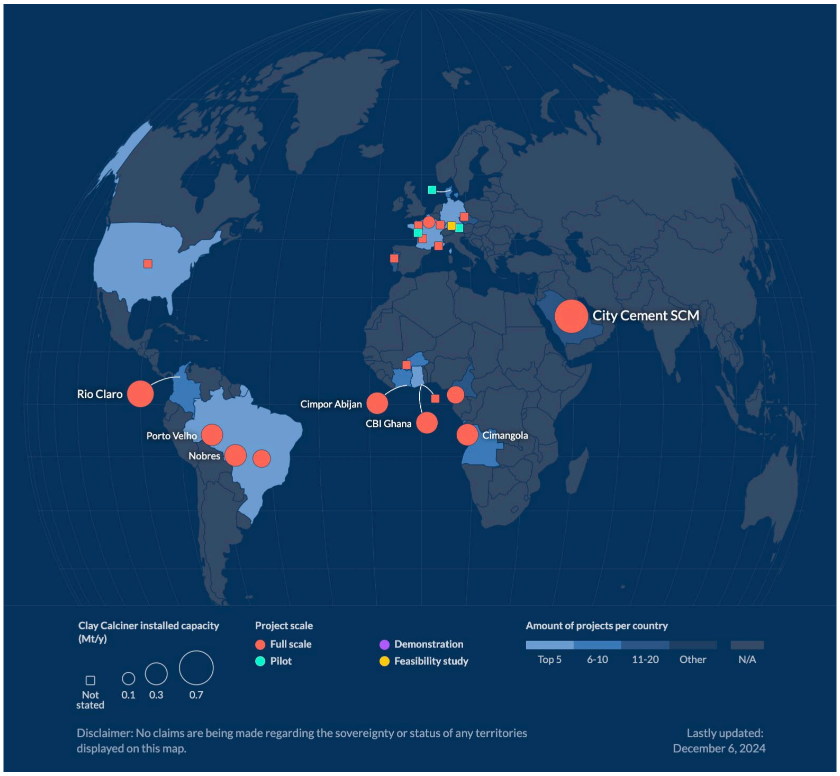
Source: Leadership Group for Industry Transition, 2024

Clay calcination kilns: Heidelberg Materials announced a 65-million Euro investment in a French plant in 2023 to decarbonize its operations through low-carbon calcinated clay. The company is also piloting the technology in Ghana, where the world's largest flash calciner is currently being built.[42] Holcim launched calcinated clay cement operations in France, via its subsidiary Lafarge France, in 2021 that is claimed to deliver cement with a 50% reduction in CO_2 footprint compared to standard cement. Its Saint Pierre la Coer plant can produce 500,000 tons of such cement per year. The operations are powered

[42] Heidelberg Materials, 'Low-Carbon Cement Based on Calcined Clay: Heidelberg Materials Invests €65 Million in France', Heidelberg Materials, 2023, https://www.heidelbergmaterials.com/en/pr-2023-05-15.

with biomass-based fuels to make the process “nearly carbon free”.[43] Other companies with full scale plants under development or in operation include CIMAF (Burkina Faso), NeoCem (France), Cementos Argos (Colombia), Vicat (Brazil and France), Cimpor (Ivory Coast and Cameroon), Ash Grove Cement (U.S.), Votorantim (Brazil), CBI Ghana (Ghana), and Cimangola (Angola).

International Clay Calcination Kiln Projects



Source: Leadership Group for Industry Transition, 2024

[43] Holcim, ‘Holcim Launches Europe’s First Calcined Clay Low-Carbon Cement Operation’, Holcim, 2023, https://www.holcim.com/media/media-releases/first-calcined-clay-cement-operation.

Alternative chemistries. Terra CO_2 Technologies, based in Colorado (U.S.) is developing a drop-in replacement for traditional SCMs using a variety of silicate rocks, including granite, basalt, alluvial sand and gravel, glacial flood gravel and clay-sand mixtures. The estimates provided suggest that every replaced metric ton of cement will result in a 70% reduction in CO_2 emissions compared to pure Portland cement because silicate rock for the most part does not contain embodied CO_2. Brimstone, another U.S.-based company, has developed a new production process that uses calcium silicate rocks like basalt to produce Portland cement. The company turns the calcium silicates into CaO to produce the same product as conventional cement plants, but without CO_2 process emissions inherent in current cement production processes.[44] Brimstone was recently approved for a U.S.-DOE grant of up to $189 million to build its first-of-a-kind commercial-scale demonstration plant for its technology that will be capable of producing 140,000 metric tons per year of the carbon-free Portland cement. Last year, Brimstone earned third-party certification verifying that its Portland cement is structurally and chemically identical to conventional supplies.[45] The company is planning to start building its first pilot plant in 2025 while it starts to plan and design its first commercial-scale plant in 2027 or 2028.

Fuel switching. Sublime Cement is piloting a novel process that switches out fossil-fuel-burning cement kilns with an electrolytic technology, similar to those used to produce clean hydrogen to make cement, in a way that does not emit carbon and runs at close to room temperature. Sublime's electrolyzer uses electricity to extract calcium from calcium

[44] Lauren Kubiak, 'California Companies Secure $700 Million for Cement Decarbonization', *Natural Resources Defense Council* (blog), 2024, https://www.nrdc.org/bio/lauren-kubiak/california-companies-secure-700-million-cement-decarbonization.

[45] Jeff St. John, 'The "clean Cement" Projects Getting $1.5B in Biden Admin Funds', *Canary Media* (blog), 2024, https://www.canarymedia.com/articles/clean-industry/the-clean-cement-projects-getting-1-5b-in-biden-admin-funds.

silicate materials and then precipitate that calcium in a form that can be used to make its final cement product. The company has earned an industry designation finding that its product meets certain performance-based standards for hydraulic cement, and in late 2022, it finished a pilot plant that can produce up to 100 metric tons of cement per year. Its new DOE grant of up to $87 million will fund its first commercial-scale plant in Holyoke, Massachusetts, capable of producing tens of thousands of tons of its cement per year. CemVision[46] claims a 95% CO_2 reduction through industrial byproduct use. Their cement has a unique chemistry that requires less energy. By having to only heat ovens to 1200 degrees Celsius, biofuels and other alternatives such as electrical ovens can be used to replace fossil fuels or waste. In 2022, the startup was admitted to Bill Gates' Energy Breakthrough Fellowship program and was awarded a loan to finance research as well as a demonstration facility for two years.

Building blocks. CarbonBuilt, a company based in Los Angeles (U.S.) is currently piloting a process that eliminates the use of Portland cement in its concrete blocks, drastically reducing the amount of embodied carbon associated with its products. CarbonBuilt's approach involves creating an alternative cement "binder" with calcium-rich waste materials from undisclosed industrial sources. The startup claims its novel technology can reduce overall CO_2 emissions from concrete-making by 70-100%. In May, the company began commercial production of its sustainable concrete at a partner facility in Alabama, where an on-site biomass furnace captures and supplies CO_2. The company says it now plans to produce its Portland-cement-free blocks at "commercial volume" in Alabama starting in 2024.

[46] Mimi Billing, 'Europe's Green Cement Is Taking off — Here Are the Startups Fighting to Lead the $380bn Market', *Sifted* (blog), 2023, https://sifted.eu/articles/europes-green-cement-startups-fight-to-lead-market/.

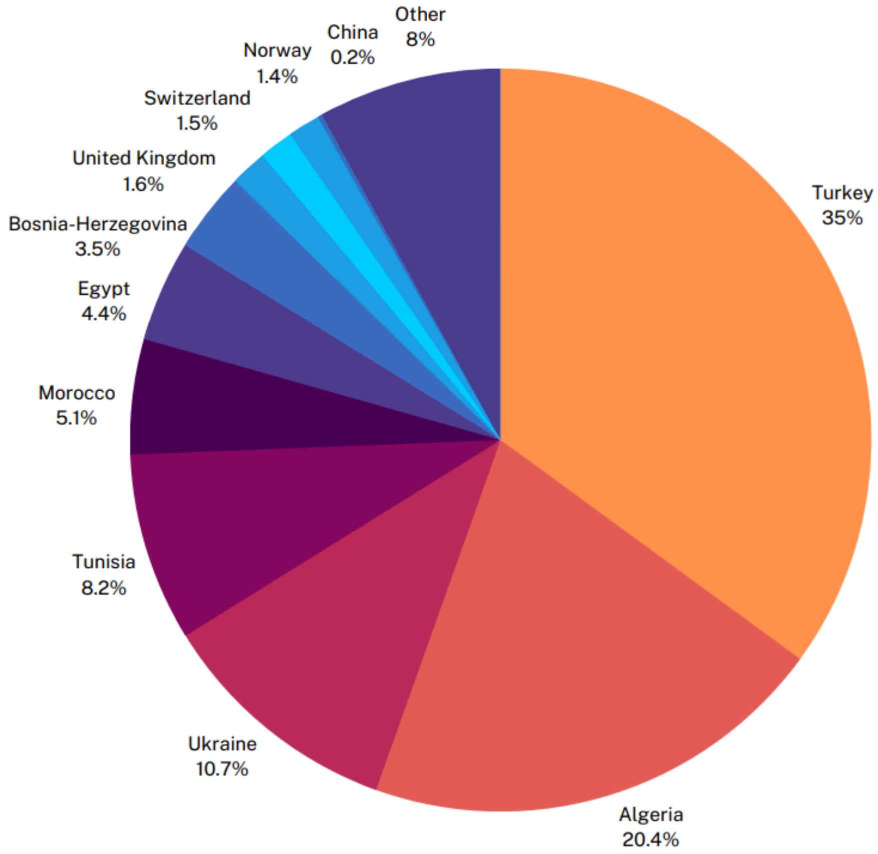
4.7. EUROPEAN CARBON BORDER ADJUSTMENT MECHANISM (CBAM) OPPORTUNITY

In 2026, the CBAM will go into effect for cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen, while anticipating that a full implementation will take around ten years.[47] CBAM levies an import tariff based on the emissions intensity of products and importers are expected to purchase CBAM credits in tons of CO_2 at the EU ETS price. Turkey is currently the largest exporter of cement and clinker to the European Union but produces cement that on average has higher embedded CO_2 per ton than Brazilian cement. Turkish producers have declared that they are determined to lower carbon emissions by focusing on alternative fuels, renewable energy, sustainable raw materials, and efficiency improvements.[48] In addition to Turkey, major cement and clinker exporters to the EU include Algeria, Ukraine, Tunisia, and Morocco. And the CBAM offers a window of opportunity for low-carbon steel manufacturers in Brazil to compete and capture a larger share of the European cement market.

[47] Rathi, 'Next-Generation Green Steel Technology Hits a Crucial Milestone'.

[48] Binny Sabharwal, 'Turkish Cement Determined to Lower Carbon Emissions', *S&P Global Commodity Insights* (blog), 2024, https://www.spglobal.com/commodity-insights/en/news-research/latest-news/fertilizers/092024-interview-turkish-cement-determined-to-lower-carbon-emissions.

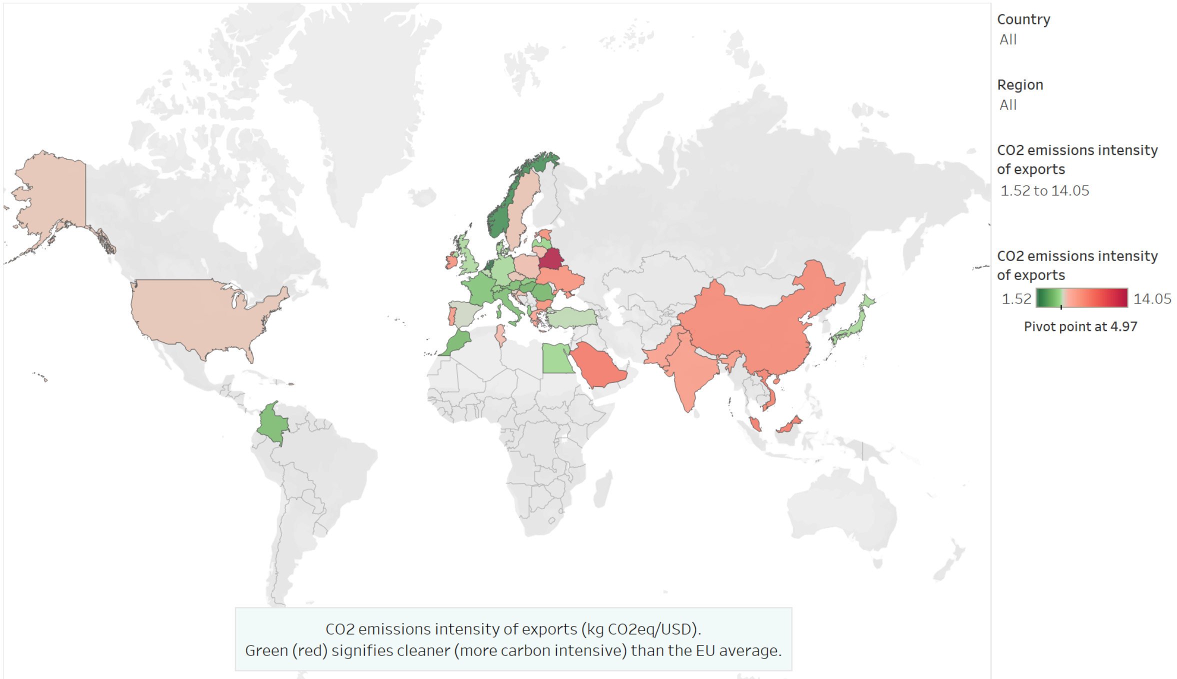
Sources of Cement and Clinker Imports to The EU In 2023



Source: Cembureau[49]

[49] Cembureau (The European Cement Association) Trade Report, 2023, https://cembureau.eu/media/3z1p4m5c/eu-cement-industry-trade-statistics-data-06-2023-edit-09-2023.pdf

CO_2 Emissions Intensity of Cement Exports (Largest Exporters to the EU)



Source: World Bank Relative CBAM Exposure Index, 2023

4.8. ANALYSES & IMPLICATIONS FOR POLICY AND INDUSTRIAL STRATEGY

A. Development and Deployment of Energy Efficiency Measures and Clinker Substitutions

The path to decarbonizing Brazil's cement sector requires a multifaceted approach, incorporating the adoption of energy efficiency measures, renewable energy sources, fuel switching, and clinker substitutions. A key short-term lever for reducing emissions is clinker substitutions, alongside improvements in energy efficiency and the use of alternative fuels. Specifically, clinker substitution reduces the emissions associated with cement by replacing a part of the clinker in the cement mix with materials of lower embodied carbon such as fly ash, ground limestone, and calcined clays. Because clay calcination projects already exist in Porto Velho and Nobres in Brazil, these substitution options can be readily diffused more broadly, providing critical assistance in decarbonizing pathway for the cement sector. Success of the low-carbon transition also depends on fostering innovation in the development of next-generation clinker substitutes, such as engineered supplementary cementing materials (SCMs).

Additionally, efficient transport systems in cement value chain, productive coolers and grinders, and high-efficiency motors and fans can offer means to lower energy consumption throughout cement production. Alternative fuels such as waste energy and biomass are technologically and commercially mature and can be incorporated in cement manufacturing. Given Brazil's strong research and development capabilities, it is critical to incentivize both basic and applied research relevant to clinker substitution options and energy efficiency measures. Government-led financial mechanisms, including grants and tax incentives, are options to support innovation in low-carbon cement. Moreover, the government can consider establishing cement industry standards that are based on energy consumption, clinker composition, and clinker-to-cement ratios, with the goal of progressively strengthening these standards over time. Such a framework would not only ensure emissions reductions but drive the necessary push positioning Brazil as a standard setter in low-carbon industrial materials.

B. Verification, Financing, and Public Sector Support for Low-Carbon Cement

As Brazil passed a new law in 2024 to set up a national cap-and-trade system, and starting from 2026, EU cement imports will be guided by the European Carbon Border Adjustment Mechanism (CBAM), verifiable methodology and standards to conduct carbon accounting for Brazilian cement are vitally important. Without such accounting and management framework, biofuels used in cement production may not be recognized as green, particularly in key markets such as the EU, where rigorous standards are in place. In addition, although full scale carbon capture projects in the cement industry have demonstrated success in Canada, Norway, and Belgium, the use of CCUS in low-carbon cement should be carefully assessed. The introduction of a transparent verification and standardized system for calculating the carbon content of fuel use and cement manufacturing is therefore crucial for establishing credibility among global cement producers. Additionally, the adoption of low-carbon technologies in the cement sector requires substantial financial support. One policy option to facilitate this low-carbon transition is through targeted financing mechanisms, such as loan guarantees, which would help cement manufacturers retrofit existing facilities with energy-efficient technologies and deploy emerging low-carbon technologies. To further incentivize this shift, the government can consider aligning funding for national initiatives like Novo PAC, Nova Indústria Brasil, and the Ecological Transition Plan to create a cohesive strategy for low-carbon cement. This would not only enable greater adoption of existing technologies but also provide the necessary foundation for the demonstration and scaling of emerging technological innovations.

C. Low-Carbon Cement Hubs and Industry Synergies

Strategic locations of cement manufacturers and carbon capture, utilization, and storage (CCUS) facilities present a promising opportunity to lower transport costs and enhance the scalability of emissions reduction efforts. By establishing green cement hubs in regions that have access to abundant renewable energy sources and feasible CCUS infrastructure, Brazil can create a concentrated ecosystem where cement production, renewable energy, and CCUS technologies can be deployed at scale. This ecosystem can generate synergies with other low-carbon industries, particularly the chemical industry, where overlaps in technical knowledge related to emerging chemical materials and clinker substituting options can further drive innovations in low-carbon cement. These hubs could act as centers of technological innovation, facilitating research and development, as well as the demonstration and scaling of green cement technologies. This enables Brazil to capitalize on the economies of scale and build a robust infrastructure for industrial processes, setting the stage for domestic use and exports of low-carbon cement.

D. Expanding Cement Exports and International Market Positioning

Brazil currently ranks low among global cement exporters, with export value of only USD 32 million in 2022, yet the country holds significant potential to increase its exporting share in regional and international markets. As global demand for low-carbon industrial materials grows, particularly in the EU with the expected implementation of the CBAM in 2026, Brazil faces a unique window of opportunity to position itself as a key exporter of low-carbon cement. To capitalize on this potential, targeted industrial policies such as government-led export incentives can enhance the visibility and market recognition of Brazilian cement. The government could consider investing in export promotion initiatives and forging strategic partnerships that highlight the country's low-carbon cement credentials. A regulatory framework for Brazilian cement and trade mechanisms to provide foreign consumers market information should be in place to facilitate cement exporting. By strengthening Brazil's position in the global market, particularly in comparison to existing major cement exporters to the EU such as Turkey, Algeria, and Ukraine, Brazil can seek to increase its competitiveness and better leverage growing demand for sustainable industrial materials.

5. Conclusions

Brazil has a unique opportunity to meet the challenge of the green transition in a way that catalyzes re-industrialization and growth through green industrial strategy. Windows of policy opportunity arise as recent legislation establishes the Brazilian Greenhouse Gas Emissions Trading System and outlines key frameworks and the integration of voluntary carbon credits. The key findings in this report, focused on the steel and cement industries, include the following:

- In both the steel and cement sectors, decarbonization technologies with varying levels of readiness and maturity are being developed and deployed. Immediate deployment of existing low-carbon technologies can be incentivized by sectoral policies focused on *efficiency measures* and *recycling* (*e.g*., innovative technologies used in scrap steel recycling).

- The environmental impacts of the steel and cement sectors can be significant, particularly considering trade-embodied resources utilization and trade-embodied impacts, which are most commonly captured in five dimensions: *air emissions* (incl. GHG), *embodied land use*, *water consumption*, *material consumption* and *damage to the ecosystem*.

- Basic metals manufacturing can be a driver of *ecosystem damage*, which is a key consideration for high-biodiversity areas of Brazil. *Life cycle assessment* (LCA), offering a full-flow material analysis, can reveal the ecotoxicity effect of rare earth and basic-metal processing, and the extent to which they result in biodiversity loss.

- If the most polluting life cycle stages of the extraction and processing of metals become outsourced to technologically less advanced countries, there could be efficiency losses and increase in the damage to the ecosystems embodied in the traded steel and cement products.

- Regulatory standards are a useful tool to reduce embedded carbon in a phased manner. They have the additional benefit of signaling to other markets that Brazilian products are low emission, if the regulations are strictly enforced and if a verifiable method for measuring carbon content is developed and made transparent. In this way, both the domestic and global markets for green products would likely expand.

- A uniformly applied and transparent carbon accounting system is vital if biofuel-based emissions reductions in steel and cement sectors were to translate to carbon-pricing benefits in international markets and expanded export markets.

- Because of Brazil's relatively green grid, new electricity-based low-carbon technologies are particularly promising as potential investment pathways enabling long-term decarbonization via innovative technologies in both sectors.

- Nurturing of a sufficiently skilled workforce is key for a successful green industrial transformation including the steel and cement sectors. Capabilities should be strengthened in *green skills* (*e.g.*, waste reduction and management, material science and recycling, water conservation, energy efficiency), *construction, engineering and operations* (of new, energy-efficient furnaces, renewable energy plants, and hydrogen production facilities), and *digital skills* (*e.g.*, advanced data analysis, programming, and cybersecurity).

- Existing workers' skills must be assessed so that training gaps can be identified. Re-qualification and training programs should follow a *Jobs Plan,* which clearly outlines skills development and job creation strategies for specific regions and/or industries, and includes inclusive stakeholder engagement with multiple stakeholders in decision-making (*e.g*., trade unions, industries, educational institutions, and work training agencies). If possible, state, regional, and local actors should also participate in the process to enable stronger cooperation with workers on the ground and ensure the outcomes are broadly accepted.

- Local and regional support can be provided via designated advisory bodies for each state, territory, and municipality, consisting of government, industry, labor, and where applicable, indigenous and traditional communities impacted by the transition. This way, regional and local differences can be accounted for in the green jobs legislation impacting multiple levels and aligned with the distribution of the new industries.

- The development of concentrated green industrial hubs could support Brazil's green growth strategy for several reasons: (i) the co-location of industries connected to steel and cement such as hydrogen and CCUS provide multiple knock-on benefits; (ii) stable green electricity with reduced electricity-related emissions becomes less costly and easier at specific locations or when in the vicinity (or coupled with) specific industries; (iii) upstream and downstream industries located within the industrial hubs could encourage innovation along the supply chain.

- Government procurement could be leveraged as a strategic tool to support the take-off of rapidly maturing technologies and mitigate risks of emerging technologies, and should be planned in alignment with short-, mid-, and long-term industrial strategies that include training and upskilling.

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Contact Information

KELLY SIMS GALLAGHER

CPL Director
Fletcher School Dean
Professor of Energy & Environmental Policy
Kelly.Gallagher@tufts.edu

SIDDHARTH JAIN

Junior Research Fellow, CPL
Siddharth.Jain@tufts.edu

KATE HUA-KE CHI

Junior Research Fellow, CPL
Kate.Chi@tufts.edu

NORA HAMPL

Postdoctoral Scholar, CPL
Nora.Hampl@tufts.edu

Climate Policy Lab (CPL)
Center for International Environment and Resource Policy (CIERP)
The Fletcher School
160 Packard Avenue Medford, MA 02155
Email: cpl@tufts.edu
climatepolicylab.org

CLIMATE POLICY LAB

FLETCHER
CENTER FOR INTERNATIONAL
ENVIRONMENT & RESOURCE POLICY

The graduate school of global affairs at Tufts University