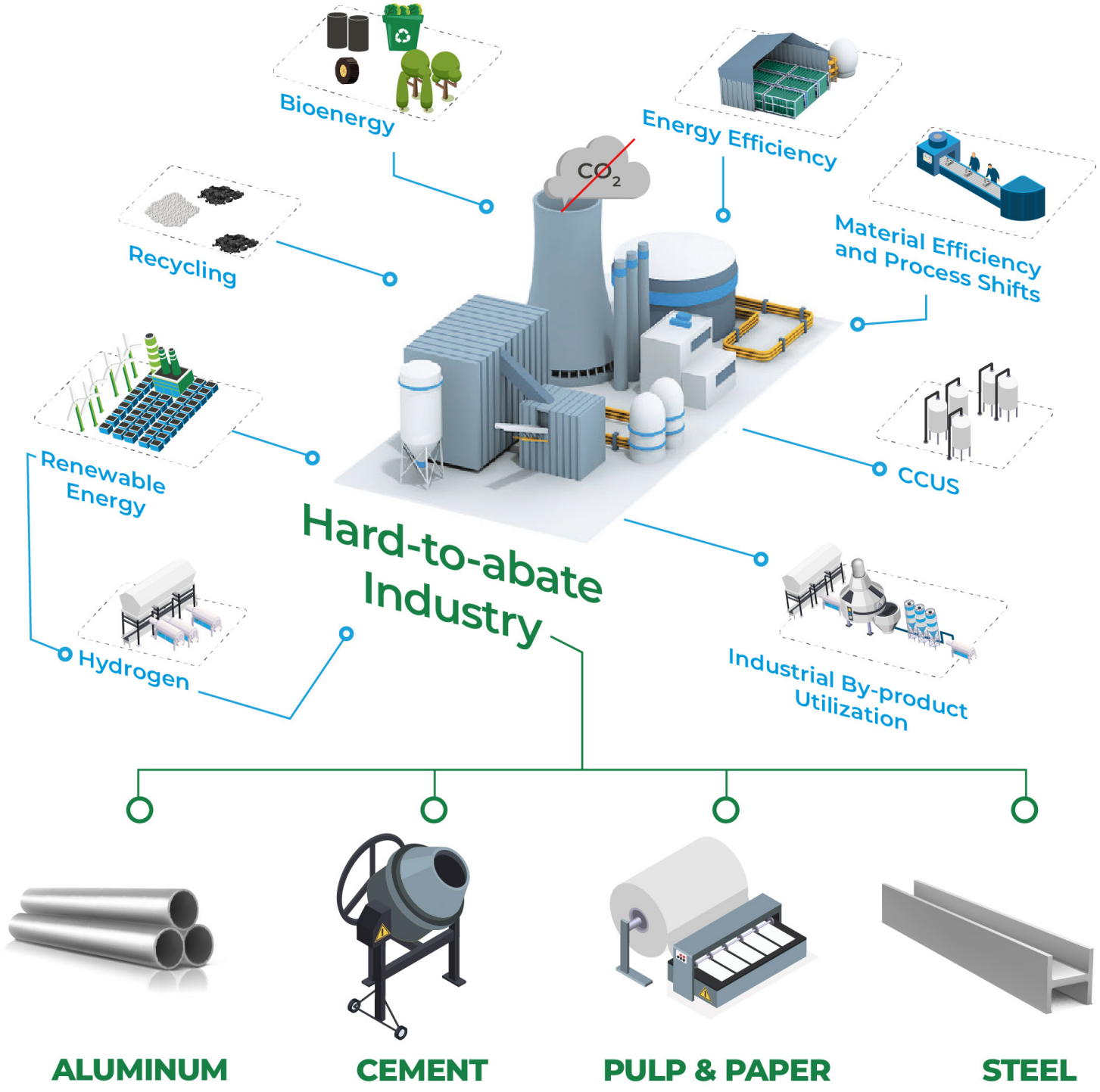

Pathways to Accelerate Industrial Transformation in Latin America and the Caribbean:

Focus on Aluminum, Cement, Pulp & Paper, and Steel

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Pathways to accelerate industrial transformation in Latin America and the Caribbean: focus on aluminum, cement, pulp & paper, and steel / Christiaan Gischler, Michelle Ramirez, Matilde Urquizo, Fernando Anaya, Jed Bailey, Paola Galeano, Ricardo Pareja, Henrique Pinheiro, Patricia Colaferro.

p. cm. — (IDB Monograph ; 1318)

Includes bibliographical references.

1. Industries-Environmental aspects-Latin America. 2. Industries-Environmental aspects-Caribbean Area. 3. Carbon dioxide industry-Latin America. 4. Carbon dioxide industry-Caribbean Area. I. Gischler, Christiaan E. II. Ramírez, Michelle. III. Urquizo, Matilde. IV. Anaya, Fernando. V. Bailey, Jed. VI. Galeano, Paola. VII. Pareja, Ricardo. VIII. Pinheiro, Henrique. IX. Colaferro, Patricia. X. Inter-American Development Bank. Infrastructure and Energy Sector. XI. Series.

IDB-MG-1318

Jel Codes: L60, L61, Q55, Q54
Keywords: industrial transformation, energy, aluminum, steel, cement, pulp & paper, hydrogen, Latin America and the Caribbean

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ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Latin American Steel Association (ALACERO, for its acronym in Spanish), the Inter-American Cement Federation (FICEM, for its acronym in Spanish), the Brazilian Aluminum Association (ABAL, for its acronym in Portuguese), the Brazilian Steel Institute (Aço Brasil, for its acronym in Portuguese), and Celuosa Arauco from Chile, in relation to pulp & paper, for their valuable comments, inputs and for reviewing the publication.

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ACRONYMS

AD	Anaerobic Digestion
AF	Alternative Fuels
Al (OH)$_3$	hydrated alumina crystals
Al$_2$O$_3$	metallurgical alumina
ARENA	Australian Renewable Energy Agency
BAU	Business-as-usual
BECCS	Bioenergy Carbon Capture and Storage
BF	Blast Furnace
BGS	British Geological Survey
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BLG	Black Liquor Gasification
BLGCC	Black Liquor Gasification Combined Cycle
BOF	Basis Oxygen Furnace
CAPEX C	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture, Use and Storage
CEPI	Confederation of European Paper Industry
CFB	Circulating fluidized beds
CfDs	Contracts for Difference
CF4	Carbon tetrafluoride
CF6	Carbon hexafluoride
CIF	Climate Investment Funds
CO2	Carbon Dioxide
CSI	Cement Sustainability Initiative
CTMP	Chemi-Thermomechanical Pulp
DAC	Direct Air Capture
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EPDs	Environmental Product Declarations
ESSP	Environmental and Social Sustainability Policy
ESPF	Environmental and Social Policy Framework
FEED	Front-end engineering and development
FICEM	Federación Interamericana del Cemento
FOAK	First-of-a-Kind
FSC	Forest Stewardship Council
GCCA	Global Cement and Concrete Association
GHG	Greenhouse Gases
GJ	Gigajoule
Gt	Gigaton
GW	Ground Wood
HBI	Hot Briquetted Iron

H2	Hydrogen
IAI	International Aluminum Institute
ICF	International Climate Fund
IDB	Inter-American Development Bank
IEA	International Energy Agency
IRAM	Instituto Argentino de Normalización y Certificación
Kt	Kilotons
LAC	Latin America and the Caribbean
LCOE	lowest levelized cost of energy
LCTPi	Low Carbon Technology Partnership Initiative
LPG	Liquefied Petroleum Gas
MDBs	Multilateral Development Banks
MEA	Absorption – Monoethanolamine
MRV	Measure, Reporting and Verification
MSW	Municipal Solid Waste
Mt	Million Tons
MWh	Megawatt-hour
$NaAlO_2$	Sodium aluminate
NG	Natural Gas
NDCs	Nationally Determiner Contributions
OPEX	Operating Expenditure
PA	Paris Agreement
PFCs	Perfluorocarbons
PPAs	Power Purchase Agreements
PPPs	Public-Private Partnerships
RCA	Recycle Concrete Aggregate
RDF	Refuse-derived Fuels
RDH	Roto Dynamic Heater
RE	Renewable Energies
RMP	Refined Mechanical Pulp
SCM	Supplementary Cementitious Materials
SiO2	Silica
SBTi	Science Based Targets initiative
t	Ton
TMP	Thermo-Mechanical Pulp
UNCITRA	United Nations Commission on International Trade Law
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
VTT	Technical Research Centre of Finland
WBCSD	World Business Council for Sustainable Development
WEF	World Economic Forum
WRI	World Resources Institute
WSA	World Steel Association's
WWF	World Wildlife Fund

EXECUTIVE SUMMARY

Aluminum, cement, pulp and paper, and steel can be found in all segments of the global economy, from short-term uses, such as packaging and personal hygiene, to durable goods, such as automobiles and appliances, to critical infrastructure, such as buildings, roads, and railways. They are also produced through energy-intensive processes that are significant contributors to global greenhouse gas emissions. Shifting these industries toward net-zero carbon pathways will be instrumental in meeting global greenhouse gas reduction targets.

This report highlights potential pathways to decarbonize these industries in Latin America and the Caribbean through a detailed examination of each industry through technical, sectoral, environmental, and policy perspectives. It aims to provide policy makers with a basic understanding of each industry's fundamentals, the challenges to decarbonization, the available options to overcome those challenges, and a broad roadmap to move toward net-zero emissions by 2050.

This Executive Summary provides an overview of each industry, including the primary production routes, global and regional markets, their environmental impacts, and potential technologies to reduce their carbon footprint. It then summarizes proposed policy and financing measures to support the development and deployment of these technologies in the region.

Aluminum Industry

The aluminum industry is among the most challenging heavy industry to decarbonize. As a key building block to the global economy, aluminum will play a critical role in creating sustainable pathways for future economic growth. In LAC, aluminum is highly concentrated, with bauxite mined in only three countries (Brazil, Jamaica, and Guyana) and aluminum produced in only two (Brazil and Argentina)[1]. Aluminum is consumed across the region, however, supporting industries including transportation, machinery and equipment, packaging, and construction. This ubiquitous demand highlights the importance of aluminum to the region's economies, and the need to align aluminum production and use with sustainable principles.

Aluminum Production Processes

Primary aluminum production involves two main processes: the Bayer process, which converts bauxite ore into alumina, and the Hall-Heroult process, which smelts alumina into metallic aluminum via electrolysis. One kg of aluminum requires roughly 2 kg of alumina, and each kg of alumina in turn requires roughly 2.5 kg of bauxite ore to produce.[2]

The Bayer process combines ground bauxite with liquid caustic soda and lime at high temperatures and pressures to create sodium aluminate mixed with insoluble bauxite mud (red mud). Sodium aluminate is separated and cooled to produce hydrated alumina crystals ($Al(OH)_3$), which are then separated from the caustic soda by levigation or centrifugation. Finally, the alumina hydrate is calcinated at high temperatures to produce metallurgical alumina (Al_2O_3) and water.

[1] British Geological Survey (BGS) World Minerals Statistics database
[2] International Aluminum Institute, 2022

During the Hall-Héroult, or smelting, process, alumina is first dissolved into an electrolytic cell and mixed with sodium fluoride. Carbon electrodes (anodes) are immersed in the cell to conduct electricity that decomposes, through electrolysis, the alumina into oxygen and aluminum. The molten aluminum metal is then deposited on the negative pole (cathode) at the bottom of the cell, while oxygen accumulates on the carbon electrodes and forms carbon dioxide. The metal is extracted from the bottom of the cell by a vacuum siphon and transferred to alloying furnaces, where the metal is amalgamated and gases and impurities are removed (aluminum refining). As a last step, the aluminum is cast into ingots or bars.

Primary aluminum production requires large amounts of energy in the form of heat to convert bauxite to alumina and to produce the anodes used in converting alumina to aluminum, as well as electricity during electrolysis. In LAC, alumina requires roughly 8.4 GJ of energy per ton to produce, and aluminum production requires 2.7 GJ of energy per ton to produce the required anodes and a further 55.8 GJ of electricity per ton for electrolysis.[3]

Secondary aluminum is produced from aluminum scrap. During this process, the scrap is recovered and pretreated by removing non-aluminum elements and shredding the aluminum scrap into a consistent size. The scrap is then melted at high temperature to create salt slag, which is then refined using additives and alloys to create the desired aluminum product. Finally, the molten aluminum is cast into ingots or bars. Because this process does not require alumina production or electrolysis, secondary aluminum production requires between 93% and 96% less energy than primary aluminum production.[4]

Global and Regional Aluminum Markets

World aluminum production reached 112 million tons in 2023, of which LAC supplied 2.6% (2.9 Mt). Primary aluminum production now accounts for nearly two-thirds of total production.[5]

In 2022, Brazil accounted for 87% of LAC's bauxite production, Jamaica 11%, and Guyana the remaining 2%.[6] LAC alumina production is similarly geographically concentrated, with 95% of regional production in Brazil and the remaining 5% produced in Jamaica.[7] Primary aluminum production is concentrated in Brazil (67%) and Argentina (33%).[8]

Secondary aluminum production in LAC reached 1.7 million tons in 2019[9]. The recycling rate in LAC is roughly 82%, with a total scrap production of 1.75 Mt in 2023[10], although this figure does not include scrap from high aluminum content products that are imported to the region. As a result, LAC's true recycling potential could be significantly higher than what the statistics currently show.

Total LAC aluminum production is expected to increase 1.31% annually, with 1% annual growth in primary production and 1.52% annual growth in secondary production[11].

Aluminum is used in short-term services, such as packaging, and longer-term industries, such as construction. Uses with short lifecycles can more easily integrate circularity and recycling into their relatively simple value chains. Industries with longer lifecycles sometimes lack a well-established value chain in recovery, processing, and smelting.

[1] British Geological Survey World Minerals Statistics database
[2] International Aluminum Institute, 2022
[3] International Aluminum Institute,2022
[4] The Aluminum Association, 2022; Ding et al., 2012
[5] International Aluminum Institute statistics database
[6] British Geological Survey World Minerals Statistics database
[7] British Geological Survey World Minerals Statistics database
[8] British Geological Survey World Minerals Statistics database
[9] International Aluminum Institute statistics database
[10] International Aluminum Institute statistics database
[11] International Aluminum Institute https://alucycle.international-aluminum.org/public-access/

Demand for final aluminum products in LAC was 2.64 Mt in 2019, equivalent to 4.13 kg of aluminum per capita per year. This level of aluminum consumption is well below the world average of 11 kg/capita[12]. The primary consuming sectors were transportation (29%), machinery and equipment (25%), packaging (18%), construction (13%), and consumer goods (8%)[13]. Brazil is the largest aluminum-consuming country in Latin America, accounting for close to 60% of the region's total. Demand for aluminum products in LAC is forecast to increase 87% to 4.93 Mt by 2050[14].

Aluminum's Environmental Impact

In 2022, the aluminum industry was responsible for GHG emissions of 1.067 $GtCO_2e$[15]. Primary aluminum production emitted an average of 15.11 tCO_2e/tAl in 2022, including direct (28% or 4.2 tCO_2e/tAl) and indirect (72% or 10.91 tCO2e/tAl) emissions[16]. These emissions are primarily from electrolysis (74.1%), alumina refining (17.2%), and carbon anode production (5.6%)[17]. The majority of these emissions are from the combustion of fossil fuels to produce heat or electricity, but roughly 10% arise from oxidation of the carbon anodes during electrolysis and a further 5% from the release of the perfluorocarbons (PFCs) that are generated during electrolysis[18].

Secondary aluminum production GHG emissions consist mainly of CO_2, from scrap melting and casting, with a smaller amount from scrap processing and transport to the foundry. Total secondary aluminum production GHG emissions are estimated at 0.55 tCO_2e/tAl for the region[19].

Aluminum Decarbonization in LAC

Achieving carbon neutrality in the aluminum industry is technically possible but will require major changes in energy-intensive technologies and production methods, as well as significant new investment. Technical options to reduce GHG emissions from aluminum production include:

- **Decarbonizing electricity generation.** Using renewable energy for electrolysis would remove indirect emissions from electricity generated with fossil fuels. Total emissions reduction depends on the share of electricity currently generated from fossil fuels and the type of fuels used. Renewable energy technologies are widespread and often less expensive than fossil fuel technologies. Aluminum companies in LAC already have experience with renewable energy PPAs.

- **Increasing aluminum recycling.** Increasing recycling to 100% in LAC could reduce overall aluminum industry emissions by an estimated 19%[20]. Secondary manufacturing is already widespread and can be implemented at existing smelters. Increasing recycling rates would, however, require investment in aluminum scrap supply chains and policies to incentivize and enforce recycling mandates.

- **Improving process efficiency.** Efficiency improvement technologies include tube heating for bauxite digestion (15% energy reduction)[21], circulating fluidized beds for calcination (up to 40% energy savings)[22], and magnetic compensation in electrolysis (10-15% reduction in electricity demand)[23]. These technologies are being used on a commercial scale, but would require significant investment to retrofit existing plants.

[12] Natural Resources Canada Bureau, 2022. https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/aluminum-facts/20510
[13] Menzie et al., 2010
[14] CM Group, 2020.
[15] International Aluminum Institute 2024
[16] Ibid
[17] Ibid
[18] Ibid
[19] Baque et al. (2020)
[20] Authors estimate based on IAI data
[21] https://www.hatch.com/Expertise/Services-and-Technologies/Alumina-Tube-Digestion
[22] Klett et al., 2011
[23] Zhang et al., 2016

- **Replacing carbon anodes with inert anodes.** Electrolysis using inert anodes produces oxygen instead of CO_2, thereby eliminating all direct GHG emissions from carbon anode degradation (roughly 1.5 tCO_2 per ton of Al). This technology is not yet available on a commercial scale, although demonstration projects are ongoing. The timing of its availability and ultimate cost are therefore unknown.

- **Decarbonizing heat production.** Emissions from process heat for alumina refining can be reduced by substituting the fossil fuels currently used with renewable hydrogen or refuse-derived fuels, such as municipal solid waste, and by deploying CCUS technologies to capture produced emissions. Each of these options has the potential to cut heat-related emissions to zero. Refuse-derived fuels have been widely deployed in the cement and steel industries but have not been used in aluminum manufacturing. Renewable hydrogen and CCUS technologies are less mature and require adaptation for use in aluminum manufacturing. All three would require extensive investment and the development of additional infrastructure and supply chains to implement.

Using renewable energy sources to provide all required electricity would provide the greatest reduction in CO_2e emissions, followed by renewable hydrogen for process heat, using inert anodes in place of carbon anodes, increasing aluminum recycling, and improving energy efficiency. Each of these potential technologies will require new investment. Many require further development for large-scale deployment and must be validated for use in each individual market. Government policies and financial mechanisms will be instrumental to advancing these technologies.

Cement Industry

Cement is a powdered binding material composed of finely ground minerals that, when mixed with water, forms a paste capable of setting and hardening through multiple exothermic hydration reactions. This allows it to bind together fragments of solid matter to create a compact, hardened structure. After the hardening process, cement maintains its strength and stability even when exposed to water.

Cement, as a fundamental component of concrete, has remarkable durability, regardless of its final application. Most building regulations establish a 50-year design economic life for conventional reinforced concrete structures[24], while for critical infrastructure, such as tunnels and dams, this service life can extend between 100 and 120 years[25]. This implies that the intervals for infrastructure decommissioning and concrete (cement + aggregates) recovery and reuse are considerably extended.

The cement industry plays a key role in building the infrastructure required for global development but is a significant contributor to global carbon dioxide emissions (CO_2), accounting for approximately 7% of total anthropogenic emissions[26].

Cement Production Processes

Standard cement is manufactured in three stages: raw material preparation, clinker production, and cement grinding. The raw materials used for cement manufacturing include limestone, which provides calcium carbonate; iron ore, which provides iron oxide; clay, which provides alumina; and, sand, which provides silica. These raw materials are first ground separately to pieces approximately

[24] Medeiros et al., 2015
[25] Nilsson, 2019
[26] GCCA, 2021; Bataille, 2019

10 cm in diameter. Next, different raw materials are ground together in the required ratios to create a product known as "crude."[27]

The second stage begins with preheating the crude to facilitate its subsequent precalcination, in which the limestone is chemically decomposed at high temperatures. This precalcined raw material then enters a kiln where it is subjected to a gradual and continuous temperature increase. The process culminates in calcination and sintering that produces clinker at temperatures close to 1,400°C.[28]

Once the clinker leaves the kiln, it is cooled for the third stage: cement grinding. In this stage, the clinker is combined with gypsum in a roughly 19:1 ratio, to control the cement's setting time. This mixture of clinker and gypsum is then ground to make ordinary Portland cement. Other mineral components can also be added to produce compound Portland cement with the specific desired properties.[29]

Cement can be produced in an integrated plant that incorporates all stages, from limestone extraction to clinker production to grinding, or in a grinding plant that acquires clinker from an external supplier then mixes and grinds it with gypsum and other inputs to produce cement.

Global and Regional Cement Markets

Cement is an essential material with end-use applications ranging from building construction to road paving and precast concrete. Cement's end use is almost evenly distributed across the residential, non-residential, and civil works sectors.

In 2023, world cement production was 4,100 million tons[30] with LAC contributing 4.6% (187.5 Mt)[31]. Brazil, Mexico, Colombia, Argentina, and Peru account for 82% of LAC cement production. In 2021, Brazil produced 60.8 Mt of cement, Mexico 51.7 Mt, Colombia 13.8 Mt, Peru 12.9 Mt, and Argentina 12.1 Mt.[32]

Cement's Environmental Impact

The cement industry is characterized by its high energy intensity and high carbon dioxide emissions (CO_2). Approximately 92% of the energy used to produce cement is employed in the thermal processes associated with clinker production[33].

A cement plant operating with highly efficient kilns consumes approximately 2.95 gigajoules (GJ) of energy per ton of clinker produced[34]. Less efficient plants can consume more than 5 GJ/t[35]. Electricity consumption may also vary significantly, ranging from 70 to 140 kilowatt-hours (kWh) per ton of cement produced[36].

Cement industry energy consumption in LAC is above the world average. In 2022, the region exceeded the global thermal intensity by 3.6%, reaching 3.68 GJ/t of clinker[37]. LAC electricity intensity was 115

[27] FICEM, 2023a
[28] John, 2020; Marenco et al., 2023
[29] FICEM, 2023a
[30] USGS statistics
[31] FICEM statistics
[32] Ibid
[33] Aristizábal and González, 2021
[34] Ibid
[35] Ibid
[36] IEA, 2021
[37] FICEM statistics
[38] Ibid
[39] Bosoaga et al., 2009

kWh/t cement, also 3.6% above the world average.[38] Clinker production accounts for about 90% of total cement production emissions, with direct emissions from fuels used to transport raw materials and from electricity self-generation accounting for another 5%, while indirect emissions from grid-supplied electricity account for the rest[39].

Within the clinker production process, the limestone decarbonation chemical process accounts for about 60% of the emissions that are produced, while the remaining 30% of emissions is generated from burning fossil fuels in the kiln[40].

Clinker production uses fossil fuels, such as coal and petroleum coke, and alternative energy sources, including solid and liquid waste, known as co-processing. The amount of waste co-processed in the cement industry varies significantly by country. Some European producers have achieved co-processing levels above 70%. LAC averages 17%, with Brazil using waste for more than 25% of the energy used for cement production[41].

Co-processing leads to indirect CO_2 emission reductions. Burning waste produces CO_2, but CO_2 and other emissions would occur even if the waste was disposed of in landfills and incinerators. Using the waste to produce heat for cement production instead, either partially or completely offsets the direct CO_2 emissions that would have resulted from burning conventional fossil fuels.

Cement industry CO_2 emissions can therefore be quantified in two ways: gross emissions, which encompass all emissions, including those from alternative fuels; and net emissions, which exclude emissions from alternative fuels. However, for net emissions to be valid, alternative fuels credits must be approved and certified. This is determined by specific local circumstances (such as national agreements or the life-cycle analysis of local alternative fuels use) and verified through third-party reporting, as necessary.

Because the decarbonation chemical reaction in clinker production produces such a large share of cement manufacturing CO_2 emissions, substituting fossil fuels for zero-carbon alternatives can only mitigate a fraction of clinker production emissions. The clinker-to-cement ratio, which denotes the amount of clinker required to produce one ton of Portland cement, also influences CO_2 emissions. Reducing the clinker/cement ratio through optimizing the raw material mix, adopting advanced technologies, or reducing process losses, reduces CO_2 emission per ton of cement produced.

In 2022, the average clinker-to-cement ratio in LAC was 70.5%[42]. Supplementary cementitious materials (SCMs) used in LAC include fly ash (from coal-fired power plants), slag (from blast-furnace steel production), and pozzolana (a naturally occurring material).

Once concrete reaches the end of its useful life, it undergoes a recycling process that involves removing unwanted materials, such as impurities and steel reinforcements, and crushing the resulting mix until it meets the required specifications. This recycled concrete aggregate (RCA), which contains coarse aggregates (stone and gravel), fine aggregates (sand), and cement between 5% and 20% can be used to manufacture new concrete products. This approach reduces the need to extract new raw materials, and also reduces construction and demolition waste.

Cement Decarbonization in LAC

Carbon mitigation strategies for cement production include improving energy efficiency, transitioning to less carbon-intensive alternative fuels, reducing the share of clinker in cement production, and integrating carbon capture technologies.

[40] John, 2020; Boyaghchi, 2014
[41] FICEM Data Report (2023c)
[42] FICEM statistics

- **Supplementary cementitious materials.** Reducing the amount of clinker in cement by substituting it with SCM would directly reduce clinker production emissions. SCMs have been used extensively in cement production and the technologies are well developed. Increasing the use of SCMs depends on establishing cost-effective SCM supply chains.

- **Electrical efficiency.** Cement manufacturing uses electricity for material grinding and motors. Replacing low-efficiency motors with higher efficiency equipment is relatively straightforward and can reduce electricity consumption by 10-15%[43]. Replacing conventional grinding mills with vertical mills is more complicated and expensive but can reduce electricity consumption by up to 65%[44].

- **Substituting fossil fuels in clinker production.** Emissions from process heat for clinker production can be reduced by substituting the fossil fuels currently used with AFs, such as MSW, or renewable hydrogen. AFs have been widely deployed in the cement industry, with some plants reaching 80-100% in precalciner processes and 50-60% in the calcination process[45]. Renewable hydrogen is a less mature technology that requires adaptation to use in cement manufacturing. Combining hydrogen and MSW is also promising, as hydrogen alone can burn too hot while MSW can burn too cold for cement production. Each of these options would require extensive investment and the development of additional infrastructure and supply chains to implement.

- **Process electrification.** Electricity can be used to generate process heat through a variety of technologies. Replacing fossil fuel combustion with renewable electricity would remove 35% of cement manufacturing emissions.[46] Electrifying cement production has not yet been proven at commercial scale, owing to the high temperatures required. Electrifying existing plants would require extensive investment.

- **Carbon capture and storage.** Deploying CCUS technologies at cement manufacturing plants would capture the emissions produced from fossil fuel combustion. These technologies could potentially remove up to 95% of emissions.[47] Some CCUS technologies are ready for industrial-scale deployment, but many require further development or adaptation for use in cement manufacturing. Deploying CCUS would require significant investment and additional infrastructure to link cement plants with CO_2 storage sites.

- **Concrete recycling.** Concrete fines that are created from concrete crushing can be used in clinker production, or be carbonated and used directly as an SCM. Using concrete fines reduces emissions by reducing mining for clinker materials and reducing the clinker share in cement as an SCM. Carbonated concrete fines are not yet commercially available. Virtually all recycled concrete is currently used as crushed waste in roadbed substructures. Increasing the use of recycled concrete in clinker production or as an SCM would require investment in concrete recycling infrastructure and supply chains.

Increasing the share of SCMs and substituting fossil fuels in clinker production provide the greatest reduction in CO_2e emissions, followed by process electrification, carbon capture, and improving energy efficiency. Each of these potential technologies will require new investment. Many require supporting investment in infrastructure and supply chains. Others require further development for large-scale deployment and must be validated for use in each individual market. Government policies and financial mechanisms will be instrumental to advancing these technologies.

[43] MGM International, 2018
[44] Ibid
[45] Sharma et al., 2022
[46] ECRA, 2022
[47] ECRA, 2022

Pulp and Paper Industry

The pulp and paper industry is the fourth-largest energy-consuming industrial sector, accounting for roughly 6% of global industry energy demand[48]. Unlike aluminum, cement, and steel, paper products all have a short lifecycle. Globally, packaging accounts for more than half of paper use (55%) and printing and writing a further 26%[49].

Pulp and paper production is based on cellulose fiber, which is extracted mainly from trees and, to a lesser extent, from other plants such as bagasse, bamboo, and cotton. Cellulose can also be obtained from secondary fibers from recycled paper and textile waste[50]. On average, 2 to 4 tons of wood is consumed for each ton of pulp produced[51]. Pulp can also be manufactured from recycled paper, requiring 1.4 tons of paper per ton of pulp on average. The paper industry, in turn, requires between 0.9 and 1 ton of dry pulp to produce one ton of paper[52].

Pulp and Paper Production Processes

Primary pulp is produced by separating out cellulose and hemicellulose fibers (typically between 70% and 75% for wood) from the lignin and other materials[53]. Logs are first debarked, chipped, and screened to ensure that the chips are the right size for further processing. The wood chips are then converted into pulp by removing the lignin from the cellulosic fibers through a mechanical or chemical method.

Mechanical pulping, accounting for 20% of global pulp production[54], separates the fibers by mechanical means, retaining some of the lignin in the paper. The main mechanical manufacturing routes are: ground wood (GW), refined mechanical pulp (RMP), thermo-mechanical pulp (TMP), and chemical-thermomechanical pulp (CTMP). In general, mechanical production processes have higher yields, with the produced pulp mass ranging between 85-90% of the original fiber mass[55]. However, the retained lignin generates fibers with lower strength compared to chemical pulps.

Chemical pulping is divided into two main types: kraft (sulfate) pulp and sulfite pulp. In both types, a digester processes the raw material with aqueous chemical solutions to extract fibers from the raw material. The kraft method accounts for about 80% of chemical pulp production[56]. This process combines sodium hydroxide and sodium sulfide (known as white liquor), to generate a fibrous material by destroying the raw material's lignin chemical bonds.[57] After cooking in the digester, the softened wood chips are transferred to a blowing tank where they are broken down into fibers. The pulp and the used cooking liquor, known as black liquor, are then separated through filtering and washing. The separated liquid is then sent to the cooking chemical and energy recovery system. Here, the water in the black liquor is evaporated to generate high pressure steam, and the remaining liquid is recausticized with lime to produce white liquor, which is returned to the digester.

Recycled pulp is obtained from a light pulping process using recycled paper as the main raw material. The process consists of mechanically shredding the paper and dissolving it in hot water to separate the fibers without destroying them. The pulp is then washed and screened to remove impurities, and

[48] Kong et al., 2020
[49] Martin & Haggith, 2018
[50] CEPI, 2021
[51] Martin & Haggith, 2018
[52] Ibid
[53] Rullifank et al., 2020
[54] Scott et al., 2002; Bajpai, 2018
[55] Rahnama et al., 2021
[56] Rahnama et al., 2021
[57] Rullifank et al., 2020

if necessary, an additional de-inking step is performed (for paper types that require white pulp). The pulp is then thickened to increase the fibers' concentration and dispersion. Finally, it is bleached and dried, depending on the pulp's final use[58].

Paper is made by processing fiber pulp into paper and paperboard. In the first pre-treatment step, the pulp is mixed and refined to ensure that it has optimal dissolution conditions and mineral fillers or chemicals are added to increase the pulp yield and change the properties of the paper produced, such as paper strength, texture, and brightness[59]. After pre-treatment, the mixture goes through four consecutive sub-processes: forming, pressing, dewatering or drying, and calendering. The forming process distributes the fibers homogeneously and removes part of the moisture from the mixture. The formed paper is then pressed, using rolls that remove the moisture content and increase the fiber density, followed by drying with steam-heated cylinders to remove the remaining moisture and further increase fiber content density. Calendering and winding consist of again pressing the paper with a roller that controls the paper's final smoothness and thickness, and then winding using a rotating reel to obtain transportable paper rolls[60].

Global and Regional Pulp and Paper Markets

Global primary pulp consumption reached 199 million tons in 2022, with LAC accounting for 17% (33.8 Mt) of global production[61]. LAC used chemical methods to produce 93.8% of its pulp and the remaining 6.2% by mechanical processes[62]. Within the chemical method, kraft pulp dominates production with a 99.7% share. Brazil accounted for 74.1% of LAC pulp production in 2022, followed by Chile (13.8%), Uruguay (8%), and Argentina (2.1%)[63].

Brazil has the region's highest primary pulp apparent consumption at 6.04 Mt in 2022, followed by Mexico (1.12 Mt), Chile (0.88 Mt), Argentina (0.81 Mt), and Colombia (0.62 Mt).[64]

World paper and cardboard production reached 414 million tons in 2022, with LAC supplying 5.7% (23.7 Mt) of world production[65]. Packaging paper dominates production in LAC, reaching a 65% share (15.4 Mt) in 2022, followed by household and sanitary paper (17%), printing and writing paper (14%), newsprint (1%), and other papers with the remaining 3%[66]. LAC paper production in 2022 was concentrated in seven countries: Brazil (46.7%), followed by Mexico (27.6%), Argentina (7.3%), Chile, (5.5%), Colombia (5.3%), Peru (2.2%), and Venezuela (1.4%)[67].

In 2022, Mexico and Brazil had the highest paper and cardboard apparent consumption (over 9 Mt), followed by Argentina, Colombia, Chile, and Peru, with consumption between 1.0 Mt and 2.5 Mt[68]. In 2022, LAC consumed an average of 45.5 kg per inhabitant per year (kg/inhab/yr), while industrialized countries such as the United States, Japan, and Germany consumed between 150 and 200 kg/inhab/yr[69].

Paper can be recycled between three and eight times. A percentage of virgin pulp is added each time to maintain the recycled fiber's strength and quality[70]. This allows recovered paper and forest products to complement each other, generating a circular economy. Paper packaging's short lifecycle also facilitates paper use circularity.

[58] Furszyfer Del Rio, et al. (2022).
[59] Rahnama et al., 2021
[60] ICF, 2015
[61] FAO statistics
[62] Ibid
[63] Ibid
[64] Authors calculated from FAO statistics
[65] FAO statistics
[66] Ibid
[67] Ibid
[68] Authors calculated based on FAO statistics
[69] Authors calculated based on FAO statistics and World Bank statistics
[70] Paper and Board Recycling Report. Bureau of International Recycling (BIR), 2019

In 2019, LAC recycled pulp production consisted of 80% packaging paper, followed by tissue paper (7%), printing and writing paper (3%), newsprint (2%), and other papers (1%)[71]. Between 2010-2022, LAC's annual paper recovery averaged 44% of total apparent consumption. This suggests the potential for additional recovery to displace primary pulp consumption.

Pulp and Paper's Environmental Impact

Mechanical and chemical pulp production processes have distinct energy requirements. Approximately 77% of mechanical pulp production energy consumption is electrical. CTMP is the most energy intensive, averaging 2,677 kWh/t, followed by TMP (2,371 kWh/t), RWP (2,242 kWh/t), and GW (1,920 kWh/t)[72]. The refining and milling stage consumes the most energy.

Chemical (kraft) pulp production consumes half as much electricity as mechanical processes but has a significant thermal energy demand, using 9.87 GJ/t, which accounts for 85% of the total energy demand. Pulp digestion, bleaching, and drying processes consume 87% of the electricity and 59% of the heat required, with the remainder used in the auxiliary black liquor recovery line.[73]

Recycled pulp production requires much less energy: 34% of mechanical pulp production and 73% of chemical production, on average[74].

Paper production uses energy to form, press, and dry the paper. It consumes, on average, 503 kWh/t of electricity and 4.7 GJ/t of heat energy[75]. Machinery operation consumes between 79% and 82% of the total energy, while 7% to 9% is used for general services and 9% for boilers and cooling systems. Steam generation accounts for between 60% and 70% of thermal energy use, followed by heat processes (20% to 30%), machines (3% to 4%), and other uses (2%).[76]

In LAC, bioenergy supplies 70% of the pulp and paper industry's energy on average, well above the global average. Uruguay has the highest share of biomass use (85%).[77]

In 2021, the pulp and paper industry emitted a combined 190 Mt CO_2, equivalent to 2% of global industrial emissions[78]. On average, producing a ton of paper generates between 0.6 t and 0.95 t CO_2e,[79] while producing a ton of pulp generates between 0.4 t CO_2e (recycled pulp) and 0.51 tCO_2 e.[80]

LAC mechanical pulp production is estimated to emit between 0.4367 tCO_2 /t and 0.6112 tCO_2 /t of dry pulp, depending on the process used[81]. Kraft chemical pulp is estimated to produce 0.617 tCO_2 /t of dry pulp in LAC, assuming 50% of electricity is self-generated with biomass (pulp waste) and 50% is from the grid[82]. If 100% of the required electricity was supplied by self-generation with biomass, the total emissions factor would be reduced to 0.112 tCO_2/t of dry pulp[83]. Many pulp producers in Latin America report co-generation in excess of their own needs, and so help to reduce CO_2 emissions from grid-supplied electricity in addition to their own processes.

Substituting virgin pulp with recycled paper reduces emissions intensity by 50% to 70%. Pulp from recycled fibers emits 0.334 tCO_2 /t of dry pulp, largely from the drying process which represents 100% of direct emissions and 62% of total emissions, followed by paper shredding and fiber separation, with 25%.[84]

[71] BIR, 2021
[72] Authors based on ICF (2015), Bajpai (2018) and Rahnama et al. (2021)
[73] Ibid
[74] Ibid
[75] Authors based on Rahnama et al. (2021).
[76] MIEM, 2016
[77] Authors using energy balances BNE Chile 202 , BEN Brazil 2021 and BEN Uruguay 2021
[78] IEA, 2022
[79] Furszyfer Del Rio, et al., 2022
[80] Sun et al., 2018
[81] Authors based on energy consumption presented by Rahnama et al. (2021) and CO2 emission factors from IPCC (2006).
[82] Ibid
[83] Ibid
[84] Ibid

LAC paper production emission factors average 0.396 tCO_2/t of product[85]. Producing printing and writing paper generates the highest emissions while packaging and newsprint generate the lowest. Direct emissions account for 73% of total emissions, all of which are from thermal energy for paper drying.[86] Paper forming and pressing generates 91% of indirect emissions, the rest is from drying.[87]

Pulp and Paper Decarbonization in LAC

Several technologies and approaches are available to mitigate CO_2 emissions in the pulp and paper industry. Substituting low-carbon energy sources for fossil fuels to generate process heat can reduce direct emissions, especially from pulp production. Low-carbon options include:

- **Biogas from wastewater.** Pulp wastewater contains biological material that can be converted into methane through anaerobic digestion (AD). It has been used in mechanical mills and recycled paper production, but the presence of chemicals in wastewater has limited its use in kraft mills.
- **Biogas from MSW landfills.** Landfill gas can directly substitute for natural gas to produce process heat, including in the pulp and paper industry. Its deployment may be limited by high investment and operating costs, as well as by logistical barriers.
- **Geothermal.** Geothermal heat has been used as a source of process heat in the pulp and paper industry globally, and can be applied in LAC countries with geothermal resources. High investment costs, geological risk, and the availability of geothermal resources near existing pulp and paper plants have limited its deployment to date.
- **Biomass gasification.** Gasifying biomass waste from pulp and paper production can replace fossil fuels for process heat. Potential biomass sources include wood and paper industrial wastes, and black liquor from pulp production. Black liquor gasification is estimated to be twice as energy efficient as traditional recycling processes but requires significant capital investment.
- **Electrification for heat generation.** Electricity can be used to generate process heat through a variety of technologies. For pulp and paper production, electrifying heat production is simpler than other heavy industries because the required temperatures are much lower (typically less than 200° centigrade).
- **Clean hydrogen.** As in other industries, clean hydrogen would require validation and extensive investment in additional infrastructure to be deployed in the pulp and paper industry.

Options to reduce pulp and paper industry emissions outside of process heat production include:

- **Electricity from RE sources.** Using renewable energy would remove indirect emissions from electricity generated with fossil fuels. Kraft pulp production already uses biomass waste from the process for co-generation, often in excess of the plant's requirements.
- **Carbon capture and storage.** CCUS technologies can be applied to boilers and kilns used in pulp manufacturing. If applied to processes fired by biomass (and, therefore, already carbon neutral), the processes would become carbon sinks and could offset emissions from other sectors.
- **Energy efficiency.** Energy efficiency technologies can be applied to wood chip digestion and refining, black liquor evaporation, and paper dewatering and drying. Potential energy savings typically range between 15% and 50%[88] and cover a wide range of investment costs.

[85] Ibid
[86] Ibid
[87] Ibid
[88] Bajpai, 2016, Suhr et al. 2015, Berger et al., 2021

- **Manufacturing pulp from recycled fibers.** Producing pulp from recycled fibers can reduce energy consumption by 30-70%[89]. Some virgin pulp must be blended with the recycled fibers and there is a limit to the number of times fibers can be recycled.

Replacing fossil fuels with renewable sources to provide process heat would provide the greatest reduction in CO_2e emissions, followed by increasing the share of electricity from renewable energies, carbon capture, increasing manufacturing from recycled fibers, and improving energy efficiency. Each of these potential technologies will require new investment and may require new supply chains and supporting infrastructure. Many require further development for large-scale deployment and must be validated for use in each individual market. Government policies and financial mechanisms will be instrumental to advancing these technologies.

Steel Industry

The steel industry is a cornerstone of the global economy, contributing significantly to industrial CO_2 emissions. In LAC, the steel industry is not only a vital driver of economic growth and infrastructure development but also a critical sector to address in advancing sustainable and low-carbon pathways. While steel production is concentrated in six countries (Brazil, Mexico, Argentina, Colombia, Chile, and Peru), the material is consumed in every LAC country, supporting essential industries such as construction, manufacturing, and energy.

Steel Production Processes

Crude steel, the basic material used to manufacture steel products, is composed of iron, carbon, and other elements, such as chromium, copper, phosphorus, manganese, molybdenum, nickel, silicon, vanadium, and titanium, among others. The carbon content (typically between 0.02% and 2%) and the other elements give crude steel specific properties tailored for its final use.

Crude steel is produced from iron ore through chemical and metallurgical processes in three stages: materials preparation, ironmaking, and steelmaking.

Crude steel production begins with preparing key input materials, including iron and coke (to provide the needed carbon). To prepare the iron, iron ore is crushed, homogenized, and mixed with limestone, coke breeze, slag-forming agents, and fluxes at high temperatures to produce iron sinter or iron pellets. To produce coke, coal is heated at high temperatures in a coke oven in the absence of air, to remove volatile matter, resulting in a solid material composed mainly of carbon.[90]

In the ironmaking stage, iron ore is either converted into pig iron in a blast furnace (BF) or into sponge iron through direct reduction (known as Direct Reduced Iron, or DRI). In the BF route, iron, coke, and limestone are added in layers into the upper part of the BF while air and fuels are introduced below to heat the inputs and produce carbon monoxide gas. The heat then melts the iron sinter while the carbon monoxide gas removes oxygen from it through a chemical process. The molten pig iron and slag waste then flow to the bottom of the BF.

DRI transforms iron into sponge iron by combining iron pellets and a mixture of carbon monoxide and hydrogen (known as the reducing gas) in a reactor. The gas chemically reacts with the ore to reduce the ore's oxygen content to produce sponge iron, which is then pressed into briquettes known as hot briquetted iron (HBI). The reducing gas can be generated from natural gas, syngas, or from

[89] Rahnama et al., 2021; Moya and Pavel, 2018; Kramer et al., 2009
[90] https://worldsteel.org/about-steel/about-steel/steelmaking/

the partial combustion of coal, similar to coke production. The chemical reactions in DRI require high temperatures, but not high enough to melt iron. In this way, the DRI process requires less energy than BF ironmaking.

In the steelmaking stage, the pig iron or sponge iron is refined to produce crude steel through either a Basic Oxygen Furnace (BOF) or an Electric Arc Furnace (EAF). Both processes melt the iron inputs and add oxygen and other elements to achieve the desired chemistry for the steel product. Both processes also typically melt steel scrap along with the iron inputs, allowing a high degree of recycling. For a BOF, the materials are heated by burning a fuel, while an EAF applies high voltage electricity directly to the materials to melt them.

The produced steel is then refined to remove most residual impurities. Steelmaking culminates with a continuous casting process, in which molten steel is poured into open-bottomed, water-cooled molds to create standardized semi-finished shapes (known as slabs, billets, and blooms).

About 70% of global steel production uses the BF-BOF route, and about 25% uses the EAF route, with variations and combinations of production routes accounting for the rest.[91] In LAC, 73% of primary iron is pig iron produced via BF, and the remainder is sponge iron produced via DRI. Crude steel production is largely balanced in the region, with 49.2% produced via BOF and 50.1% produced via EAF. Within individual countries, one technology tends to dominate: EAF accounted for 93.4% of Mexican steel production in 2023 and 93.2% of production in other smaller producing countries. BOF accounted for 76.2% of production in Brazil and 61.5% in Chile. Argentina had the most balanced production, with 42.9% BOF and 57.1% EAF.[92]

Although steel is highly recyclable, most steel products have a useful life that lasts for decades. Therefore, more than recycled steel scrap is required to meet growing steel demand.

Global and Regional Steel Markets

Global crude steel production reached 1,893 Mt in 2023, of which LAC contributed 58.32 Mt (3.1%)[93]. The construction and infrastructure sectors constitute 52% of global steel demand, followed by mechanical equipment (16%), automotive (12%), and tools (10%).[94] Other means of transportation (trains, ships, airplanes), domestic appliances, and electrical equipment make up the remaining 10%.[95]

Steel is produced in 13 LAC countries, with Brazil (55%) and Mexico (28%) being the largest producers. These two countries, along with the next four largest producers (Argentina, Colombia, Chile, and Peru) account for 98% of the region's production.[96]

Steel's Environmental Impact

In 2022, the steel sector consumed, on average, 20.99 gigajoules (GJ) of energy per ton of crude steel produced[97]. Within this average, energy intensity varies significantly according to the production route used. Producing steel from iron ore requires eight to ten times more energy than using scrap steel as a raw material, owing to the need to heat and process the iron ore. Steelmaking using the BF-BOF route has an energy intensity of 21.4 GJ/t, the DRI-EAF route 17.1 GJ/t, and recycling steel scrap into new steel products using an EAF requires only 2.1 GJ/t.[98]

[91] Ibid
[92] World Steel Association, 2022b
[93] World Steel Association statistics
[94] Ibid
[95] Ibid
[96] Ibid
[97] Ibid
[98] IEA, 2020

Steel manufacturing emitted an estimated 3.43 Gt of CO_2 globally in 2022[99]. The average emission factor for crude steel production in LAC is 1.66 tCO_2/t, 9% less than the world average due to a higher share of EAF production and renewable energy use[100]. The average total emission intensity of the BF-BOF route, as calculated by the IEA, is 2.2 tCO_2/t. This is 7.3 times higher than the IEA's estimated 0.3 tCO2/t average total emissions from the EAF route using only scrap steel. Combining the EAF route with DRI-produced sponge iron, instead of scrap, increases average total emissions to 1.4 tCO_2/t but remains 37% lower than BF-BOF. In addition, the BF-BOF route contributes more to direct emissions than do the other production routes[101].

Total CO_2 emissions associated with crude steel production in LAC were an estimated 102.8 Mt in 2022. Direct emissions account for 93.37% of total emissions (96 Mt, or 1.55 tCO_2/t of steel produced), while indirect emissions account for the remaining 6.63% (6.8 MT, or 0.11 tCO_2/t of steel produced).

Disaggregating emissions by production route shows that BOF production in LAC generates approximately 1.91 tCO_2/t of crude steel, while EAF-based production generates about 0.55 tCO_2/t of crude steel or 29% of the carbon intensity of BOF production per ton produced. Although the EAF process is more electricity intensive and therefore represents higher indirect emissions, the direct emissions associated with EAF are 82% lower.[102]

Sectors that provide short-term services, such as packaging, have relatively short lifecycles (less than two years) and simpler value chains. This facilitates the circularity and integration of recycled steel use. Other industries, such as construction and infrastructure, have longer lifecycles, with periods of at least 50 years before the steel can be recycled. This requires a well-established value chain for recovery, processing, and smelting.

Around 630 Mt of steel scrap is globally recycled annually, equivalent to 33% of the total crude steel production recorded in 2023[103]. Roughly 38% of recycled steel scrap is pre-consumer generated during the manufacturing and processing of steel products before they reach end consumers. The remaining 62% is post-consumer scrap purchased on the market.[104]

Steel Decarbonization in LAC

Reducing greenhouse gas emissions in the steel industry is a complex challenge due to various technical realities of steelmaking, and requires significant investment and policy support. Promising mitigation technology options include:

- **Replace coal with biomass.** Biomass can partially replace coal and coke to provide the process heat and carbon needed to make pig iron. The emissions reductions from this option are directly related to the share of coal or coke replaced. Biochar is currently used in some plants, but other feedstock sources are less developed[105]. Sustainable feedstocks need to be certified and supply chains established to reach commercial volumes.

- **Replace natural gas with biomethane.** Biomethane from biodigesters, landfills, or wastewater treatment plants can substitute for natural gas in providing process heat or for DRI. Plants currently using natural gas do not require additional investment to use biomethane instead, although investment is required to produce, gather, and process the biomethane itself.

[99] World Steel Association statistics
[100] CRU, 2022
[101] These estimates are based on steel production energy intensities in final energy terms. The World Steel Association's (WSA) methodology estimates steel production energy intensities in primary energy terms. This difference is most pronounced for electricity inputs, as the WSA methodology uses a 37% conversion efficiency factor to calculate the primary energy required to produce the electricity used in the steel production process.
[102] CRU, 2022
[103] BIR, 2022
[104] Ibid
[105] Draxler et al., 2021

- **Use ammonia or methanol as a hydrogen carrier.** Using low-carbon hydrogen would reduce emissions associated with burning fossil fuels for process heat in steel making. Because hydrogen is difficult to transport and store, using ammonia or methanol produced from low-carbon hydrogen may be more effective. Ammonia and methanol are well established industries, but are not widely used in steel making.

- **Electrify with renewable energy sources.** Using renewable energy in EAFs would remove Scope 2 emissions from electricity generated with fossil fuels. Total emissions reduction depends on the share of electricity currently generated from fossil fuels, as well as the type of fuels used. Renewable energy technologies are widespread and often less expensive than fossil fuel technologies. Steel companies in LAC already have experience with renewable energy PPAs.

- **Increase scrap use.** Manufacturing steel from scrap (secondary manufacturing) uses far less energy than primary manufacturing. Secondary manufacturing is already widespread and can be implemented at existing EAFs. Increasing recycling rates may, however, require policies to incentivize and enforce recycling mandates, and to retain scrap steel for domestic use.

- **Innovative production routes.** The options described above can be applied to traditional BF-BOF and DRI-EAF production routes. Innovative new production routes may also be available in the near future, including applying CCUS technology with DRI reactors, HIsarna technology that combines direct reduction and smelting to directly produce pig iron for the BF-BOF route without coke (and can also be paired with CCUS), and the H2/DRI-EAF route that uses hydrogen in the DRI process to produce sponge iron. CCUS technology is currently in use in a small number of steel mills, including two mills in Mexico, but the other technologies are not yet commercially available. For all proposed new routes, significant investment is needed, making them more suitable for new steel plants than for retrofitting existing plants.

Steel industry decarbonization must consider multiple factors, including available resources, production routes, geographic locations, energy costs, and geopolitical conditions. The most appropriate decarbonization strategy will depend on each steel industry's specific circumstances. Technical analysis based on good-quality information, supportive government policies, and resources to promote research and development are essential.

Policy Measures to Promote Decarbonization

Aluminum, cement, pulp and paper, and steel are all essential to modern economies, but are also significant contributors to climate change and are difficult to decarbonize. Large-scale investment, strong policy frameworks, and funding to support research and development, as well as demonstration projects and innovative business models, are necessary to enable the transition toward net-zero emissions.

This section first presents a vision and baseline that every country can establish for these four industries in LAC. It then outlines common actions that can be taken to develop policies and regulations; support projects, technologies and infrastructure; provide funding and incentives; and promote the capacity building and regional cooperation that can support decarbonization.

The policy recommendations presented here are based on technological pathways identified for each industry, highlighting areas of common need and cross-industry synergies. Detailed policy options and framework decarbonization policy roadmaps are included in each industry chapter of the main report.

Vision and Baseline

Governments seeking to draft effective industry decarbonization strategies should first establish their national position within global and regional value chains and to articulate the role they aspire to play. This includes identifying all relevant stakeholders that can be affected by government policies.

For producing countries, this may entail detailed mapping of existing production pathways for the relevant industries to establish baseline GHG emissions and evaluate the resilience of their operations and supply chains. Exporting countries should also analyze the evolving requirements of importing countries and their implications, such as the EU carbon border adjustment mechanism.

For non-producing countries, this would focus on their role as importers, consumers, recyclers, and traders within the relevant value chains. To meet their decarbonization plans, non-producing countries should consider the carbon footprint of imported industrial goods. Additionally, they can also increase their recycling and scrap recovery, either for export or to support secondary production locally.

It is also important to recognize and assess the unique comparative advantages inherent to each jurisdiction when considering decarbonization strategies. The pathways toward achieving net-zero emissions can vary significantly across countries, influenced by distinct economic structures, resource availability, technological maturity, and regulatory environments.

Given the scale and complexity of the global decarbonization challenge, it is imperative that all viable pathways be thoroughly evaluated and strategically prioritized. Countries should avoid adopting technologies developed for other regions without first conducting a rigorous assessment of their own capabilities, infrastructure, and technical expertise. Tailoring solutions to local conditions will be critical to ensuring both effectiveness and efficiency in the transition to a low-carbon economy.

This baseline analysis will enable governments to design tailored roadmaps that align industrial, energy, and trade policies to reduce GHG emissions and safeguard competitiveness and long-term industrial resilience.

Policies and Regulations

Initial decarbonization policies should focus on national decarbonization strategies to 2050 that establish long-term emissions reductions goals in the context of each country's natural resource availability, role in low-carbon global value chains, energy systems, industrial and labor structures, and financial capacity. These strategies should include modeled scenarios of technology adoption, an emissions abatement curve to prioritize actions by cost-effectiveness, and an assessment of funding gaps. Policy cost curves can help identify the most appropriate measures, while just-transition measures should be included to address environmental and social considerations.

Countries should also conduct a comprehensive review of existing policy frameworks to ensure they enable the deployment of early decarbonization pathways. Governments can also establish and actively promote industrial regulatory sandboxes for innovative technologies and business models in controlled conditions.

National recycling programs and targets should be introduced to stimulate demand and improve circularity, such as mandating recycling in short-lifecycle applications, such as packaging, while promoting education, awareness, and investment in recovery, and processing infrastructure to enable circular practices in long-lifecycle sectors like construction.

In later phases, governments should introduce embodied-carbon standards in public procurement to create stable demand for low-carbon industrial products. In parallel, carbon pricing mechanisms,

such as carbon taxes or cap-and-trade programs, should be applied to domestic industry and imports. Regulations can also mandate emissions-intensity disclosure from both domestic producers and importers.

Electricity planning should prioritize industrial decarbonization loads, provided these do not compete with residential needs. Establishing permitting frameworks for CO_2 transport and storage infrastructure should be planned.

Governments can expand advanced scrap recycling systems by mandating separate collection, extended producer responsibility, and clear labeling to ensure high recovery rates. They can also introduce a minimum percentage of recycled aluminum in new packaging and vehicles, or a requirement that government-used paper contain a minimum percentage of recycled paper.

By the late 2030s, governments should mandate emissions-intensity performance standards, introduce minimum recycled-content requirements in key end uses, and align trade policies with global low-carbon standards. Non-producing countries should strengthen their role as enablers by scaling procurement of low-carbon industrial products for infrastructure and facilitating regional logistics for recycled materials.

Toward 2050, performance standards should tighten to near-zero emissions. Governments should mandate high recycled-content thresholds and enforce full recovery of end-of-life products across all sectors. Trade and customs policies should be aligned with global carbon requirements, with countries consolidating their own carbon adjustment mechanisms that are consistent with international standards.

Projects, Technologies, and Infrastructure

Initially, each country should identify champion companies, meaning large domestic or multinational companies with the willingness and resources to advance decarbonization early and implement demonstration projects. Successful demonstration projects will be critical to validating new technologies in the LAC context.

Governments should promote early adoption of no-regrets measures, such as energy efficiency measures, optimizing existing production processes, and promoting renewable and hybrid generation systems for electricity-intensive operations. Pre-development studies for renewable grid expansion, CO_2 storage capacity, recycling hubs, and industry-specific technology demonstration plants should be initiated to prepare the ground for scaling in later phases.

During the scaling phase, proven solutions should be prioritized while continuing demonstration projects for new technologies. Producing countries should continue their energy efficiency measures, prioritize the decarbonization of heat production, and introduce co-generation systems that reuse process heat for electricity generation, where applicable. Renewable hydrogen, the use of refuse-derived fuels, and CCUS demonstration projects should be deployed, with shared CO_2 hubs beginning development near plants with suitable geological conditions.

By 2040, producing countries should progress toward the deployment of transformative technologies, such as renewable hydrogen and CCUS in regions where renewables and hydrogen are not widely available. Industrial symbiosis projects can be expanded and governments should continue to support next-generation demonstration projects to keep future technology options open. To protect communities, transition packages should accompany the retirement of stranded assets.

As 2050 approaches, inefficient fossil-based plants can begin to be retired and replaced with proven low-carbon technologies. Residual emissions should be offset through CCUS-equipped facilities where necessary or other carbon removals, and supply chains should be optimized through regional integration.

Funding and Incentives

Decarbonization efforts can be supported through concessional finance, such as the Climate Investment Funds (CIF) Industry Decarbonization Investment Program now being deployed in Brazil and Mexico. MDBs can design country-specific instruments to de-risk investment, such as guarantees, low-interest loans, and results-based grants tied to verified emission reductions.

Recycling and industrial circularity can be incentivized by programs that valorize relevant by-products and create market incentives for recycled content in construction, packaging, and infrastructure projects.

In later phases, governments and MDBs should broaden concessional lending, expand green bond frameworks, and co-finance renewable energy, transmission, low-carbon industrial hubs in strategic regions, and recycling hubs. They can also provide grants or tax incentives for companies adopting secondary production technologies and new low-carbon technologies for primary production. Instruments such as contracts for difference (CfDs) can de-risk high-cost projects like CCUS, provided they are fiscally sustainable and time-bound. Public–private partnerships for industrial infrastructure, such as renewable-powered industrial clusters and CO_2 networks, should also be promoted.

By 2040, as low-carbon technologies mature, funding will increasingly come from private capital, with concessional support tapering off for well-established technologies. Public incentives should focus on transition finance to convert existing assets, and on just-transition funds to support affected workers and communities. International partnerships, anchored by MDBs, will remain essential for financing large-scale infrastructure projects.

Capacity Building and Regional Cooperation

In the early stages of decarbonization, MDBs can facilitate knowledge exchange and support the development of regional standards and certification schemes, as well as early coordination with the EU on CBAM. Countries should harmonize definitions of recycling and waste management, create common measurement tools, and enable cross-border trade in scrap and relevant by-products. Capacity building should also include training in the circular economy and recycling, low-carbon production technologies, CCUS, certification processes, and monitoring, reporting and verification processes.

In later phases, countries should harmonize their certification schemes, monitoring standards, and recycling and waste reuse and management rules to enable regional integration. Cooperation should focus on creating regional scrap, recycling, and waste markets; coordinating logistics for hydrogen and CO_2; and sharing lessons from early demonstration projects. Capacity building for recycling operations and new technologies is also encouraged.

As 2050 approaches, reskilling programs, community engagement initiatives, and harmonized regional safety protocols for waste, hydrogen, and CO_2 should be scaled up to manage risks and build trust. Regional governance on standards and certification systems should continue, alongside benchmarking and data sharing to ensure continuous improvement. Latin America should also position itself as a global knowledge hub for sustainable production, exporting expertise to other regions.

INTRODUCTION

Heavy industries provide critical goods to the global economy. Cement and steel are the backbone of the built environment: the buildings, dams, roads, and rails of the world's infrastructure. Steel and aluminum are at the core of the machines–from transportation to manufacturing to home appliances–that enable modern standards of living. Aluminum and pulp and paper provide the packaging, consumer goods, and hygiene products that we rely on every day.

Producing these materials on a global scale requires enormous amounts of natural resources, especially energy. Iron ore and bauxite must be melted to make pig iron and alumina which, in turn, must be melted to create finished steel and aluminum. Limestone and clay must be heated to 1,400° centigrade to make cement. Logs must be harvested and processed to make pulp; the pulp must then be heated and dried in multiple steps to make paper.

Using fossil fuels to generate the heat and electricity that is needed to manufacture these materials produces greenhouse gas (GHG) emissions. Chemical reactions that are an inherent part of the manufacturing processes also produce GHGs: the carbon in steel is provided by coke made from coal, aluminum electrolysis relies on carbon anodes that produce CO_2 as they decompose, and limestone chemical decarbonization is the source of roughly 60% of cement manufacturing GHG emissions.

Taken together, high energy requirements and process-related GHG emissions make these industries among the most difficult to decarbonize. At the same time, their scale and importance to the global economy makes their decarbonization imperative to reaching the Paris Agreement goals of net-zero emissions by 2050.

Heavy industries in Latin America and the Caribbean (LAC) can play an important role in the global decarbonization effort. Brazil alone is the world's second-largest producer of iron ore, third-largest producer of pulp and alumina, fourth-largest producer of bauxite, and seventh-largest producer of cement. LAC heavy industries are growing as the region's economy expands and its population increases and becomes more urbanized. Per capita consumption of these goods also remains well below the average in the United States and Europe. This potential for growth provides an opportunity to invest in new productive capacity that incorporates the latest low-carbon technologies.

LAC has an advantage, as its heavy industry GHG emissions are lower than the global average, owing in part to its greater share of renewable energy in the region's electricity matrix, especially hydropower. For example, steel production in LAC produces 9% less GHGs per ton of steel than the global average. LAC pulp producers using the kraft process generate more electricity from biomass wastes than the process requires, allowing them to provide zero-carbon electricity to the grid. However, further reducing GHG emissions toward net zero in these LAC industries will require adapting low-carbon technologies to the region, structuring markets for low-carbon industrial products, and promoting cross-industry synergies and circular economy practices.

This report aims to support this effort by providing policy makers a grounding in the current technical and market realities of manufacturing aluminum, cement, pulp and paper, and steel in the region; an overview of the available technologies to reduce carbon intensity in their manufacture; and a set of potential policy and financing options to overcome the challenges to implementing these low-carbon technologies.

This report is divided into four main chapters: one chapter each for the aluminum, cement, pulp and paper, and steel industries. Within each industry chapter, the report reviews the production

processes, global and regional markets, environmental impacts, and low-carbon technology options for the industry, and outlines a policy roadmap to reach net-zero emissions by 2050, in line with the Paris Agreement's aspirations.

Emphasizing the technical processes used to produce these materials and the environmental impacts from each step gives policymakers perspective on where decarbonization challenges lie, helping them to fine-tune interventions to address specific challenges and opportunities. Placing LAC markets in a global context likewise allows governments to understand how global trade flows and their trade partners' carbon policies will impact local industries. Describing the range of technologies available to reduce carbon emissions from each industry, their technological maturity, and potential costs gives decisionmakers a perspective on the current technological landscape and how it is expected to evolve in the coming years. This perspective will be critical to devising roadmaps that are realistic but also adaptable to future technological breakthroughs.

Decarbonizing LAC heavy industry will not be easy. By stimulating connections across stakeholder groups, this report hopes to galvanize countries and industry champions to take the first steps toward reaching LAC's regional decarbonization goals.

ALUMINUM

1. INTRODUCTION

Heavy industry activities (cement, steel, and aluminum) are associated with approximately one-third of total global greenhouse gas (GHG) emissions. The Paris Agreement (PA) states that net zero GHG emissions must be achieved by 2050 to avoid an average global temperature increase exceeding 1.5°C compared to pre-industrial levels. In Latin America and the Caribbean (LAC), Mexico, Brazil, Venezuela, Argentina, Colombia, and Chile account for 85% of all industrial emissions.[106]

The aluminum industry is one of the most challenging heavy industries to decarbonize. In its commitment to align its operations with the Paris Agreement starting in 2023, the IDB Group seeks to promote decarbonization of this industry through technical assistance, loan transactions, and donations that are consistent with the Bank's main focus, its strategic infrastructure and environmental planning, and LAC countries' energy and climate change impact goals.

This chapter first reviews aluminum production processes and global and regional aluminum markets. It next describes the environmental impacts of aluminum production and decarbonization technology options for the industry such as replacing raw materials with recycled content, modernizing infrastructure, and adopting alternative energy sources. It goes on to provide a policy roadmap for countries wishing to decarbonize their aluminum industry and specific regional next steps to support each country's aluminum industry decarbonization efforts.

[106] ClimateWatch, 2021

2. Aluminum Production Processes

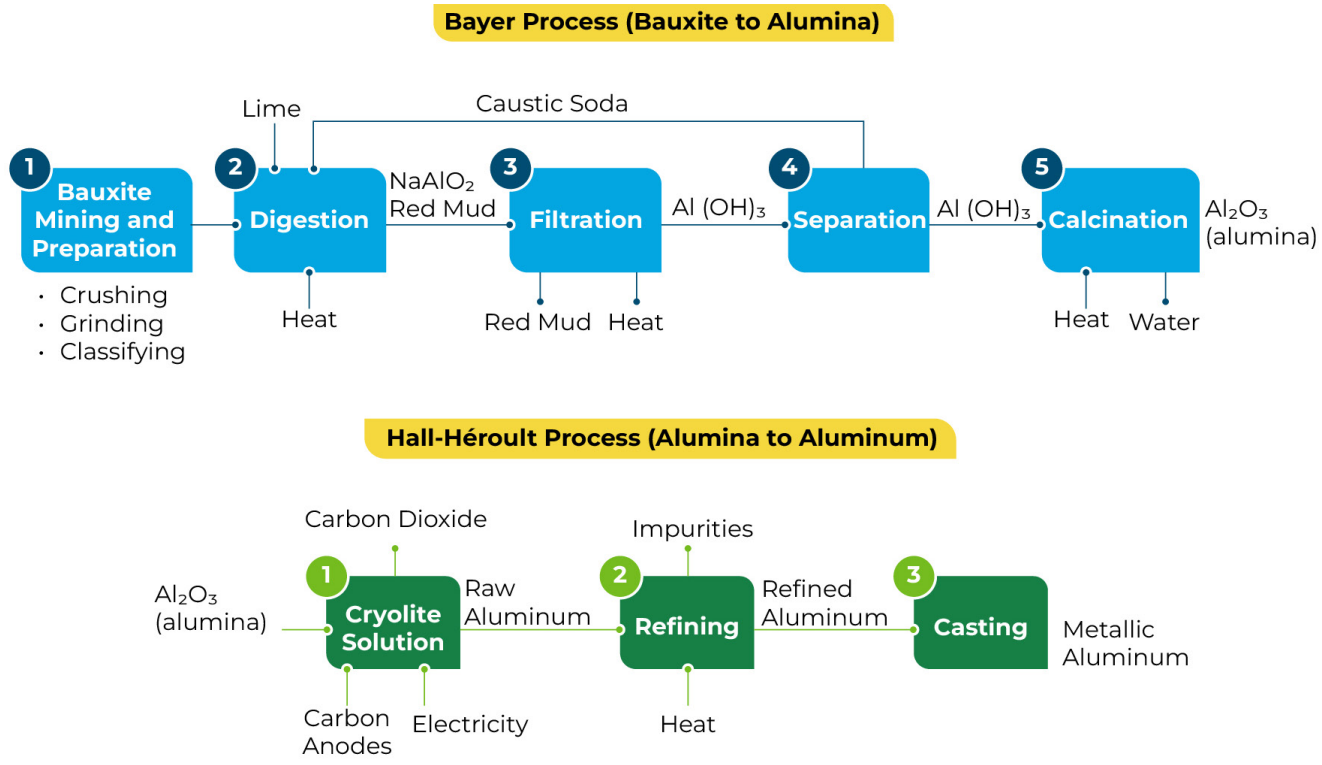
The aluminum industry includes primary aluminum production from bauxite ore and secondary aluminum production from recovered and recycled aluminum scrap. This chapter describes both aluminum production processes, the main materials and resources used, and the associated impact on pollutant gas emissions and solid waste. It also characterizes the import and export market for unwrought aluminum and estimates the growth of aluminum production and greenhouse gas emissions to 2050.

2.1 Aluminum Manufacturing Processes

2.1.1 Primary Aluminum

To produce primary aluminum, bauxite ore is first converted into alumina through the Bayer process. Next, the alumina is smelted using electrolysis through the Hall-Héroult process to obtain metallic aluminum, as shown below.

Figure 1. Primary Aluminum Production Process



Source: Produced in-house

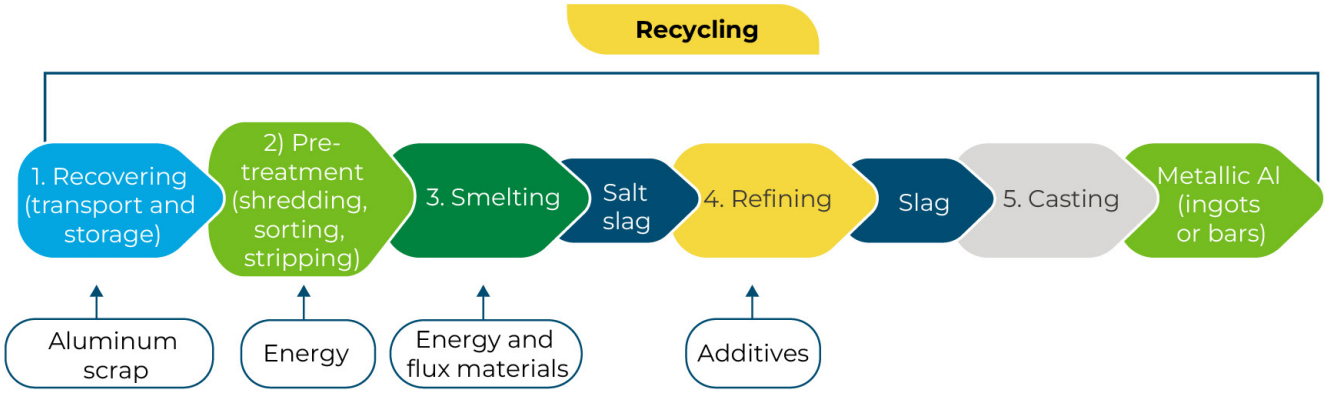
Bauxite extracted from mining deposits (Step 1) is crushed, ground, and classified to remove clays and other unwanted materials (Hasanbeigi, *et al.*, 2022). In Step 2, the refining process begins when the ground bauxite is mixed with liquid caustic soda and lime. This process, known as digestion or leaching, is carried out at high temperature and pressure (typically 150°C to 200°C and 4 to 8 kg/cm2, respectively, depending on the bauxite's properties) to obtain sodium aluminate ($NaAlO_2$) mixed with insoluble bauxite mud (red mud).[107] In Step 3, the red muds are decanted into sedimentation tanks, and the filtered aluminate solution is cooled to produce hydrated alumina crystals ($Al(OH)_3$), which are subsequently separated from the caustic soda (NaOH) by levigation or centrifugation (Step 4). Finally, in Step 5 the alumina hydrate ($Al(OH)_3$) is calcinated at temperatures between 900°C and 1,300°C to produce metallurgical alumina (Al_2O_3) and water.

During the Hall-Héroult or smelting process, alumina is first dissolved into an electrolytic cell and mixed with sodium fluoride (cryolite), where aluminum is produced through electrolysis. Carbon electrodes (anodes) are immersed in the cell to conduct electricity, which decomposes the alumina into oxygen and aluminum (Step 1). The molten aluminum metal is deposited on the negative pole (cathode) at the bottom of the cell, while oxygen accumulates on the carbon electrodes and produces carbon dioxide (CO2). The metal is extracted from the bottom of the cell by a vacuum siphon and transferred to alloying furnaces (Step 2), where the metal is amalgamated and gases and impurities are removed (aluminum refining). As a last step, the aluminum is cast into ingots or bars (Step 3).

2.1.2 Secondary Aluminum

Secondary aluminum is obtained mainly from smelting aluminum scrap and refining, as detailed below.

Figure 2. Secondary Aluminum Production Process



Source: Produced in-house based on Capuzzi & Timelli (2018)

[107] Tropical bauxite (gibbsite) is soluble in caustic soda at temperatures above 100 °C, while other types of bauxite (boehmite and diaspore) require temperatures above 200 °C to make them soluble (U.S. Department of Energy, 2007).

Scrap aluminum is recovered and transported to the plant (Step 1) and then pretreated to reduce impurities and improve the aluminum's quality before smelting (Step 2). The scrap is first shredded with rotating cutters, guillotines, and hammers to make it a consistent size, increase its apparent density, and release clumps of components. Next, unwanted elements such as plastics, rubbers, glass, metals, and other materials are separated from aluminum using manual, magnetic, airstream, and thermal separation methods. The pretreatment process concludes with chemical washes and heating to remove paints, oils, and other coatings from the scrap surface (Capuzzi & Timelli, 2018).

The scrap is then placed in melting furnaces at temperatures ranging from 700 to 760 degrees Celsius (Step 3).[108] Melting furnaces can be electric, reverberatory, or rotary, depending on energy costs; scrap type, volume, and impurity content; and final product quality. The smelted scrap is known as salt slag. In the refining process, additives and alloys are added to the liquid aluminum salt slag to create a specific product (Step 4). Finally, the molten aluminum slag is cast into ingot or bar shapes in a caster (Step 5).

2.2 Aluminum Production Inputs

Input materials, water, and energy are required at each stage of primary aluminum production. Statistics indicate that each ton of alumina produced in LAC requires 2.5 tons of bauxite and each ton of unwrought primary aluminum (ingots) requires about two tons of alumina.[109] Alumina production requires caustic soda to dissolve the aluminum contained in the bauxite and lime to reduce impurities in the alumina. Producing carbon anodes uses significant volumes of calcined coke and pitch. Electrolysis uses, in addition to carbon anodes, small amounts of carbon cathodes and sodium fluoride (cryolite) to lower the melting point of aluminum oxide (from 2,000o C to 950o C) to smelt the alumina (U.S. Department of Energy, 2007). Other inputs used in the smelting process include alloying additives such as magnesium and silicon and trace amounts of degassing elements such as chlorine, argon, and nitrogen.

Water is consumed during alumina production and smelting (about 5 m^3/t product for each), particularly for process and by-product cooling, sludge and slag washing, and caustic soda preparation and recovery (Australian Aluminum Council, 2022; Conklin, 1956; Sosa *et al.*, 2013). Electrolysis also uses large quantities of water for gas scrubbing.

Energy consumption includes fossil fuels for alumina and anode production, smelting, and, to a lesser extent, mining, in addition to electricity for electrolysis. Although high-carbon fuels such as coal and oil make up the majority of fossil fuels used, natural gas plays a significant role in anode production in Latin America. Aluminum producers in countries such as Brazil, are currently exploring options to reduce GHG emissions by increasing the share of natural gas in their fuel mix. The table below shows average input quantities used to produce primary aluminum in LAC.

[108] https://www.aluminum.org/secondary-production-101
[109] International Aluminum Institute, 2022

Table 1. Primary Aluminum Production Inputs in LAC

Materials (kg/t product)	Bauxite mining	Alumina production	Anode production	Electrolysis	Smelting
Bauxite		2,513			
Caustic soda		99			
Calcined lime		14			
Calcined coke			871		
Pitch			191		
Refractory material			0.8	6	
Steel			0.9	6	
Alumina				1,939	
Raw anodes and Soderberg paste				582	
Cathode carbon				6	
Fluoride				20	
Electrolysis metal					1,000
Alloy additives					31
Chlorine					0.009
Argon					0.1
Nitrogen					0.0002
Water consumption (m3 /t product)					
Fresh water	2.2	5	0.13	2.7	5.5
Seawater	0	0	0	0	0
Power consumption (MJ/t product)					
Heavy oil	19.9	4,483	1,018		0
Diesel oil	164.8	5	0		5
Natural gas	0	617	1,156		985
Coal	0	2,907	0	55,835	0
Electricity	3.8	399	545		400
Others		0	0		39

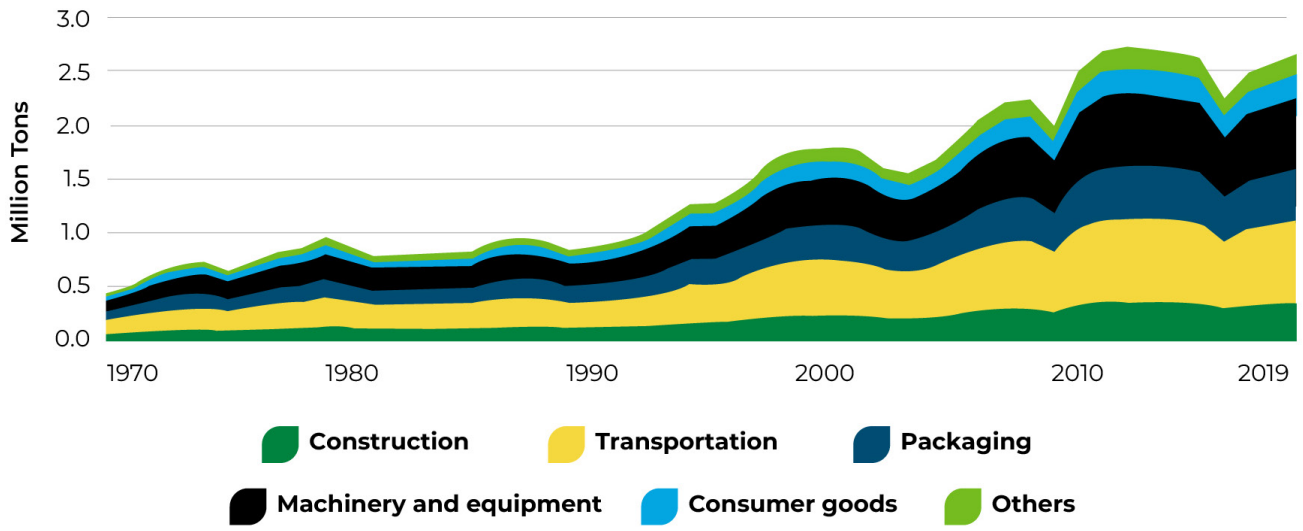
Source: Elaboration based on International Aluminum Institute (IAI),2022.

Secondary aluminum production from scrap does not require bauxite extraction, alumina production, or electrolysis, and therefore requires much less energy and water. For example, in the United States secondary aluminum production uses 4-7% of the energy and 18% of the water needed to produce primary aluminum (The Aluminum Association, 2022; Ding *et al.*, 2012).

2.3 End Uses

Between 1975 and 2019, demand for final aluminum products in LAC grew by 4.1% per year, reaching 2.64 Mt in 2019 (see Figure 3 below). The main consuming sectors were transportation (29%), machinery and equipment (25%), packaging (18%), construction (13%), and consumer goods (8%).[110]

Figure 3. Total Consumption of Final Products, LAC (1975-2019)

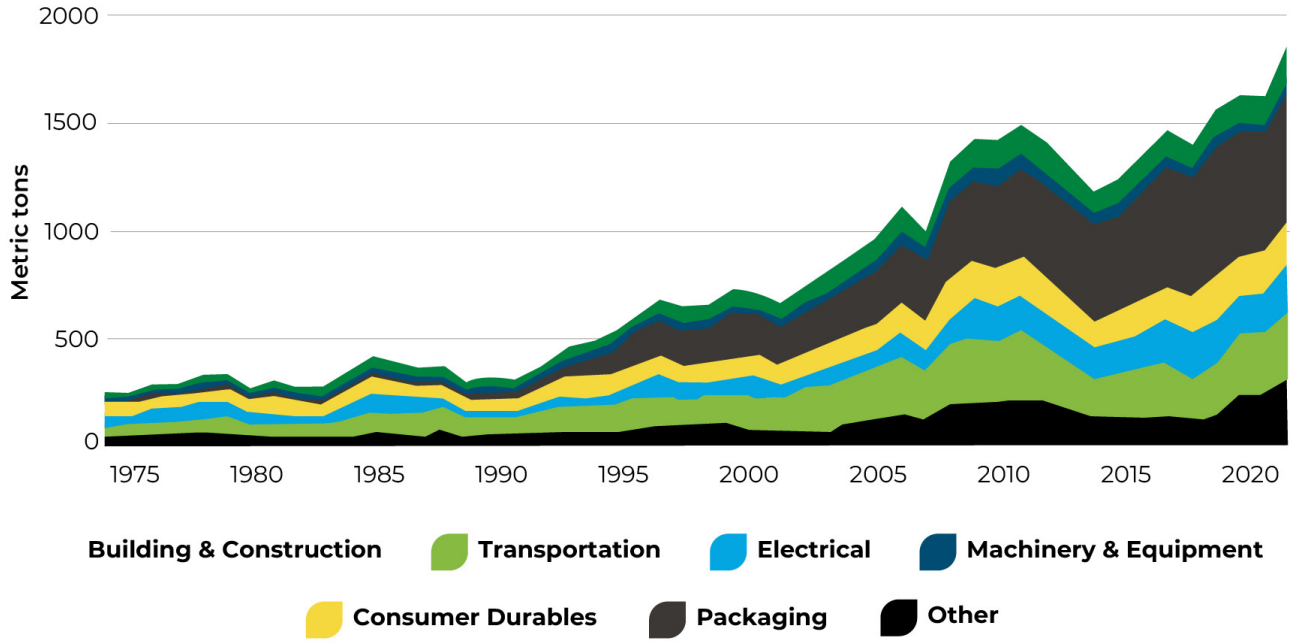


Source: Produced in-house based on IAI data and Menzie et al. (2010)

Brazil is the largest aluminum consuming country in Latin America, accounting for close to 60 percent of the region's total. Figure below shows Brazilian aluminum consumption by product type. Since the 1990s, aluminum use in packaging has increased rapidly. As of 2024 it accounted for one-third of all aluminum consumed in Brazil, followed by building and construction (18% of the total), and transportation (16% of the total).

[110] Menzie et al., 2010

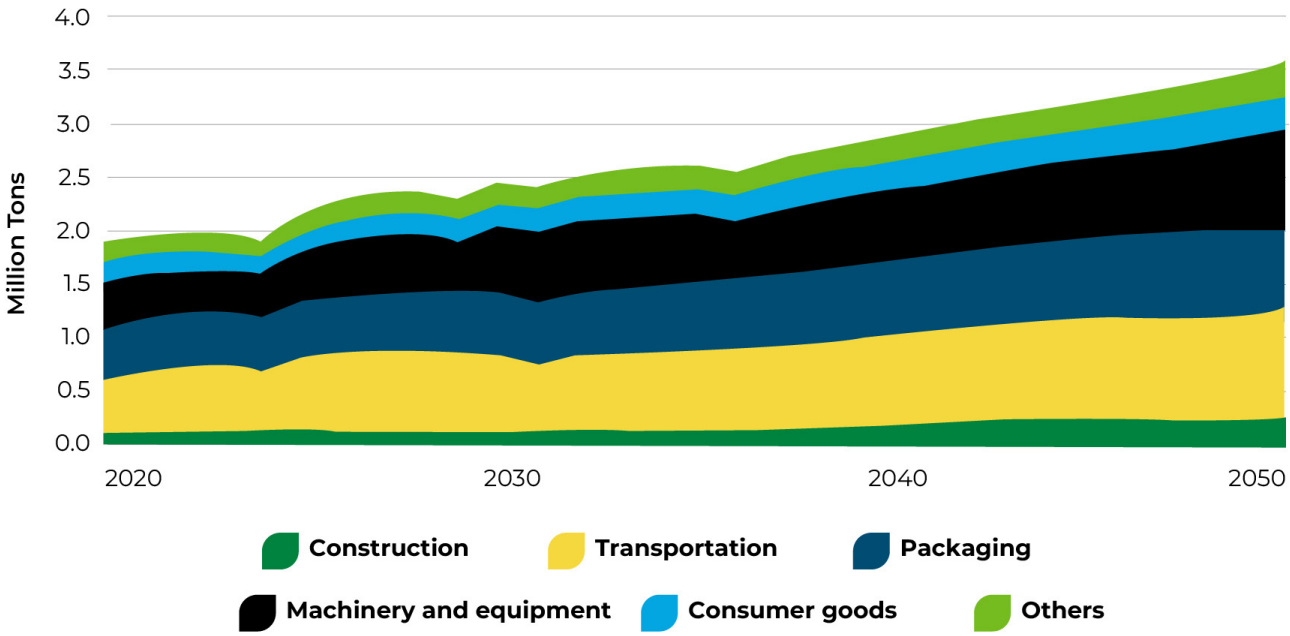
Figure 4. Total Consumption of Final Products, Brazil (1975-2024)



Source: Produced in-house based on ABAL data

Demand for aluminum products in LAC is forecast to increase by 87% to 4.93 Mt by 2050.[111] If such growth occurs, the total supply of post-consumer scrap will reach 3.57 Mt as shown below.[112]

Figure 5. Projected Supply of Aluminum Scrap, LAC (2020-2050)

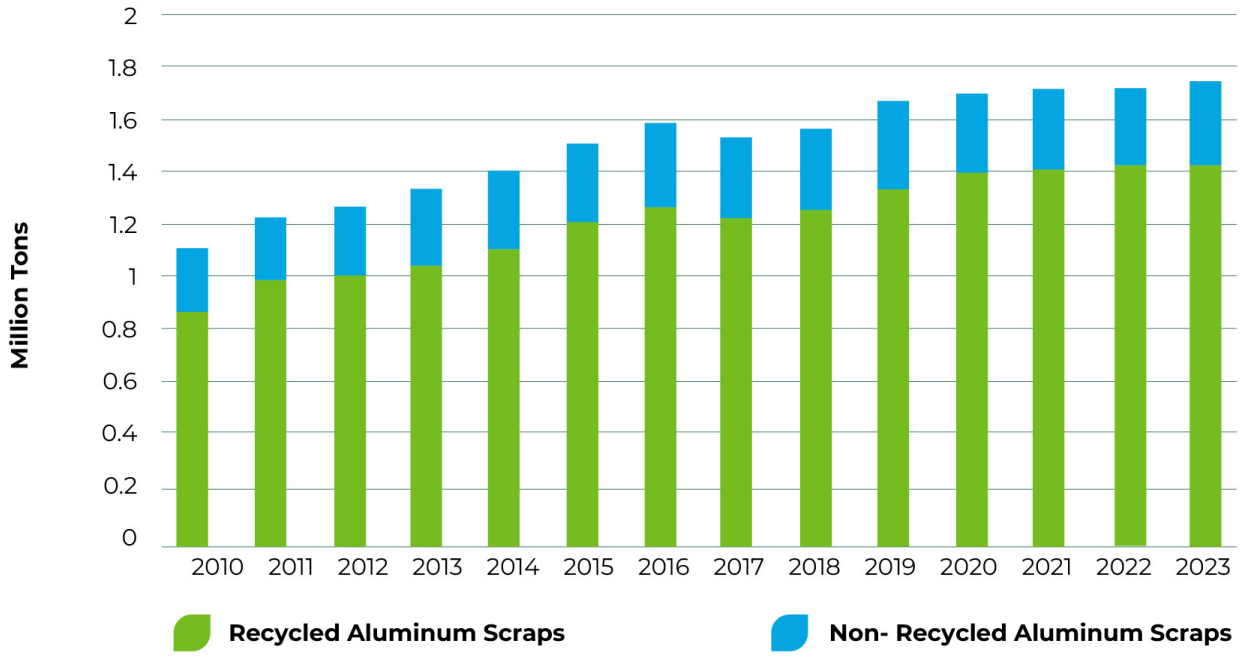


Source: Produced in-house based on IAI data

[111] CM Group, 2020.
[112] Excludes new scrap (pre-consumer) generated and recycled internally by the industry.

The scrap supply will support future secondary aluminum production growth in the region. Between 2010 and 2023, the region produced an average of 1.51 Mt/year of aluminum scrap, 81% (1.22 Mt/year) of which was destined for secondary aluminum production. The remaining 19% of the scrap (0.29 Mt/year) could not be recovered during waste management and ended its life in landfills. For example, the Colombian city of Bogota is sending to landfills about 1,278 ton/year of aluminum scrap, generated mainly by the residential sector, small producers, and commercial establishments (Millán *et al.*, 2015).

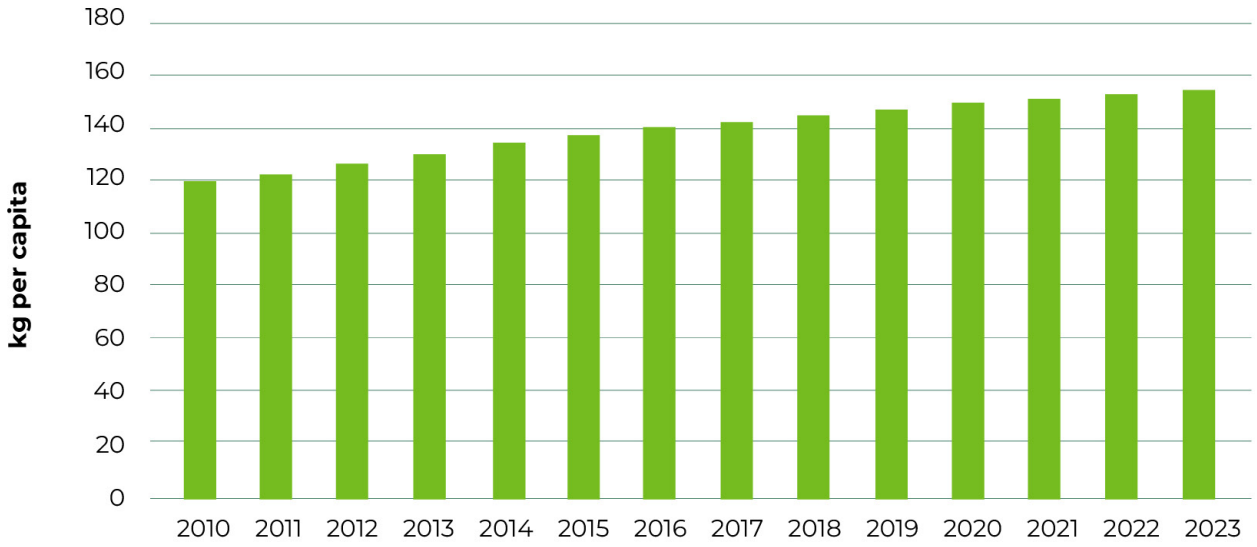
Figure 6. Aluminum Scrap Management, LAC (2010-2023)



Source: Produced in-house based on IAI data

Additionally, the stock includes captive aluminum that is neither discarded nor used. Growth per capita of aluminum stock in LAC increased by 31% from 119 kg per capita in 2010 to 156 kg per capita in 2023.

Figure 7. Aluminum Stock per Capita Growth, LAC (2010-2023)

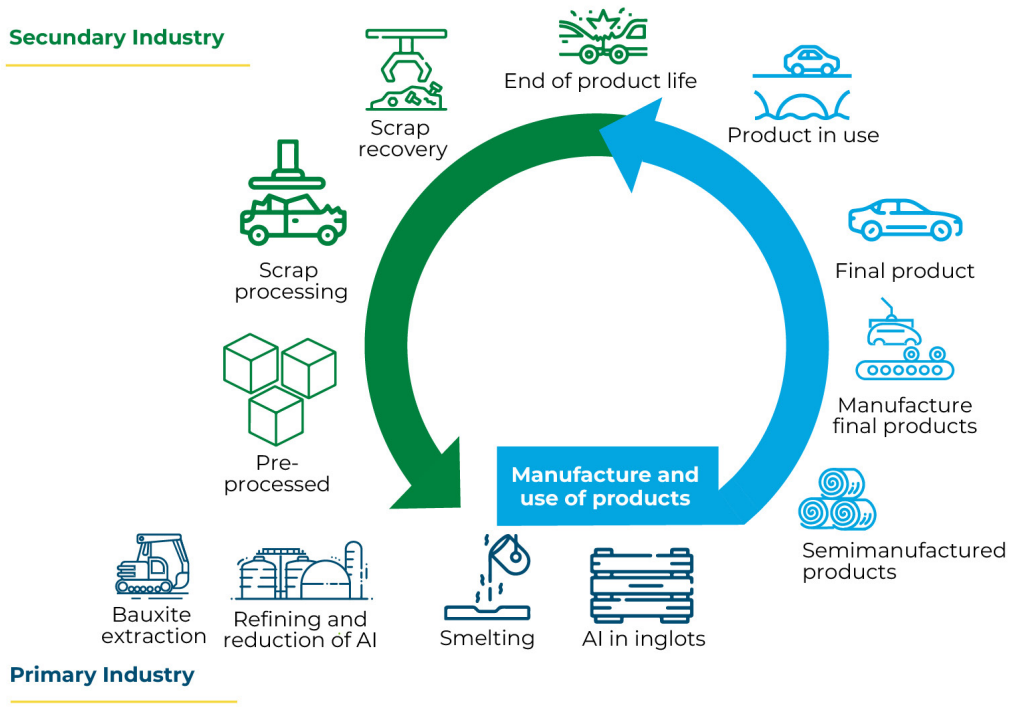


Source: Produced in-house based on IAI data

2.4 Lifecycle

Aluminum is used in short-term services such as packaging and longer-term industries such as construction. Uses with short lifecycles can more easily integrate circularity and recycling into their relatively simple value chains. Industries with longer lifecycles sometimes lack a well-established value chain in recovery, processing, and smelting.

Figure 8. Lifecycle of Aluminum

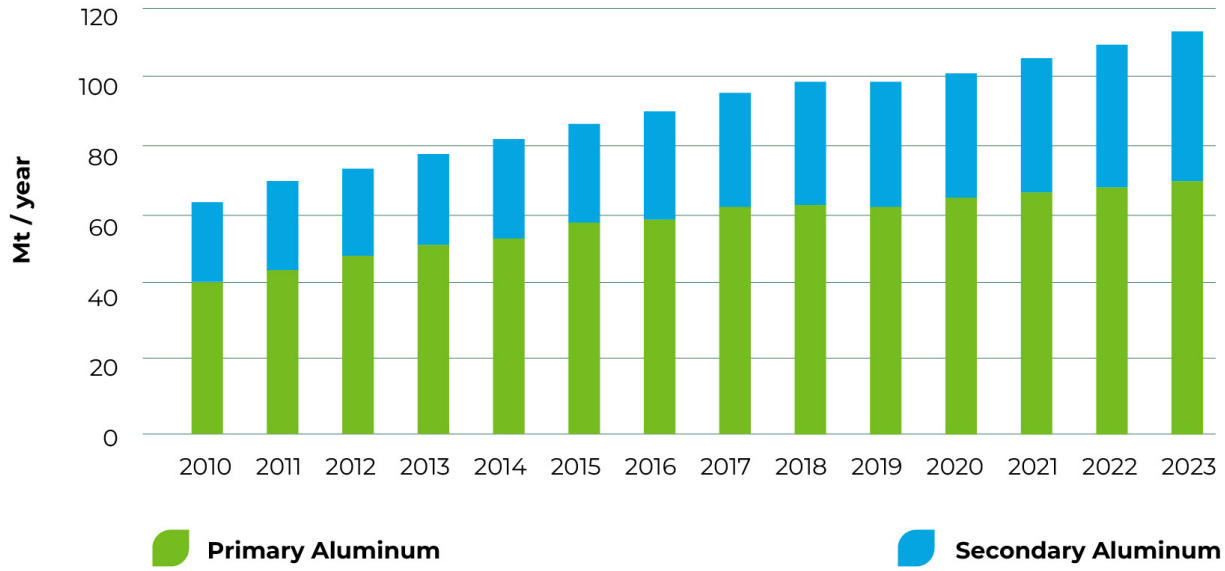


3. Global and Regional Markets

3.1 Global Production

World aluminum production grew by 75% between 2010 and 2023, reaching a total of 112 million tons. In 2023, LAC supplied 2.6% (2.9 Mt) of world production. Primary aluminum production now accounts for nearly two-thirds of total production.

Figure 9. World Aluminum Production, 2010-2023



Source: Produced in-house based on IAI data

3.2 Aluminum Industry in LAC

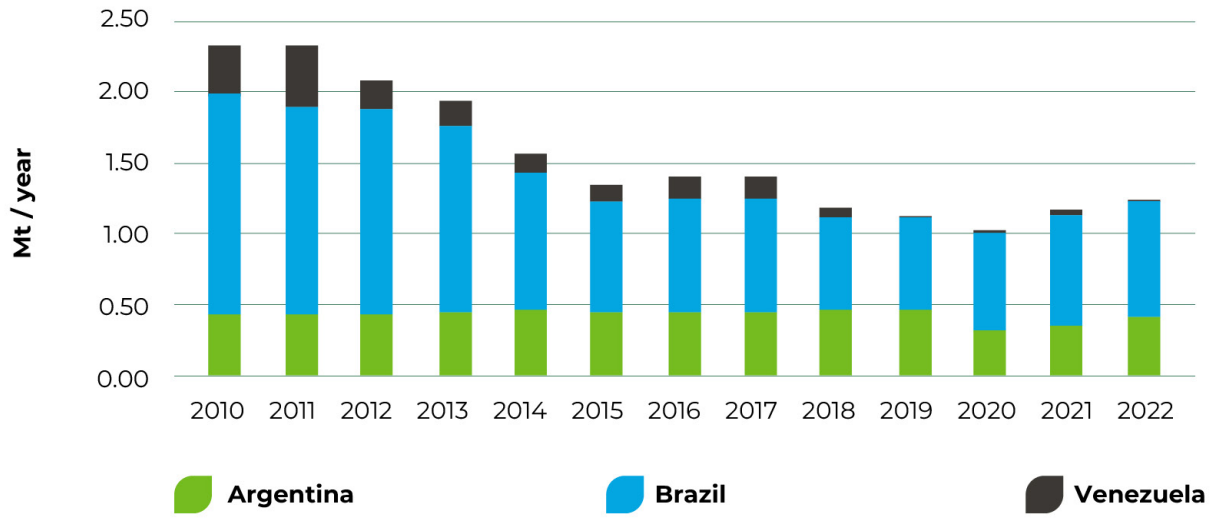
From 2010 to 2023, total aluminum production in LAC averaged 2.98 million tons per year. Primary aluminum production decreased by 56% from 2010 to 2020 and then recovered by 46% from 2021 to 2023. The decline in primary aluminum production was partially offset by a 14.3% growth in secondary aluminum production during this period. In 2023, secondary aluminum production accounted for 49.6% of total aluminum manufacturing in LAC, significantly above the global average.

Figure 10. Aluminum Production in LAC (2010 - 2023)

Source: Produced in-house based on data from IAI

Most primary aluminum production in Latin America is concentrated in Argentina, Brazil, and Venezuela. Between 2010 and 2022, Brazil averaged a 63% share, followed by Argentina (29%) and Venezuela (8%). During this period, Argentine production was relatively steady, while production in Brazil and Venezuela declined (by 47.2% and 97.6%, respectively).

Figure 11. Disaggregated Production of Primary Aluminum in LAC (2010-2022)

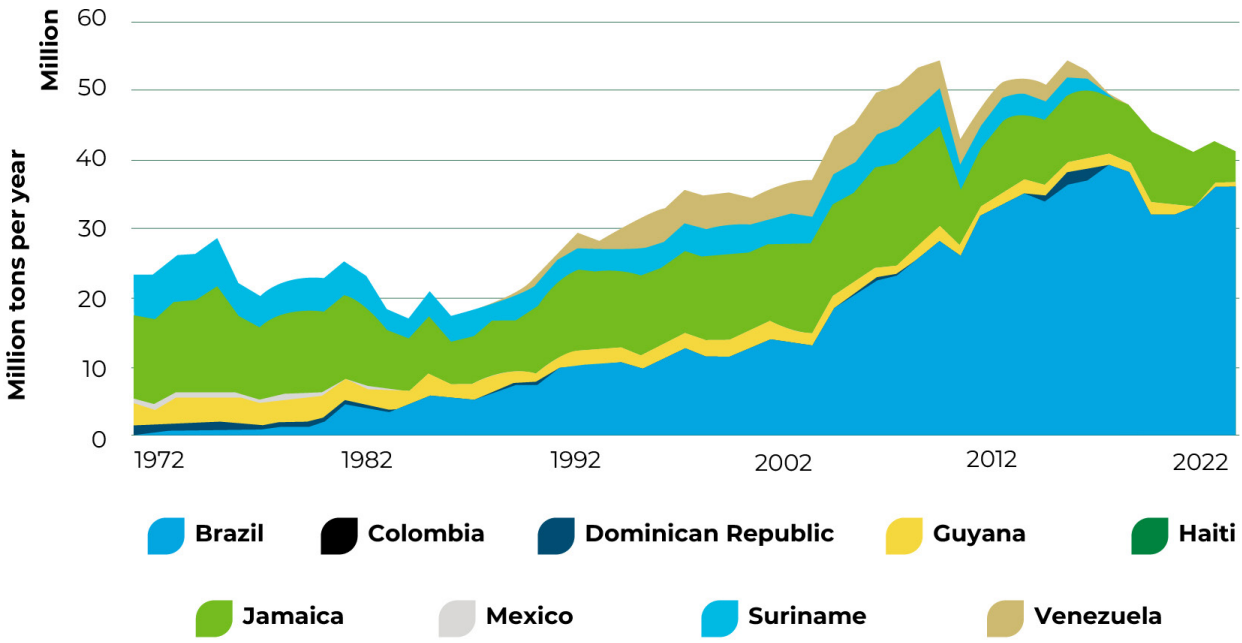


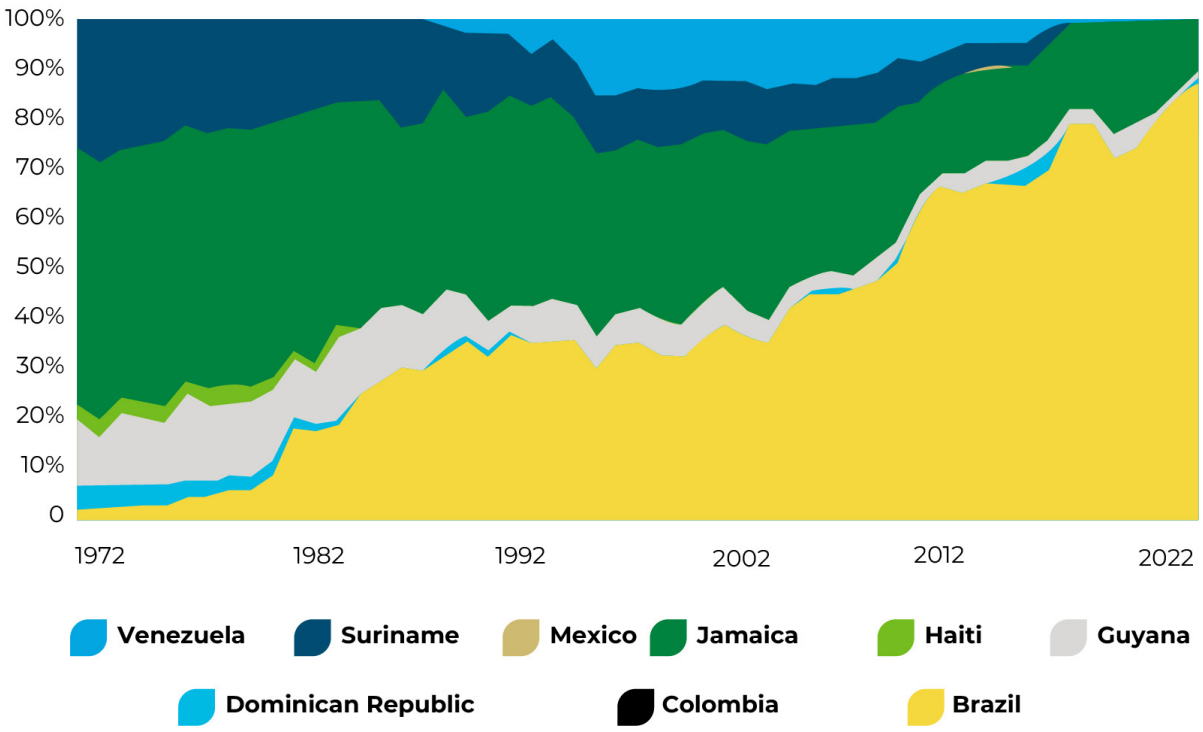
Source: Produced in-house based on BGS data

3.2.1 Production in LAC

Bauxite production in the region began in the Caribbean in Guyana and Suriname in the 1910s. In the 1970s, Jamaica was producing half of the region's bauxite. By the late 1980s, Venezuela was also beginning to produce significant volumes and by the mid-1990s Brazil's production equaled Jamaica's. Brazil became the region's largest producer in 1999. Suriname ceased production in 2015, and Venezuela followed suit a year later. Smaller producers such as Colombia, Mexico, and the Dominican Republic remained in operation but never contributed more than a small percent of the region's total production. In 2022, Brazil accounted for 87% of LAC's bauxite production, Jamaica 11%, and Guyana the remaining 2%.

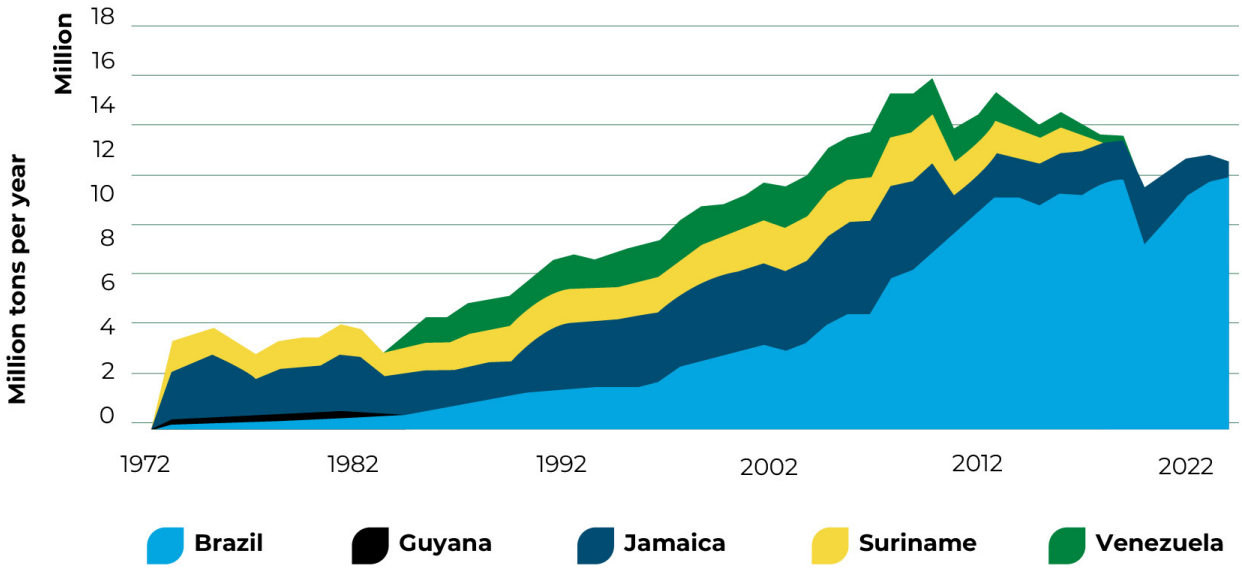
Figure 12. Bauxite Production in the Region, 1970 – 2022

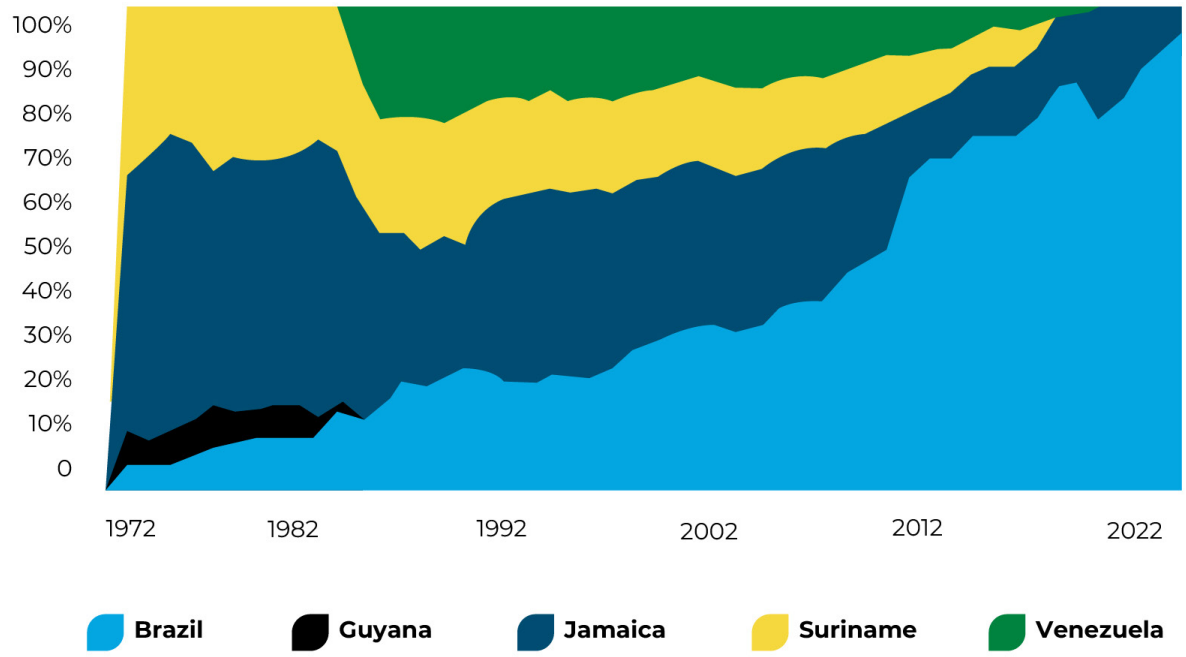




Alumina production in the region has followed a similar trajectory. Jamaica (producing half of the regional total) and Suriname (roughly one-third of the total) dominated in the 1970s with Brazil and Guyana producing the rest. In the 1980s, alumina production was roughly evenly distributed among the four countries (Brazil, Jamaica, Suriname, and Venezuela), while in the 1990s Brazilian production increased, reaching a 50% share of the total in 2008. After the 2009 global financial crisis, alumina production in Jamaica, Suriname, and Venezuela declined, giving Brazil an even greater share of the total. Suriname stopped producing in 2015 and Venezuela stopped in 2017. As of 2022, Brazil produced 95% of the region's alumina with Jamaica producing the rest.

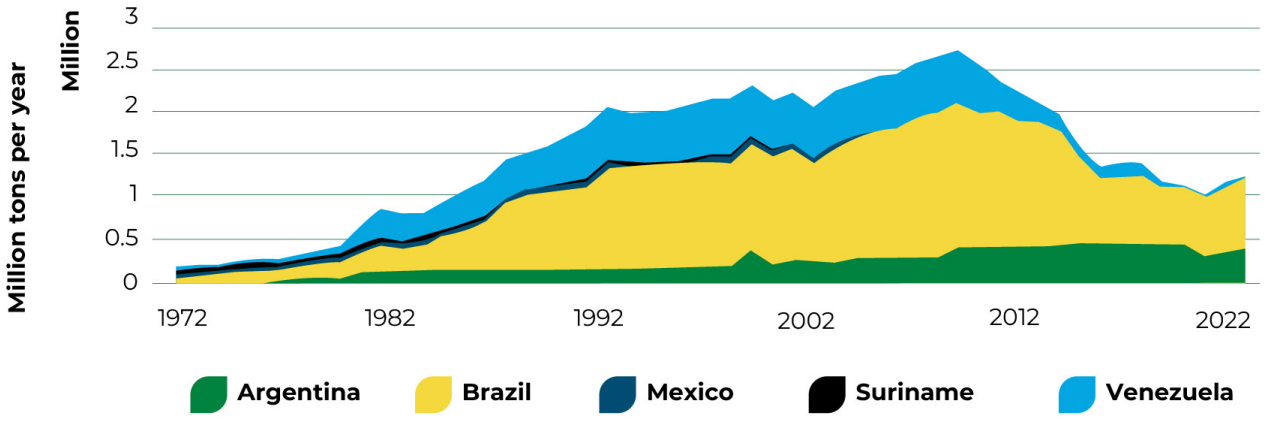
Figure 13. Alumina Production in LAC, 1970 – 2022

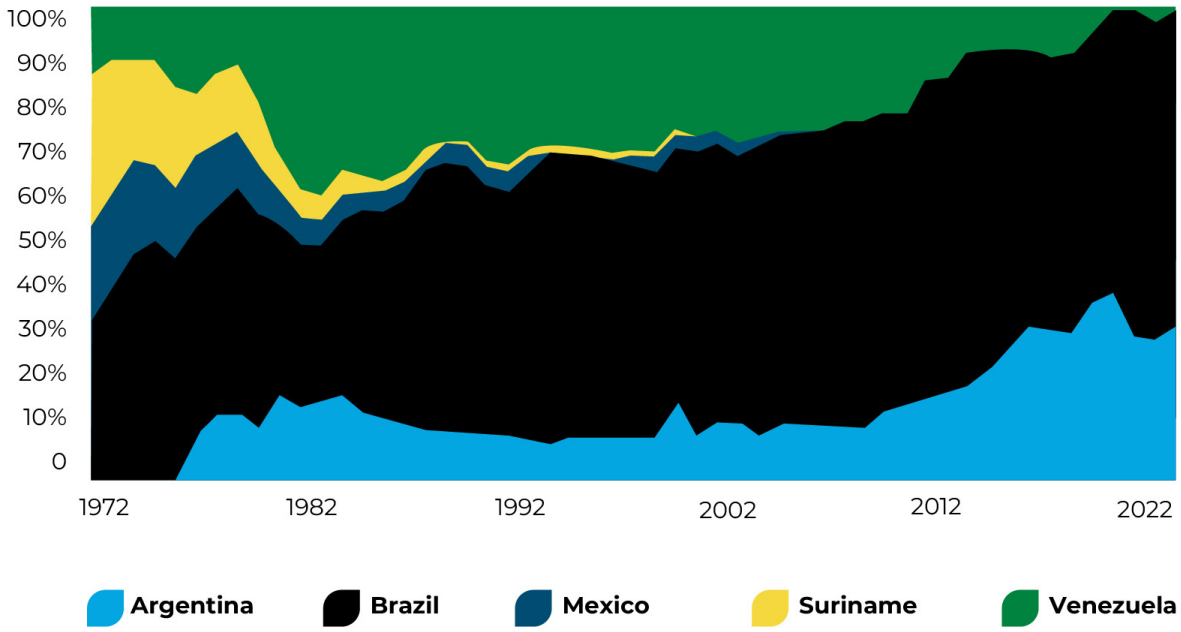




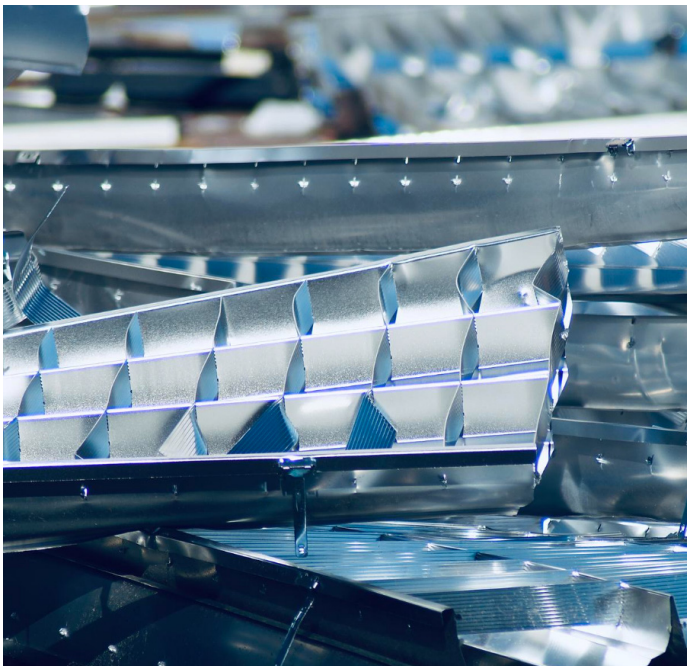
With regard to primary aluminum production, Brazil began in the 1950s, followed by Mexico, Suriname, and Venezuela in the 1960s and Argentina in 1972. From the beginning, Brazil has been the main primary producer, reaching maximum production in 2008. Venezuela comes in second, with production in decline since 2009, and Argentina comes in third.

Figure 14. Primary Aluminum Production in LAC, 1970 – 2022





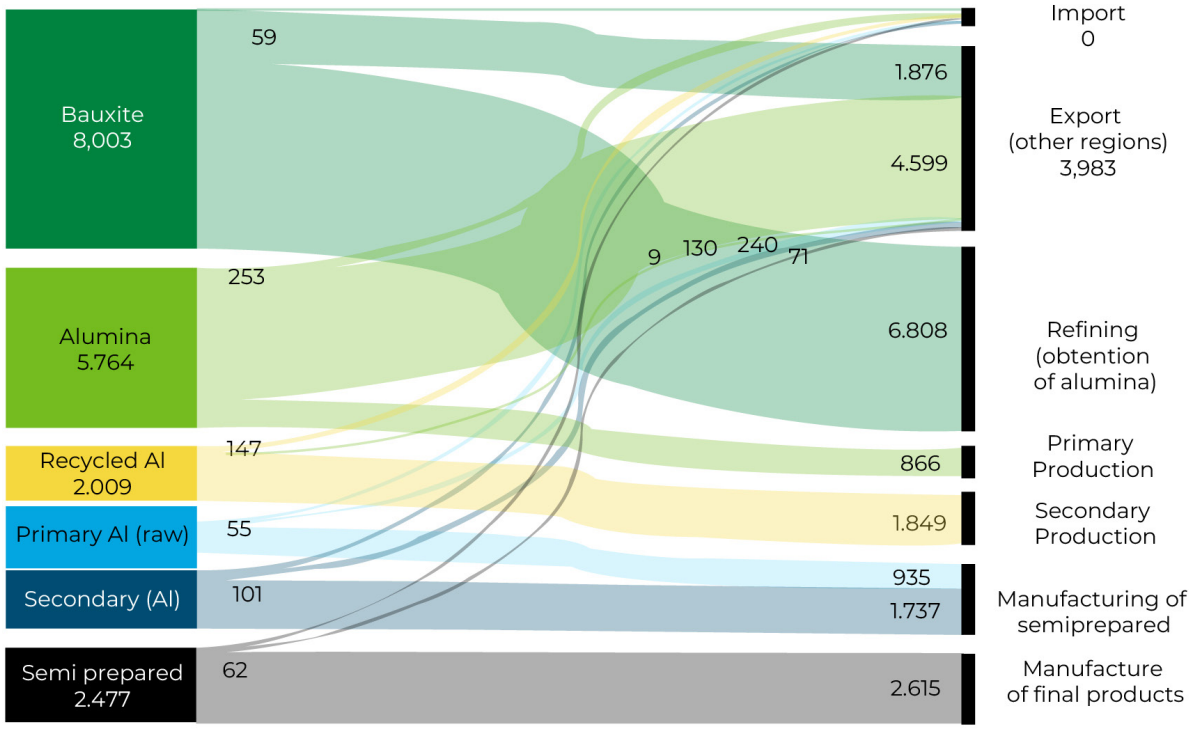
Secondary aluminum production in LAC grew tenfold between 1970 and 2000, increasing from 68 thousand tons to 692 thousand tons. Since 2000, growth has averaged 5% per year, reaching 1.7 million tons in 2019, with total scrap production of 1.75 Mt in 2023. Although recent data indicates a regional recycling rate of 82% of total scrap production, the figure does not include high aluminum content products that are imported to the region. This suggests LAC's true recycling potential could be significantly higher than what the statistics currently show.



3.2.2 Regional Chain Project Flows

In 2023, LAC produced 8,003 kt of bauxite. Of this, 19.7% (1,577 kt) was exported to other regions and the remaining 80.3% (6,426 kt) was refined in LAC. Of the total alumina obtained (5,764 kt), 69.1% was exported to other regions and the remainder used to produce 1,466 kt of primary aluminum. In addition, 2,009 kt of recycled aluminum was converted into 1,878 kt of secondary aluminum. Of the total produced aluminum (3,344 kt), 12.3% (431 kt) was exported to other regions and the surplus went to manufacturing semi-finished aluminum products. Finally, 2,477 kt of semi-finished products (semis) were used in the manufacture of final products and 621 kt were exported.

Figure 15. LAC Aluminum Production Product and Process Flow (kt) (2023)



Source: Produced in-house based on IAI data

3.2.3 Exports and Imports

The regional market for unwrought aluminum in LAC represents a small fraction of total primary aluminum production.[113] During 2022, the region's total unwrought aluminum imports amounted to 368 thousand tons, the main buyers being Brazil (85%), Colombia (6.8%), Costa Rica (2.6%), and Argentina (1.8%).[114]

Table 2. LAC Unwrought Aluminum Importing Countries, 2022

2022 data

Country	Tons	Participation
Brazil	312,880	85%
Colombia	25,012	7%
Costa Rica	9,402	3%
Argentina	6,685	2%
Uruguay	4,674	1%
Other	9,321	3%
Total	367,974	100%

2023 data

Country	Tons	Participation
Brazil	304, 981	88%
Colombia	20,962	6%
Costa Rica	7,248	2%
Uruguay	4,736	1%
El Salvador	3,842	1%
Other	4,038	1%
Total	345,806	100%

Source: Produced in-house based on UN Comtrade statistics

[113] Unwrought aluminum comprises ingots, plates, bars or similar forms from the castings from electrolytic vats or melting of aluminum scrap.
[114] https://comtrade.un.org/data/

Unwrought aluminum exports reached 248 thousand tons in 2022, dominated by Brazil, which accounted for 92% of the total, as shown below. Exports represented 6% of aluminum production, leaving 2.47 Mt for the domestic manufacture of semi-finished and final products.

Table 3. LAC Unwrought Aluminum Exporting Countries, 2022

2022 data

Country	Tons	Participation
Brazil	227,205	91.6%
Argentina	18,824	7.6%
Colombia	1,218	0.5%
Chile	388	0.2%
Ecuador	146	0.1%
Other	271	0.1%
Total	248,052	100%

2023 data

Country	Tons	Participation
Brazil	328,900	99.1%
Colombia	1,898	0.6%
Dominican Rep.	777	0.2%
Bahamas	89	0.03%
Paraguay	85	0.03%
Other	50	0.02%
Total	331,798	100%

Source: Prepared in-house based on UN Comtrade and ABAL statistics

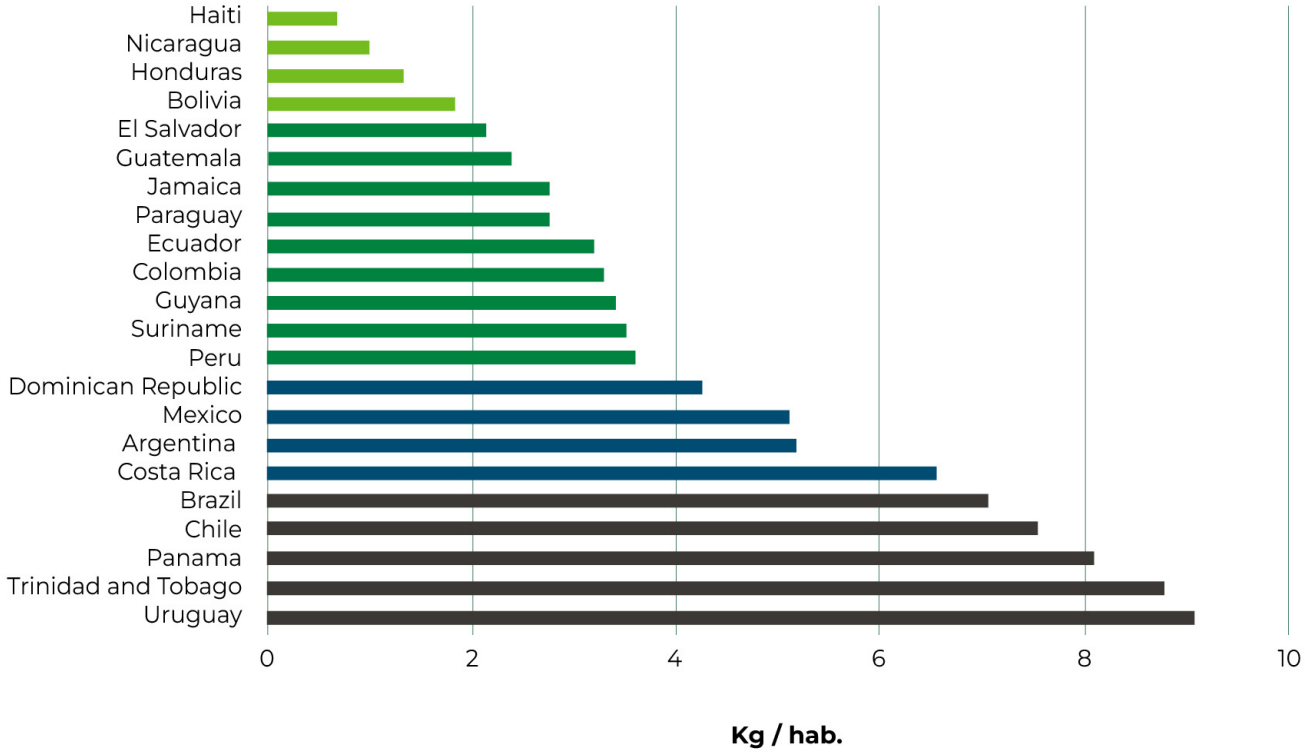
3.2.4 Per Capita Aluminum Consumption in LAC

Per capita consumption in LAC, estimated by balancing production, imports, and exports for the 2015–2019 period, was 4.13 kg/inhabitant/year. This is below the world average of 11 kg per capita and far below the consumption of industrialized countries. Highly industrialized and high-income countries such as South Korea consume 46.7 kg per capita, followed by Germany (29.9 kg), the U.S.A. (18 kg), and Japan (16 kg).[117]

In 2019, Uruguay, Trinidad and Tobago, Panama, and Chile ranked the highest in per capita consumption of more than 6 kg/inhabitant. These are followed by Brazil, Costa Rica, Argentina, Mexico, and Dominican Republic. For the same year, the countries with the lowest consumption (below 2 kg/inhabitant) were Bolivia, Honduras, Nicaragua, and Haiti.

[117] Natural Resources Canada Bureau, 2022. https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/aluminum-facts/20510

Figure 16. Aluminum Consumption per Capita, 2019



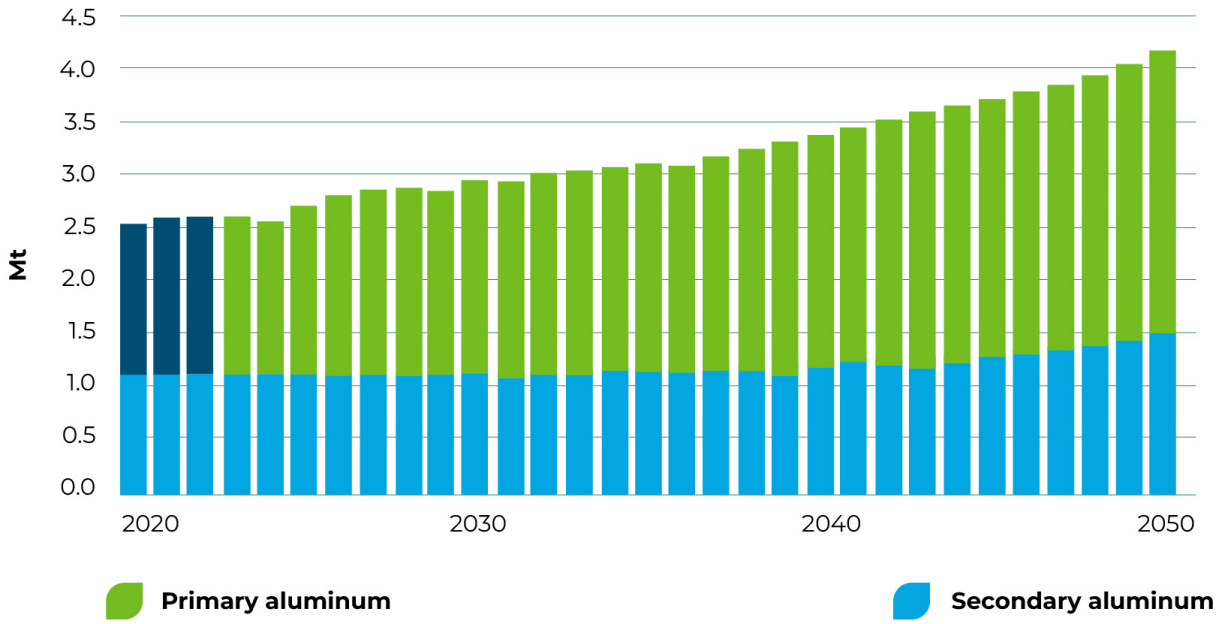
Source: Produced in-house

3.2.5 Projected Demand

Total LAC aluminum production is expected to increase 1.31% annually,[115] with 1% annual growth in primary production and 1.52% annual growth in secondary production.[116]

[115] International Aluminum Institute https://alucycle.international-aluminum.org/public-access/
[116] Assuming a recycling rate of 80% and a process efficiency of 95%.

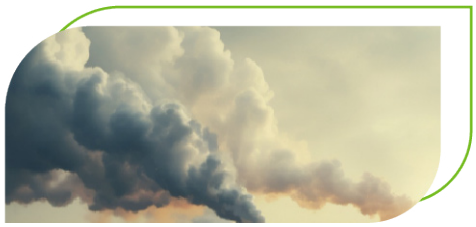
Figure 17. Projected Growth of Aluminum Production in LAC to 2050



Source: Produced in-house based on IAI global projections

4. Environmental Impact of the Aluminum Industry

Aluminum manufacturing may impact air, soil, and water quality. Uncontrolled liquid effluent, solid waste management, and land use change have the greatest potential local impact (BGR, 2020; Katz, 2011; WBG, 1998).



CO_2 is the main GHG emitted in aluminum production. Emissions are primarily generated in the electrolysis process, alumina production, and carbon anode production. Other polluting gases include sulfur dioxide, nitrous oxide, tar vapor, polycyclic aromatic hydrocarbons, carbon tetrafluoride (CF4), and carbon hexafluoride (CF6). Moreover, secondary aluminum production also emits CO_2 and methane, in addition to hydrogen (H2) chloride and fluorinated and chlorinated compounds from scrap smelting.

4.1 Global Environmental Impact

In 2022 the aluminum industry was responsible for GHG emissions of 1,067 $GtCO_2e$.[118] About 98% of its emissions come from primary production processes, including bauxite mining, alumina production, and primary aluminum smelting. Bauxite mining accounts for just 0.3% (2.9 $MtCO_2e$) of the sector's total emissions, followed by supporting activities for the smelting processes with 0.6% (7.0 $MtCO_2e$), carbon anode production with 5.6% (60 $MtCO_2e$), refining to obtain alumina with 17.2% (183 $MtCO_2e$), and electrolysis with 74.1% (789 $MtCO_2e$). Refining and electrolysis together account for 87.4% of total emissions. Primary aluminum production emitted an average of 15.11 tCO_2e/tAl in 2022, including direct (28% or 4.2 tCO_2e/tAl) and indirect (72% or 10.91 tCO_2e/tAl) emissions as shown below.

Table 4. Primary Aluminum Production Direct and Indirect Emissions (tCO2e/tAl) (2022)

2022 update

Direct (Scope 1)	Mining	Anode Production	Refining	Electrolysis (1)	Smelting	Total
Process Emissions		0.1		1.5		1.6
Anodic Effect (PFC)				0.8		0.8
Thermal Energy			1.7		0.1	1.8
Subtotal	**0**	**0.1**	**1.7**	**2.3**	**0.1**	**4.2**

Indirect (Scope 2)	Mining	Anode Production	Refining	Electrolysis	Foundry	Total
Electric Consumption		0.03	0.3	8.9	0.04	9.27
Use of Ancillary Materials		0.6	0.4	0.1		1.1
Fuels	0.04	0.1				0.14
Transportation			0.2	0.2		0.4
Subtotal	**0.04**	**0.73**	**0.9**	**9.2**	**0.04**	**10.91**
Total	**0.04**	**0.83**	**2.6**	**11.5**	**0.14**	**15.11**

Source: Produced in-house based on IAI data

[118] Excludes emissions from the production of semi-finished products and the internal remelting of aluminum scrap. IAI, 2024

Direct GHG emissions from electrolysis are due to oxidation of the carbon anodes during the conversion of aluminum oxide (alumina) into metallic aluminum. GHGs are also emitted in anode manufacturing and thermal energy generation for refining and smelting. Direct GHG emissions also include perfluorocarbons (PFCs), a greenhouse gas generated by the "anode effect" in which fluorides are released. Indirect GHG emissions result from the use of ancillary materials, electricity for electrolysis, and fuels used to mine and transport materials (Hasanbeigi et al., 2022; Marks *et al.*, 2006).

Secondary aluminum production GHG emissions consist mainly of CO_2, from scrap melting and casting, with a smaller amount from scrap processing and transport to the foundry. Total secondary aluminum production GHG emissions are estimated at 0.55 tCO_2e/tAl for the region. The following table shows the energy intensity and emissions for secondary aluminum production.

Table 5. Carbon Footprint of Secondary Aluminum Production

Power Consumption	Energy Intensity (GJ/tAl)	tCO2 (e/tAl)	Emissions Share
Transport	-	0.016	3%
Scrap processing	1.37	0.08	15%
Foundry and casting	7.77	0.45	82%
Total	9.14	0.55	100%

Source: Elaboration based on The Aluminum Association (2022), Baque et al. (2020)

4.2 Latin America Environmental Impact

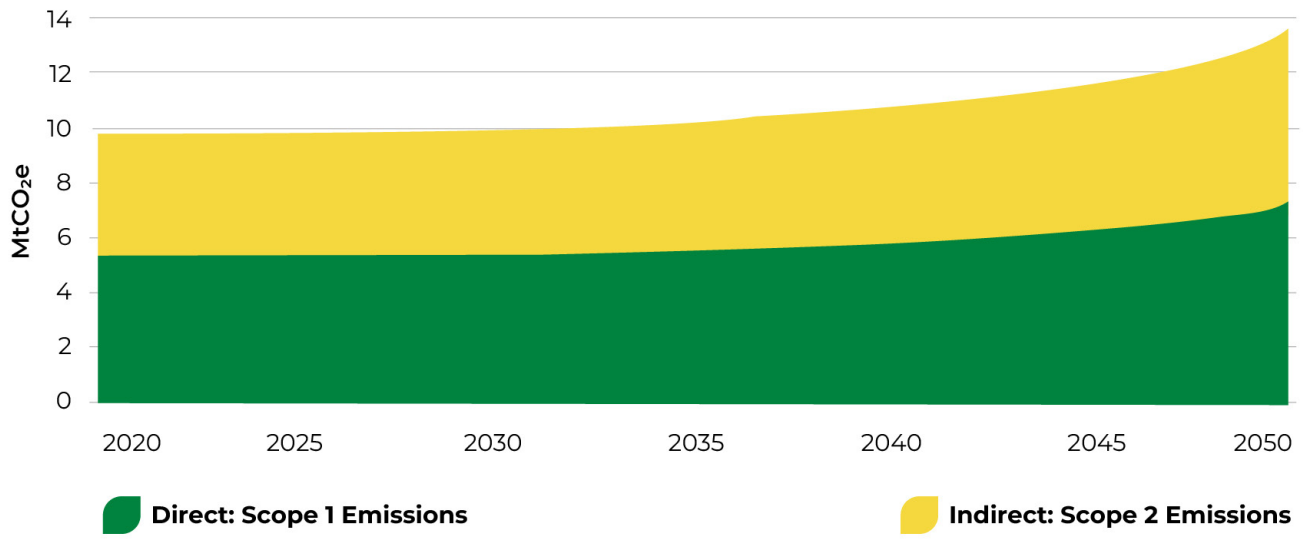
Aluminum manufacturing in LAC affects local air, soil, and water quality in addition to producing GHG emissions. Effluents discharged into groundwater include suspended solids from dust washing and oils and greases from the use of fuels and hydrocarbons. Red sludge from alumina plants is especially notable among solid wastes since 800 kg are produced for every ton of alumina in LAC (IAI, 2022). Reduction plants (electrolysis) in LAC generate about 100 kg of non-recyclable solid waste per ton of molten aluminum, 61% of which is carbon waste, 32% spent oxidation vat linings, 4% sludge, and 3% alumina waste (IAI, 2022).

Bauxite mining and primary aluminum production plants require land use changes and lead to loss of biodiversity. On average, an open pit mine with a production of 2 million tons of bauxite per year and an average deposit thickness of 5 meters would involve a mining area of 20 hectares for ore extraction alone, without taking into account areas for embankments, roads, and temporary stockpiling of rubble (BGR, 2020).

4.2.1 LAC Projected GHG emissions to 2050

Primary aluminum emissions were projected using the expected production by 2050 multiplied by the emission factors for each activity in the chain. Between 2020 and 2050, total GHG emissions increase by 37% from 9.8 million tCO_2e to 13.5 million tCOe2. Of this total, 54% are direct emissions as shown below.

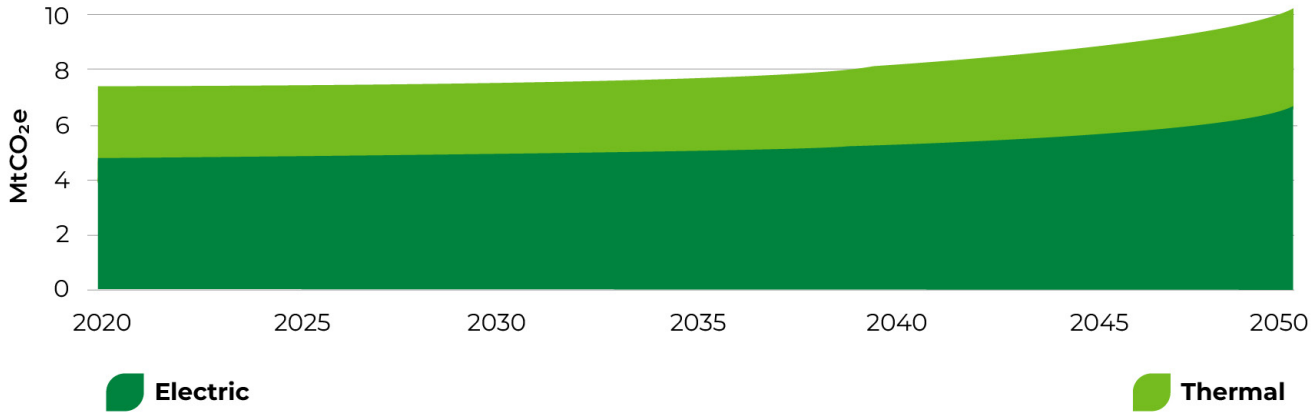
Figure 18. Primary Aluminum Production GHG Emissions in LAC



Source: Produced in-house based on information from IAI

Emissions from energy consumption alone increase from 7 million tCO_2e in 2020 to 9.6 million tCO_2e in 2050. Sixty-five percent are energy-related emissions from electricity consumption, as shown below.

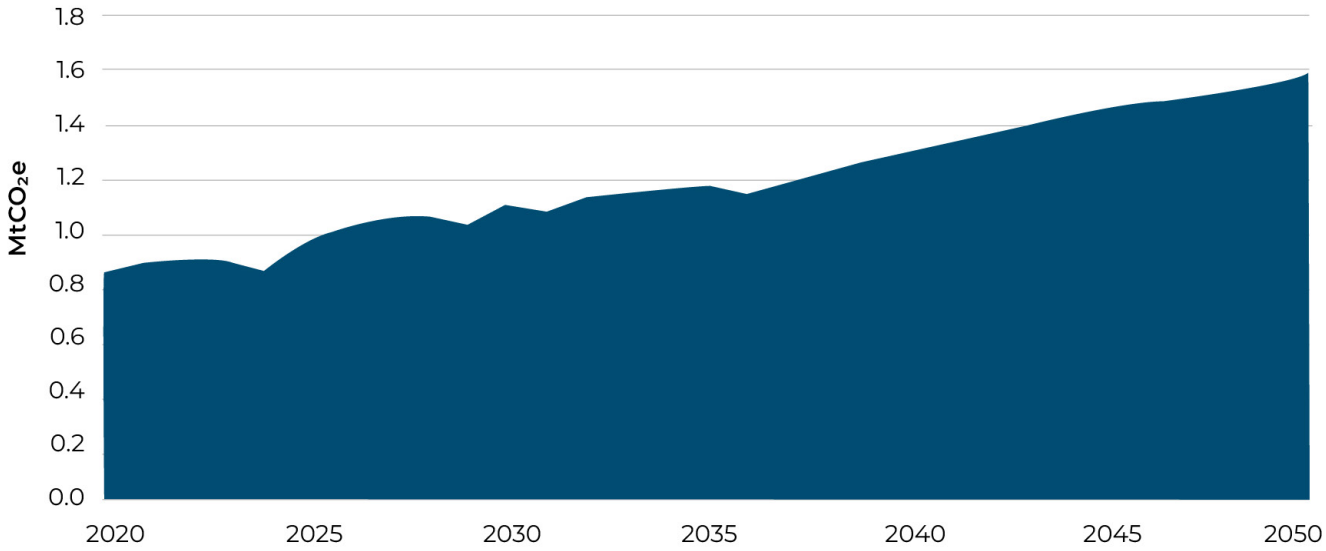
Figure 19. Primary Production Energy Consumption GHG Emissions in LAC



Source: Produced in-house based on IAI data

Emissions associated with secondary production increase by 87% from 0.9 million tCO_2e to 1.6 million tCO_2e, as shown below.

Figure 20. Secondary Aluminum Production GHG Emissions in LAC



Source: Prepared in-house based on IAI data

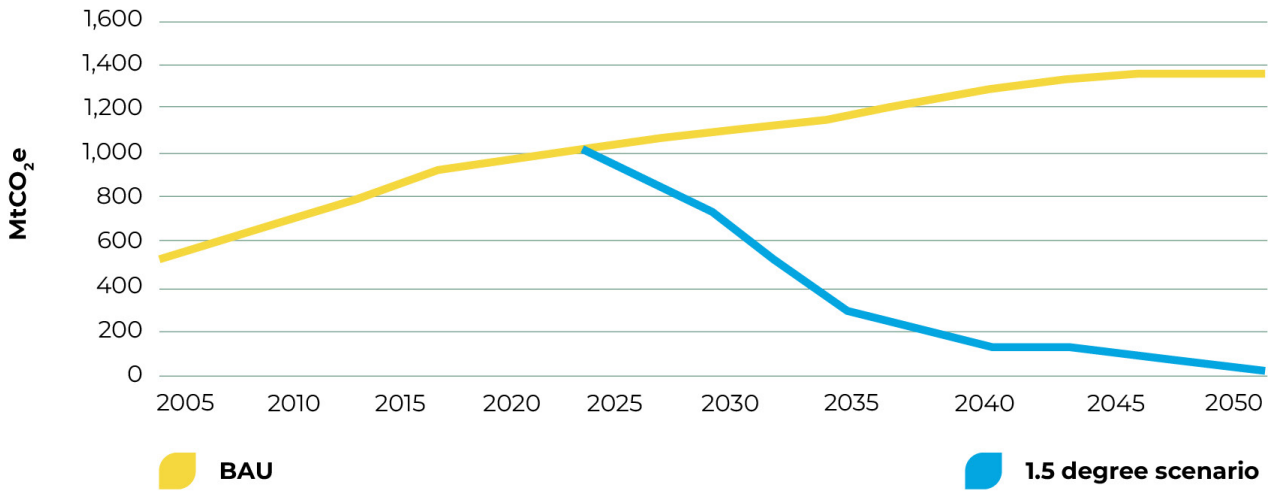
5. Decarbonization in LAC

Achieving carbon neutrality in the aluminum industry is technically possible but will require major changes in energy-intensive technologies and production methods and significant new investment. This section describes the global context for aluminum decarbonization scenarios and potential pathways to decarbonize the industry in LAC.

5.1 Global Decarbonization Scenario

The IAI modeled a 1.5-degree scenario to guide its members' efforts to achieve global climate goals consistent with the Paris Agreement. The model is based on the IEA's "Net-Zero by 2050" scenario combined with IAI's materials flow analysis and future demand scenarios. In this context, GHG emissions from global primary aluminum production will be 35 $MtCO_2e$ by 2050, equivalent to a 97% reduction from 2018, as shown below.

Figure 21. Decarbonization of Global Primary Production (IAI 1.5 °C Scenario)



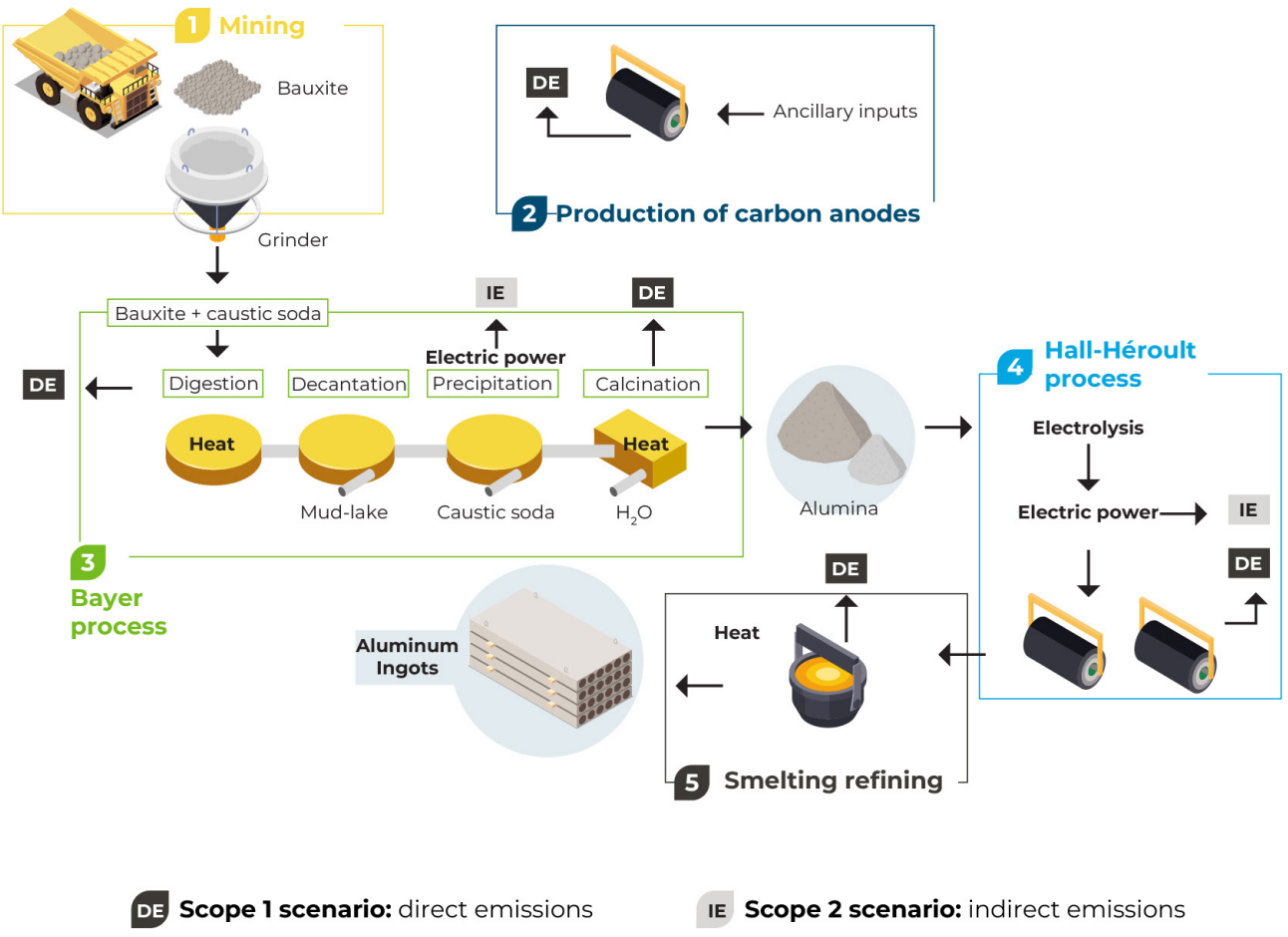
Source: Produced in-house based on IAI data[119]

[119] https://international-aluminum.org/resource/1-5-degrees-scenario-a-model-to-drive-emissions-reduction/

5.2 Industry Decarbonization Routes in LAC

A net-zero emissions by 2050 scenario is proposed for the region with reduction of direct (scope 1) and indirect (scope 2) emissions from aluminum production. The scope 1 scenario requires total reduction of emissions from processes that emit carbon directly, such as carbon anode production, and those that require heat, such as digestion, calcination and smelting. The scope 2 scenario contemplates mitigating total emissions from electricity consumption in the electrolysis and refining process. The processes with scope 1 and scope 2 emissions are shown below.

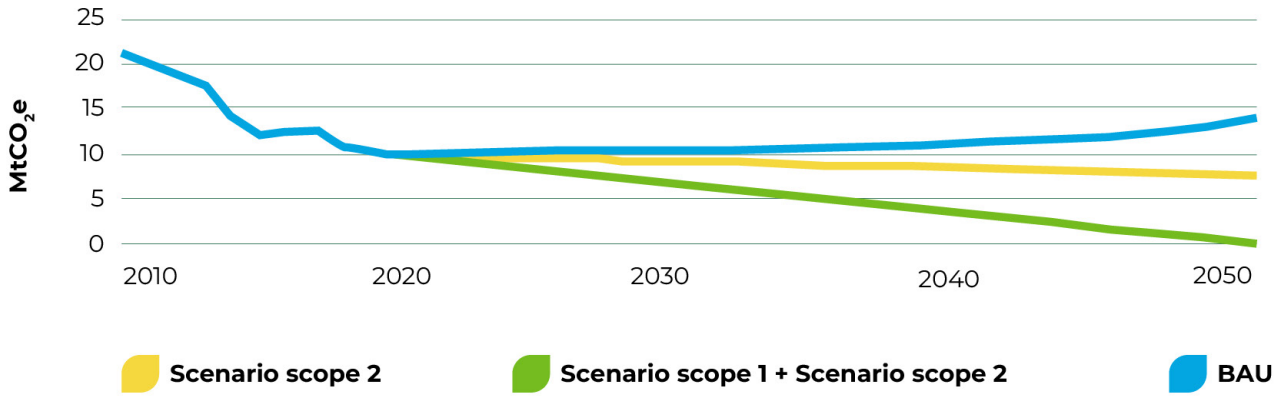
Figure 22. CO2 Emissions by Process



Source: Prepared in-house

The decarbonization scenarios compare a business-as-usual (BAU) scenario plus the two scenarios described above. The aggregate mitigation contribution of Scope 1 and 2 emissions is the reference used in the following sections to evaluate the industry's decarbonization investments. Decarbonization scenarios for the region are shown below.

Figure 23. LAC Primary Aluminum Production Decarbonization Scenarios



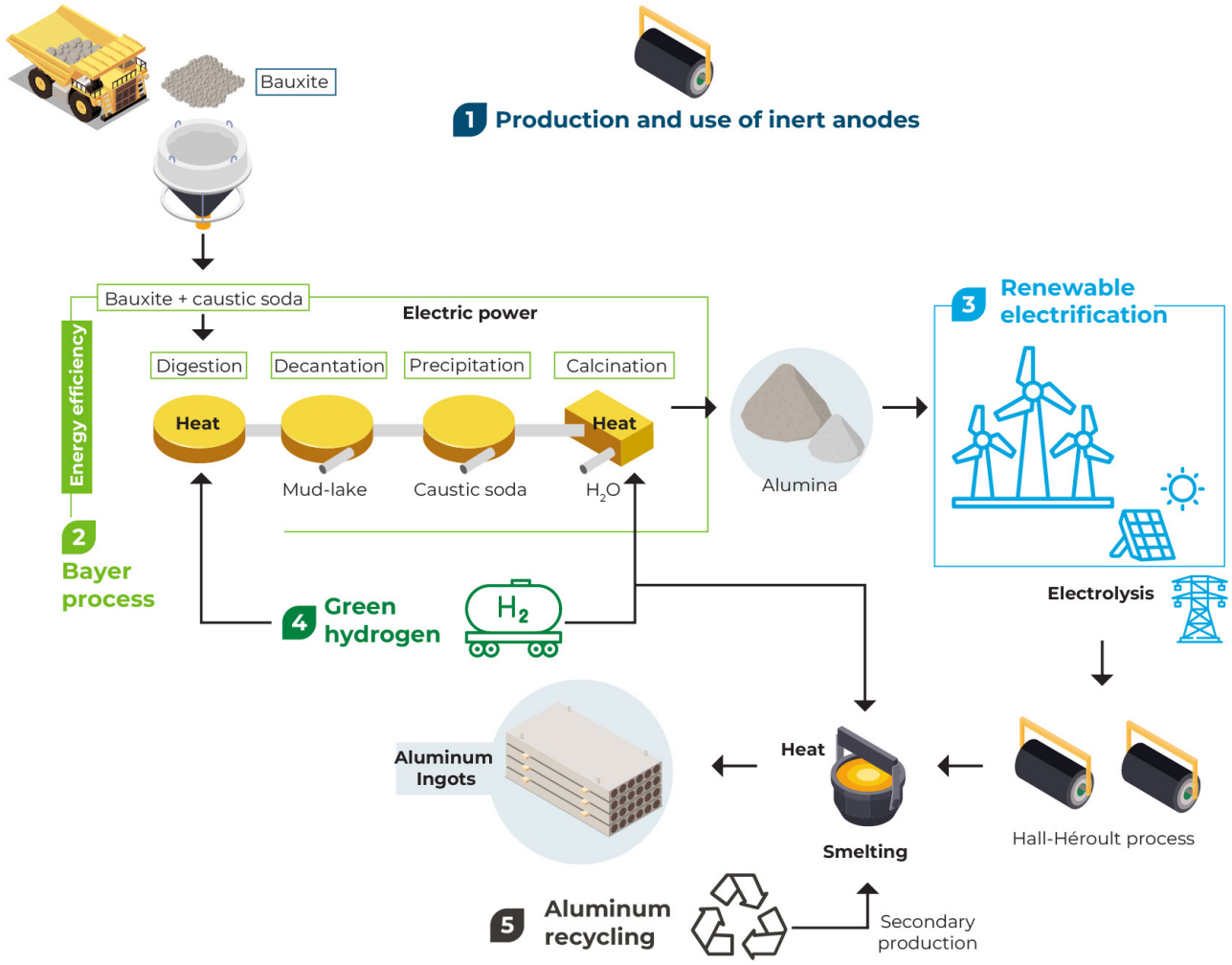
Source: Produced in-house

These scenarios exclude emissions from bauxite ore extraction and processing, use of ancillary materials, and transport of ancillary materials for different processes. As can be seen from the graph, reducing only scope 2 emissions by using only renewable electricity for aluminum production, for example, would have a relatively limited impact on overall emissions. Reducing scope 1 emissions, in particular emissions from carbon anode production and process heat, will require significant investment and innovation.

5.3 Mitigation Trends

The primary aluminum industry decarbonization pathways implement simultaneous measures to reduce both scope 1 and scope 2 emissions. Producing and using inert anodes, achieving energy efficiency, generating electricity from renewable energy sources, generating process heat with renewable hydrogen (H2), and recycling aluminum for secondary production are the measures with the greatest mitigation potential. The figure below illustrates how these measures can be implemented across the different primary aluminum production processes.

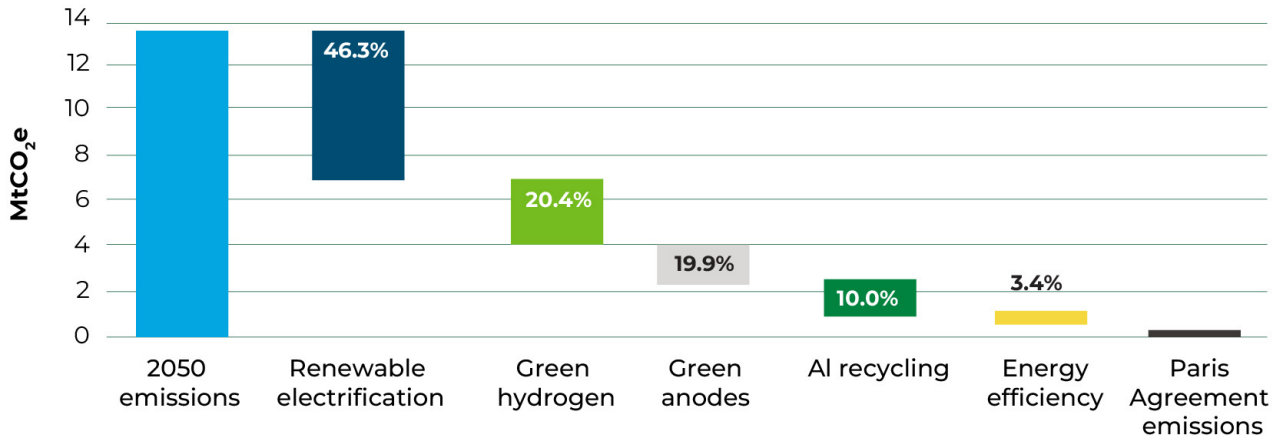
Figure 24. LAC Aluminum Primary Production Decarbonization Measures



Source: Produced in-house

Of these pathways, electrification processes using renewable energy sources would provide the greatest reduction in CO_2e emissions, followed by renewable hydrogen, use of inert anodes, aluminum recycling, and energy efficiency, as shown below. However, each of these potential technologies will require new investment and further development for large-scale deployment and must be validated for use in each individual market.

Figure 25. Aluminum Decarbonization Measures in LAC



Source: Produced in-house

5.3.1 Replacing Carbon Anodes with Inert Anodes

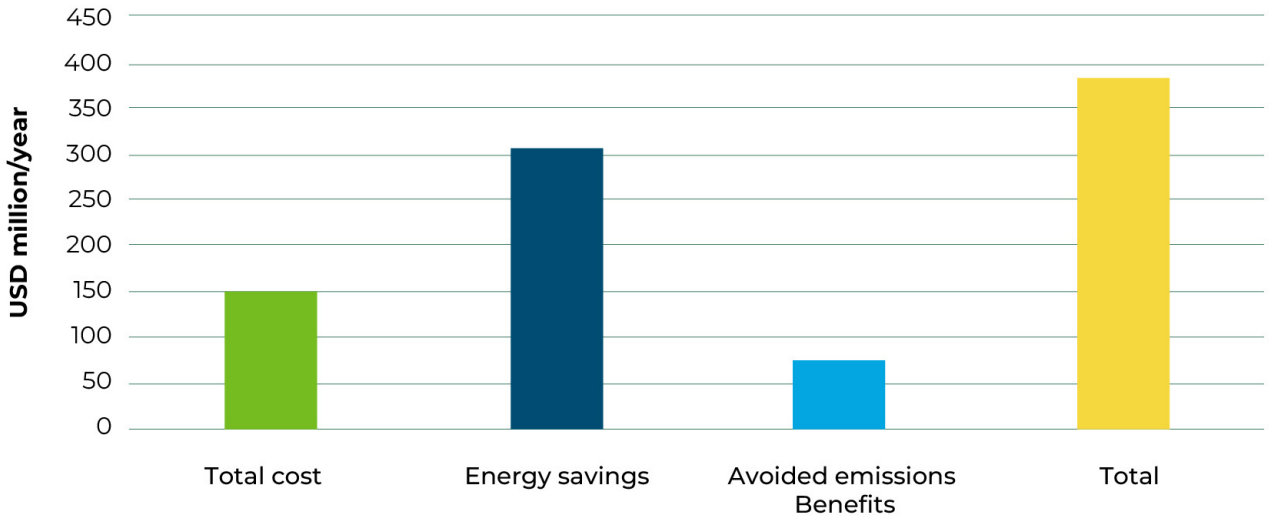
Electrolysis uses carbon anodes that release CO_2 as they degrade (Ros, 2015), resulting in the production of more carbon dioxide than aluminum (about 1.5 tCO_2/tAl) (WEF, 2021). Inert anodes produce oxygen instead of CO_2, eliminating all direct emissions associated with carbon anode consumption (WEF, 2020). In addition, inert anodes could have a lifetime thirty times longer than their carbon equivalents, resulting in lower operating costs and increased productivity. Currently, inert anodes are at a pre-commercial development level with prototypes operating under optimal conditions at a pilot project scale (IEA, 2022).[120] In 2018, Alcoa and Rio Tinto formed Elysis, a joint venture to advance the development of this technology. Elysis began construction of its first commercial-scale prototype cells at a smelter in Quebec, Canada, in June 2021 and aimed to complete the demonstration phase by the end of 2024, but it has missed that target and has not yet begun commercialization.[121] RUSAL's Krasnoyarsk plant in Russia has been producing primary aluminum using inert anode technology on a pilot scale since 2021 and continues working toward full-scale manufacturing.

Inert anodes are not yet commercially available, so the timing of their availability, cost estimates, and retrofitting requirements for existing facilities are difficult to estimate. The technology will most likely be commercialized outside of LAC first and so may require further time and adaptation before it is deployed in the region. Current estimates suggest inert anodes could cost 10% to 30% less to produce than conventional carbon anodes once they are manufactured at commercial volumes (Springer and Hasanbeigi, 2016) and could reduce aluminum smelter operating costs by 15% (IEA, 2022). The cost of upgrading existing electrolysis cells is estimated to average about USD 200 per ton but could be much higher if the smelter requires extensive adaptations during the retrofit.

The present investment value of replacing the anodes is estimated to be USD 1,204 per ton. Purchasing of inert anodes accounts for 83% of this, while modernization of electrolysis cells accounts for the remaining 17%. All told, modernization of the smelting industry for the region requires a capital investment of USD 239 million and annual operating expenses of USD 153 million/year. The benefits, then, add up to USD 384 million/year, giving a positive cost-benefit differential of USD 231 million/year. The figure below shows the annual operating cost and benefits associated with the introduction of inert anodes to the aluminum electrolysis process should they become available on a commercial scale.

[120] According to the IEA, TLR has a scale ranging from 1 (initial idea) to 11 (stable and predictable growth technology).
[121] https://www.elysis.com/

Figure 26. Operating Cost and Annual Benefits of Introducing Inert Anodes



Source: Produced in-house

Furthermore, inert anode use has a levelized cost of USD 15.5/tCO_2e in emission reductions.

5.3.2 Improving Process Energy Efficiency

The aluminum industry has extensive experience investing in new technologies to reduce energy consumption costs. The following are the best-known technologies that can be applied:

- **Tube digestion.** Hatch Associates Ltd. (Hatch) developed a patented tube heating technology for bauxite digestion that increases the process's thermal efficiency (Kelly *et al.*, 2006) and can reduce energy consumption by 15%.[122] The technology is in operation at Aluminum Oxid Stade in Stade-Bützfleth, Germany, and at Zhengzhou Guandong Aluminum Industry Co., Ltd. in China.

- **Calcination in fluidized bed.** Because of their heat recovery efficiency, calciners in circulating fluidized beds (CFB) were introduced as an alternative to rotary furnaces. Replacing rotary furnaces with CFB furnaces would reduce calcination energy demand by up to 40% (Klett *et al.*, 2011).

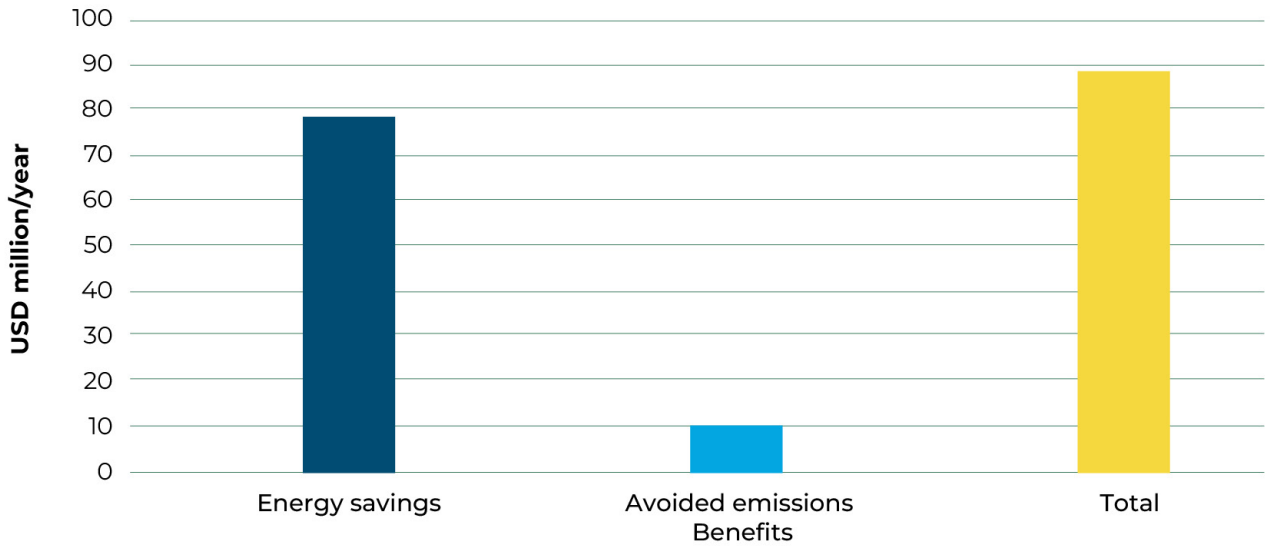
- **Magnetic compensation.** Compensating for magnetic field effects that can destabilize the alumina reduction process can reduce electrolysis electricity demand by 10-15%. This compensation is achieved through improved electrolysis cell design (Zhang *et al.*, 2016). In 2018, the energy and aluminum company Hydro implemented a magnetism control mechanism in the electrolysis cells that stabilized the bath, decreasing energy consumption from 13.8 kWh/tAl to 12.8 kWh/tAl.[123]

Utilizing in-tube digestion and fluidized bed calcination can reduce alumina refining energy consumption. For tube digesters, replacing current digesters would cost an estimated USD 140 per ton of product (ter Weer, 2016). Improving energy efficiency by using fluidized bed calcination is estimated to cost USD 23 per ton of aluminum (Chan *et al.*, 2019).

[122] https://www.hatch.com/Expertise/Services-and-Technologies/Alumina-Tube-Digestion
[123] https://www.hydro.com/es-CL/acerca-de-hydro/es-stories-by-hydro/the-worlds-most-energy-efficient-aluminum-production-technology/

Implementing both technologies involves investments of USD 188/t, equivalent to USD 981 million in capital expenditures (CAPEX C) to incorporate new equipment. A total estimated benefit of USD 88 million/year includes USD 78 million/year in reduced energy costs and USD 10 million/year in avoided CO_2 emissions costs. The measure does not involve additional operating costs, so the cost-benefit differential would be positive (equal to the total benefit). The annual benefits associated with implementation of equipment to improve energy efficiency in the alumina refining process are shown below.

Figure 27. Operating Cost and Annual Benefits of Increasing Energy Efficiency in Refining



Source: Produced in-house

The levelized cost of GHG emissions reduction from improving energy efficiency in the refining process is estimated at USD 13.9/tCO_2e.

5.3.3 Decarbonizing Electricity Generation

Electrolysis requires large amounts of electricity to produce metallic aluminum. By 2050, emissions associated with electricity consumption could be reduced to zero by progressively replacing fossil fuels with electricity produced from renewable energy sources. LAC has an advantage in that most of the electricity production in its energy matrix is from renewable energy. Of the different electricity generation technologies, hydroelectric power, thanks to the base load it supplies to energy systems, allows for better stability and control in the electrolytic bath where aluminum production occurs than intermittent renewable energy sources such as wind and solar.[124]

In 2020, hydropower also had the lowest levelized cost of energy (LCOE) of all generation technologies used in LAC, despite having a higher capital expenditure (CAPEX) than photovoltaic energy and onshore wind energy. The CAPEX and LCOE for the main electricity generation technologies used in the region are shown below.

[124] https://www.hydro.com/es-CL/acerca-de-hydro/es-stories-by-hydro/the-worlds-most-energy-efficient-aluminum-production-technology/

Table 6. CAPEX and LCOE of Electricity Generation Technologies in LAC (2020)

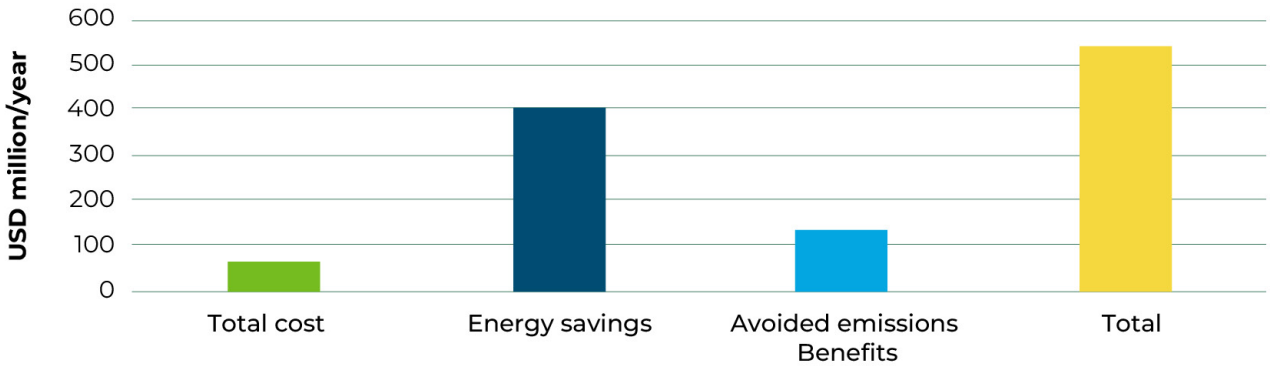
Technology	CAPEX (USD/kW)	LCOE (USD/MWh)
Combined cycle gas	824	67
Solar photovoltaic	1,411	51
Onshore wind	1,662	52
Hydraulic	3,619	48
Coal	3,622	75
Offshore wind	3,746	130
Biomass	4,116	81
Geothermal	4,240	56
Concentrated solar power (CSP)	6,003	129
Nuclear	6,766	82

Source: Produced in-house based on data from Lazard, EIA, IRENA, IEA, NREL (Timilsina, 2020)

The aluminum industry is implementing mechanisms such as PPAs (Power Purchase Agreements), which can cost as little as USD 15/MWh, to promote investment and guarantee clean energy supply.[125] In 2022, the Brazilian aluminum company Albras signed a USD 320 million agreement with Hydro Rein and Atlas Renewable Energy to develop, build, and operate a solar energy project for self-supply in Minas Gerais. Through a PPA, the project will deliver 815 GWh per year to the Albras plant from 2025 to 2044 with an energy cost of USD 20/MWh.

Sourcing electricity exclusively from renewable sources would require an investment of USD 1,383/t in present value terms. This includes USD 524/t in electricity purchase costs (37.9% of the total) and USD 859/t for new renewable electricity generation infrastructure. The total capital required to implement this option is estimated at USD 1,026 million for projects with a life horizon of 25 years. The benefits from the avoided cost of fossil fuels amount to USD 403 million/year, while the annual cost of producing renewable electricity is USD 80 million/year. The avoided cost of indirect CO emissions reduction is USD 128 million/year, which added to the avoided cost of fuel consumption totals USD 530 million/year, giving a positive cost-benefit differential of USD 451 million/year as seen in the figure below.

Figure 28. Operating Cost and Annual Benefits of Electrification with Renewable Energy



Source: Produced in-house

[125] https://about.bnef.com/blog/green-aluminum-is-competitive-today-its-time-to-start-transforming/

Finally, the levelized cost of emissions reduction reaches USD 10.8/tCO_2e. However, if the capital cost of new infrastructure for renewable electricity generation is not considered, this value would be reduced to USD 4.1/tCO_2e.

5.3.4 Decarbonizing Heat Production

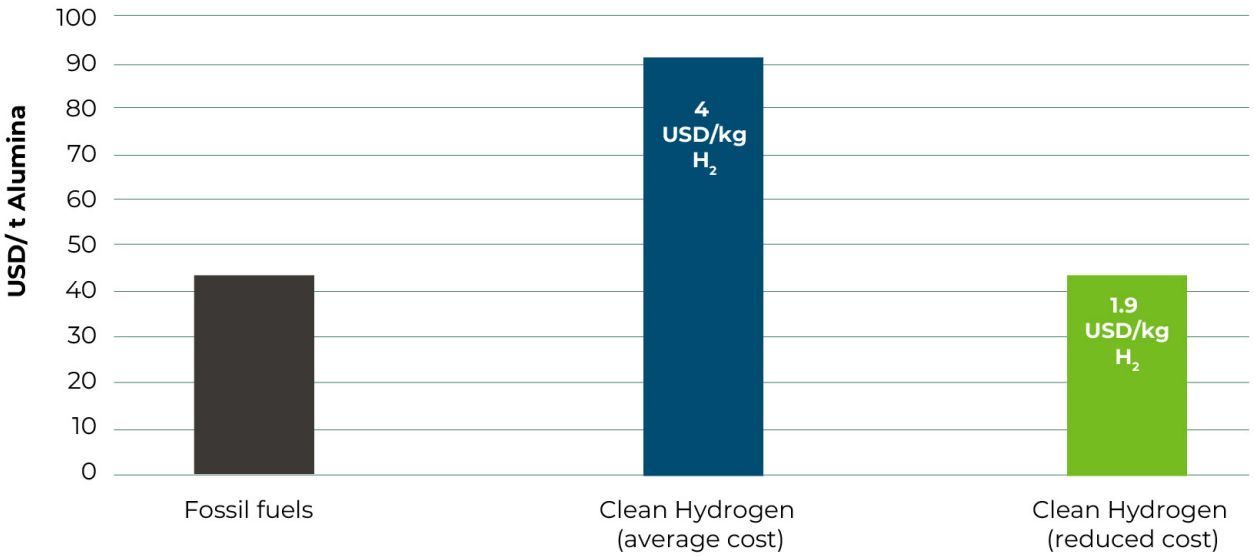
Alumina refining uses fossil fuels for process heat. Three options to reduce emissions from the production of process heat include substituting renewable hydrogen for fossil fuels, utilizing carbon capture and sequestration to prevent generated CO_2 from entering the atmosphere, and using refuse-derived fuels (RDF). Each of these three options is described below.

5.3.4.1 Renewable hydrogen

Renewable hydrogen has the greatest potential to displace direct emissions by serving as an energy carrier for storing and transporting excess renewable energy to industries in remote areas (WEF, 2021). For some stages of the industry, renewable hydrogen development is still at an early prototype level (IEA, 2022). However, successful experiences are driving new studies to scale up implementation. In 2021, for example, the Australian Renewable Energy Agency (ARENA) and Rio Tinto funded a feasibility study to decarbonize alumina refining operations using renewable hydrogen.[126] The research sought to determine the tolerance levels of hydrogen-natural gas blends with up to 100% hydrogen. Unfortunately, estimates indicate that hydrogen cannot directly replace natural gas for industrial heat generation. The biggest obstacle to the growth of renewable hydrogen in LAC is its high production cost.

The scalability of renewable hydrogen is determined by its production cost, which in turn depends mainly on the price of the renewable energy sources used. Currently, hydrogen costs from USD 3/kg to USD 5/kg on average. Using an average cost of USD 4/kg, displacing fossil fuels with renewable hydrogen in aluminum refining would increase aluminum production costs by 113.6%. Renewable hydrogen costs would have to be USD 1.9/kg to match the current cost of fossil fuels, as shown below.

Figure 29. Heat Generation Costs of Fossil Fuels vs. Renewable Hydrogen



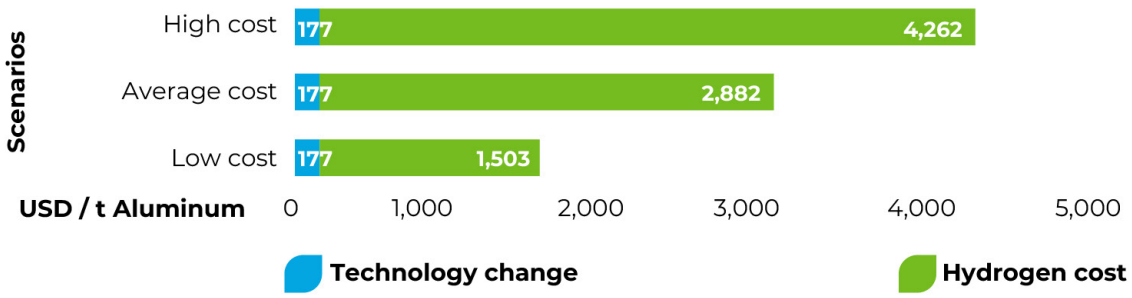
Source: Produced in-house based on energy intensities for alumina production from IAI

[126] https://arena.gov.au/news/renewable-hydrogen-could-reduce-emissions-in-alumina-refining/

The cost of hydrogen production is falling faster than expected and is estimated to fall to USD 1.2-2/kg by 2030 and USD 0.75-1.25/kg by 2050 (Hydrogen Council, 2021). Hydrogen would be a competitive option in LAC if such costs are achieved and sufficient supply is available. Regional studies indicate that Uruguay could be among the first countries to reach a value of USD 1.51/kg by 2030, which could be introduced in regional aluminum value chains. In Colombia for this same year, the expected cost of hydrogen would vary according to the technology used (WEC, 2022); the lowest cost would be for hydrogen produced from wind energy, estimated at USD 2.8/kg and expected to fall to USD 2.2/kg. Three cost scenarios for introducing renewable hydrogen in the alumina refining process were analyzed: low cost (USD 2.8/kg); medium cost (USD 5.4/kg); and high cost (USD 7.9/kg) (WEC, 2022). Considering that the technological development of hydrogen in the aluminum industry is at a trial stage, the following was assumed: i) renewable hydrogen will be produced in sufficient quantities to displace 100% of fossil fuels in alumina production; and ii) the cost involved in adapting existing technology for hydrogen use will be equal to the cost of standard equipment currently used by the industry, about USD 150/t (ter Weer, 2016).

The results indicated that the present value of the investment required to adapt aluminum production facilities to renewable hydrogen use is USD 177/t. With the current "low cost" hydrogen purchase price of USD 1,503/t, the total cost per ton of aluminum would be USD 1,680/t. For the medium and high-cost scenarios, the total cost (technology + hydrogen) would reach USD 3,059/t and USD 4,439/t, respectively, as shown below.

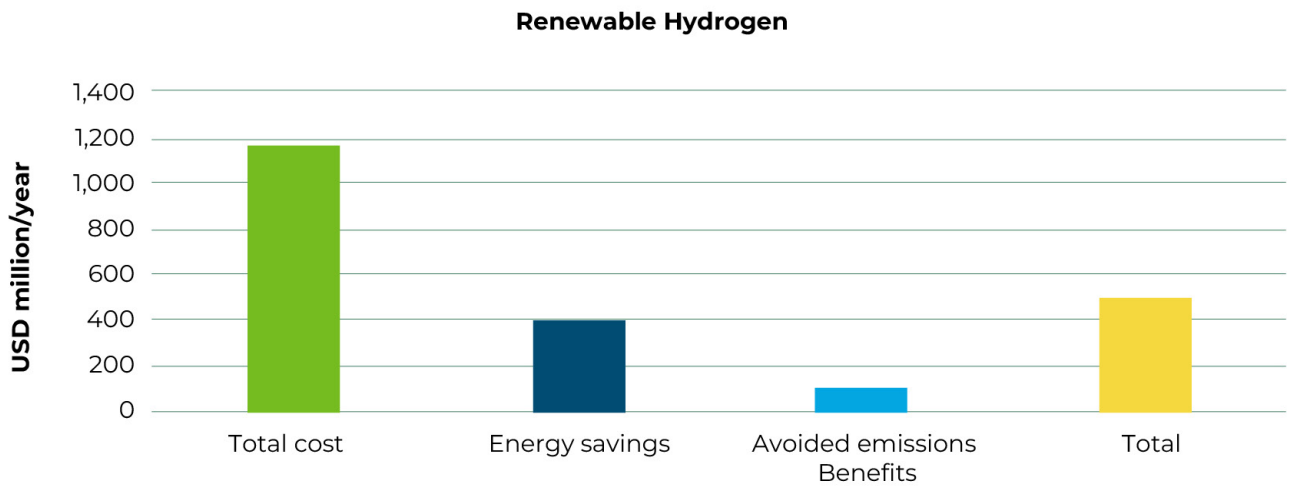
Figure 30. Present Value of Cost to Use Renewable Hydrogen for Aluminum Production



Source: Produced in-house

To implement the low-cost renewable hydrogen path over a 25-year horizon, the LAC aluminum industry would need to deploy USD 1,075 billion in capital for new technologies to adapt current processes and about USD 1,168 billion/year in operating expenses. These costs are in addition to the investment required to produce the renewable hydrogen, which is a component of the assumed future hydrogen price. The expected benefit is estimated at USD 469 million/year, including USD 400 million/year in savings generated by displacing natural gas and USD 21 million/year in avoided CO_2 emissions. This results in a negative cost-benefit differential of USD 699 million/year. In the case of high-cost hydrogen, the annual operating costs would increase to USD 3,237 million, resulting in a negative cost-benefit differential of USD 2,768/year. The figure below shows the costs and benefits for the low-cost scenario.

Figure 31. Annual Operating Costs and Benefits of Using Renewable Hydrogen (Low-Cost Assumptions)



Source: Produced in-house

The levelized cost for CO_2e reduction is USD 114/tCO_2 for the low-cost hydrogen scenario, USD 216/tCO_2 for the medium-cost scenario, and USD 318/tCO_2 for the high-cost scenario.

5.3.4.2 Carbon Capture, Use, and Storage (CCUS)

The technological development for CCUS in the aluminum industry is currently at the concept level (IEA, 2022). In principle, CCUS could be applied to emissions from alumina refining and aluminum smelting, although its application for smelting is questionable as CO2 makes up less than 1% of released gases (IEA, 2022). High-performance CCUS applications are adopted in industries with higher concentrations of CO_2, typically above 4%.

CCUS entails the definition of standards for large-scale CO_2 transport and storage systems (IPCC, 2005). This in turn entails the creation of new regulatory frameworks to ensure operational control and accountability. The Bahraini company Alba and Mitsubishi Heavy Industry have agreed to study CCUS for aluminum smelting. Other initiatives include the Norwegian company Hydro, which has evaluated more than 50 CCUS technologies for the aluminum industry and developed a roadmap for adopting new projects by 2030.[127]

Due to the low technological development of CCUS for the aluminum industry, no economic assessment was made for implementing it in LAC before 2050. CCUS might, however, increase production costs by an estimated 40% (WEF, 2022). Moreover, the pathways of renewable hydrogen and inert anodes in the aluminum electrolysis process are more technically feasible than CCUS in LAC.

5.3.4.3 Refuse-derived Fuels (RDF)

RDF consists of municipal solid waste (such as paper, textiles, pruning wood, rubber, and plastics) and agro-industrial waste (such as sawdust, rice husks, and sugarcane bagasse, among others). It has been used as a fuel in cement and steel industries and could be applied to aluminum (Kopytynski, 2014).

Although the potential and challenges of RDF use in the cement industry are well documented, RDF has not yet been used in the aluminum industry. Further information is needed to determine the technical feasibility of using it in aluminum refining or smelting.

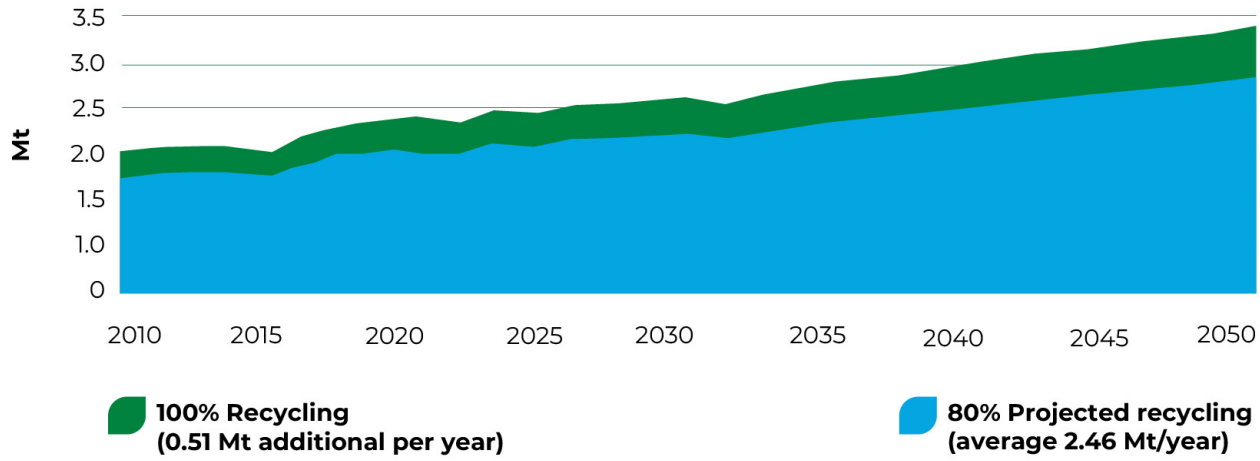
[127] https://www.hydro.com/en/media/on-the-agenda/hydros-roadmap-to-zero-emission-aluminum-production/developing-carbon-capture-and-storage-technology-for-aluminum-smelters/

Given the uncertainty regarding the technical feasibility and minimal contribution to reducing CO_2 emissions, the use of RDF for heat generation was not economically valued. Similar or better emissions reduction results are obtained with the implementation of energy efficiency measures, which have a mature technological development for the industry.

5.3.5 Increasing Aluminum Recycling

Promoting aluminum recovery and recycling would help displace primary aluminum production and reduce GHG emissions. With a recycling rate of 100%, LAC could reduce emissions by up to 19% (assuming a recycling efficiency of 95%). At the maximum recycling rate, the region would displace 510 thousand tons of primary production per year as shown below.

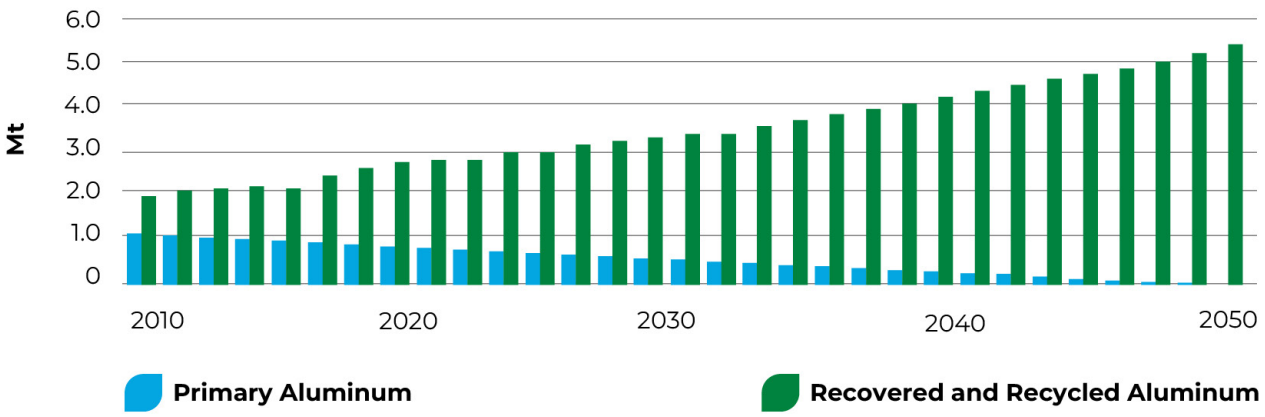
Figure 32. Projected Aluminum Scrap Management



Source: Produced in-house based on IAI data

Greater efforts to recover captive aluminum scrap (that is, aluminum in the owner's custody that is not used and is potentially recoverable) could be the most effective approach to increasing the recycling rate. Reaching a recycling rate of 100% by 2050 means an annual growth of 3.4% in scrap recovery in the region, as shown below. Achieving even close to a 100% recycling rate would require supporting policies and regulations, investment in improved material separation technologies, and financial support to expand the recycling Industry's logistics network and processing capacity.

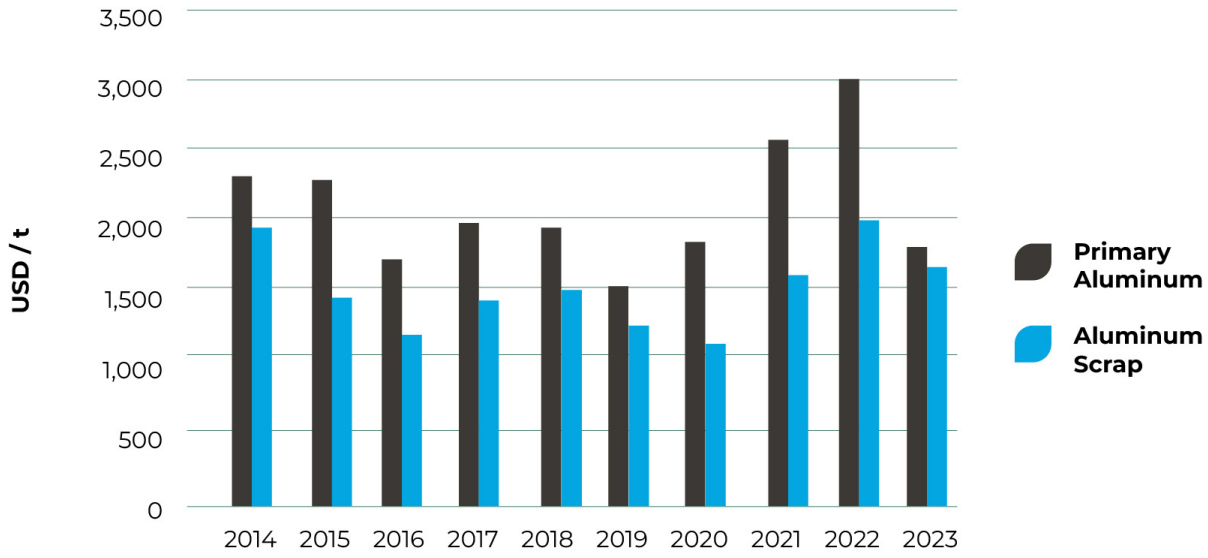
Figure 33. Projected Displacement of Primary Aluminum Production



Source: Produced in-house based on the IAI reference scenario

Industry studies indicate that secondary aluminum production may avoid up to 93% of the energy costs associated with primary production (The Aluminum Association, 2022). Market prices for aluminum scrap suggest that its production cost is 29% lower than primary aluminum. The evolution of aluminum prices in LAC is shown below.

Figure 34. Average Aluminum Prices in LAC (2017-2023)



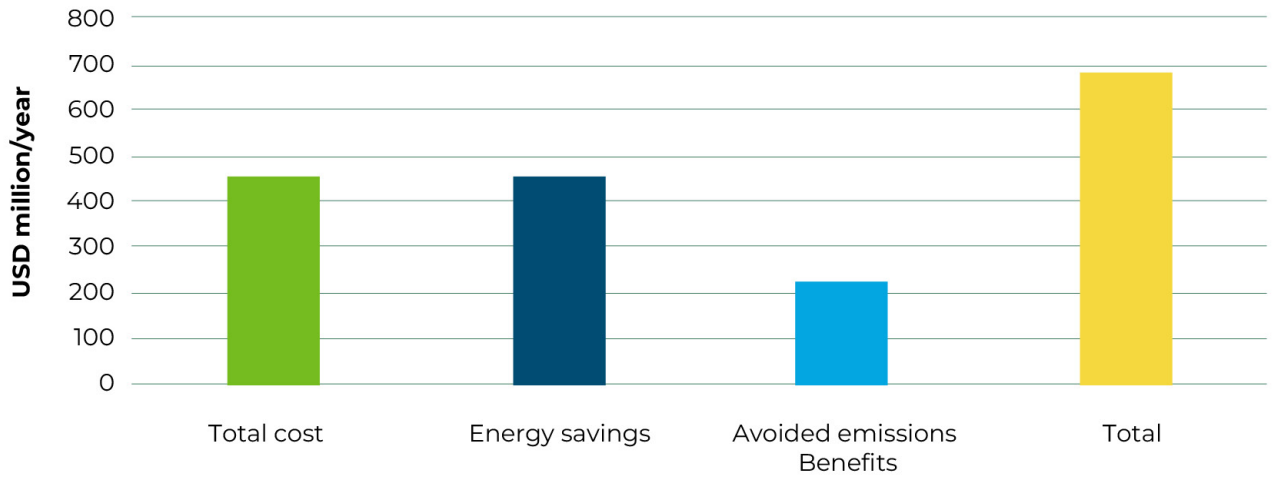
Source: Produced in-house based on data from UN Comtrade

Aluminum recycling would displace primary production, thereby avoiding the alumina refining and aluminum smelting processes, saving up to 93% of the costs associated with energy consumption and proportionately reducing CO_2 emissions. Our economic valuation assumed an average cost of aluminum scrap of USD 725/t and an energy cost of 7% (USD 60/t) of the energy price associated with primary production in LAC (estimated at USD 858/t). Additionally, the capital cost for installation of scrap pretreatment (shredding), scrap pickling (cleaning), and aluminum smelting (furnaces) equipment was valued at 10% of the capital equipment cost required by the primary industry (approximately USD 2,700/t) (IEA, 2012).[128]

Aluminum recycling has a present investment value of USD 1,421/t. Inputs (scrap and energy) represent 94.97% (USD 1,349/t) and capital investment (equipment) accounts for the remaining 5.03% (USD 72/t). The current capital investment amount means that LAC is mobilizing close to USD 196 million in addition to an annual operating cost of USD 459 million. The benefits accumulate to USD 681 million/year, above the annual investment cost, generating a positive cost-benefit differential of USD 222 million/year, as shown in the figure below.

[128] https://www.eia.gov/todayinenergy/detail.php?id=16211#tabs_SpotPriceSlider-2

Figure 35. Operating Cost and Annual Benefits of Aluminum Recycling



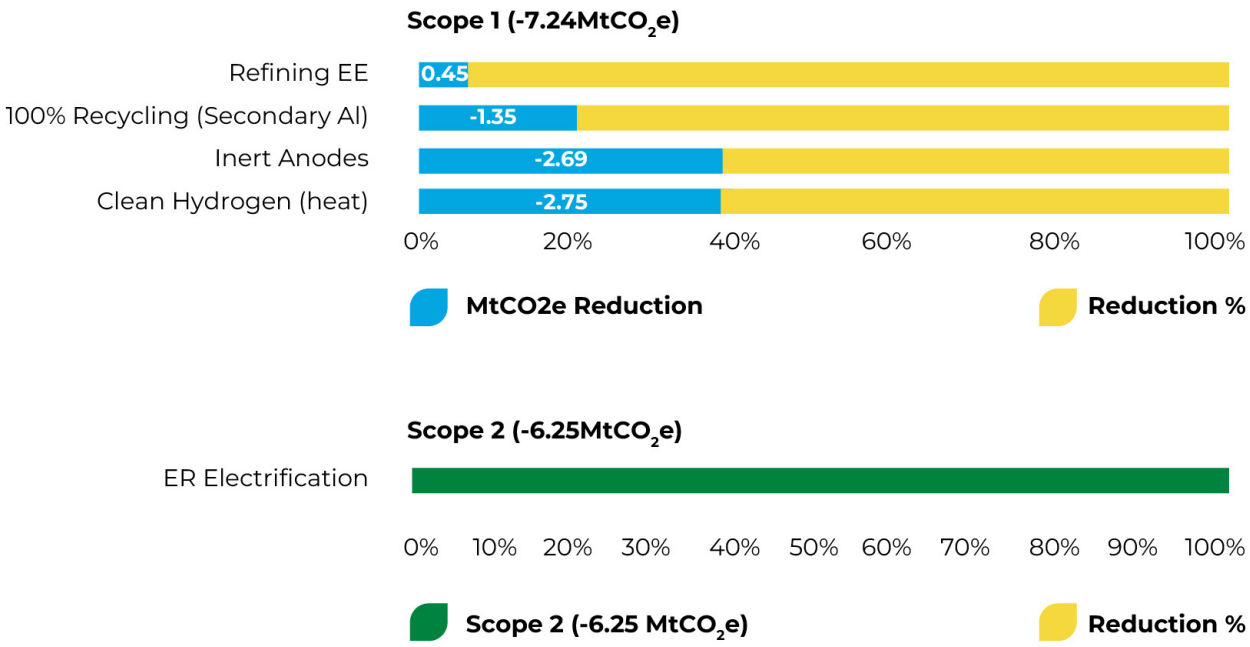
Source: Produced in-house

The levelized cost of emissions reduction for aluminum recycling reaches USD 11.5/tCO_2e.

5.4 CO_2 Reduction Scenario Results

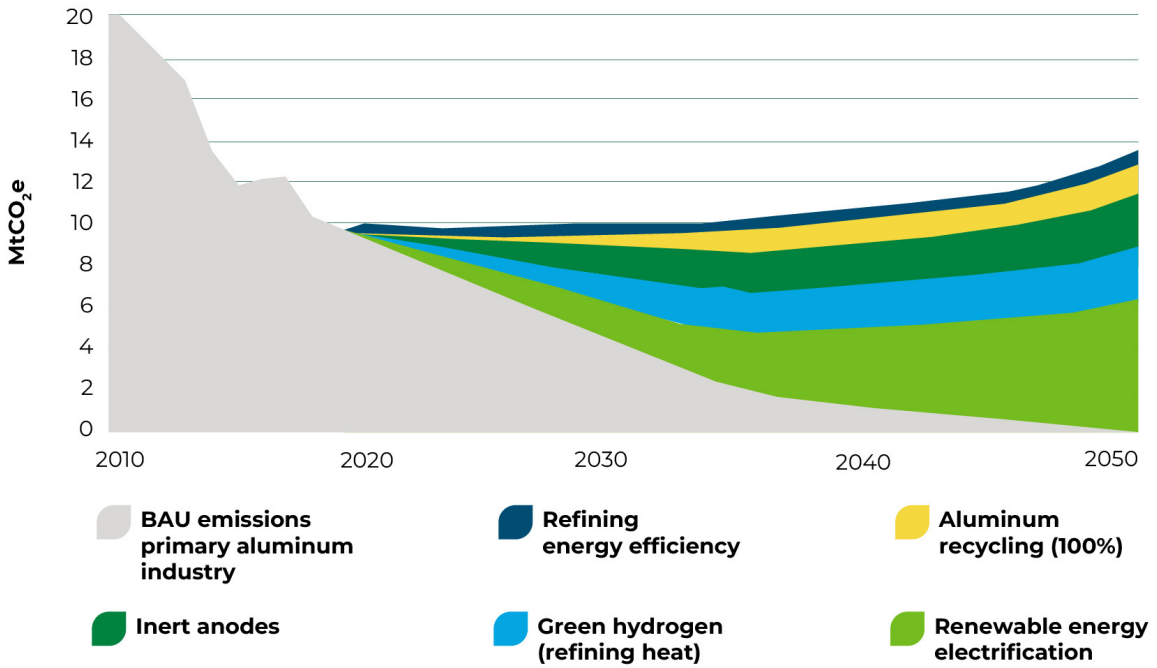
The proposed decarbonization scenarios would reduce industrial emissions by 13.5 MtCO_2e by 2050. In the scope 1 scenario, using renewable hydrogen to generate heat generation for refining would reduce direct emissions by 38%, or 2.75 MtCO_2e, by 2050. This method is followed by those of using inert anodes (2.69 MtCO2e reduction), recycling 100% of aluminum scrap (1.35 MtCO2e reduction), and implementing technologies to improve refining's energy efficiency (0.45 MtCO2e reduction). Scope 1 actions account for 54% of total primary industry emissions reduction in the region, while scope 2 actions account for the remaining 46%. The figure below shows the emissions reduction potential of these actions through 2050 and their share within each scope.

Figure 36. Reduction of Emissions from Primary Aluminum Production in LAC by 2050



Source: Produced in-house

Figure 37. Primary Net Zero-emission Aluminum Production by 2050



Source: Produced in-house

It is important to note that these theoretical scenarios highlight the potential contributions from each technology option. As noted above, implementing renewable hydrogen will require substantial investment in hydrogen production capacity. Moreover, inert anodes are not yet available and the timing of their commercial availability is unknown. Additionally, increasing recycling levels to 100% would also be technically and commercially challenging. For this reason, government policies and financial mechanisms will be instrumental to advancing these technologies. Although these technologies can theoretically reach net-zero by 2050, carbon offsets may be needed to achieve net-zero if the proposed technologies do not mature as expected or cannot be implemented to their full potential.

The table below shows the operating costs and annual benefits for each proposed decarbonization measure. Electrification with renewable energy has the highest operating benefit, followed by the use of inert anodes, increased aluminum recycling, and improved refining efficiency.

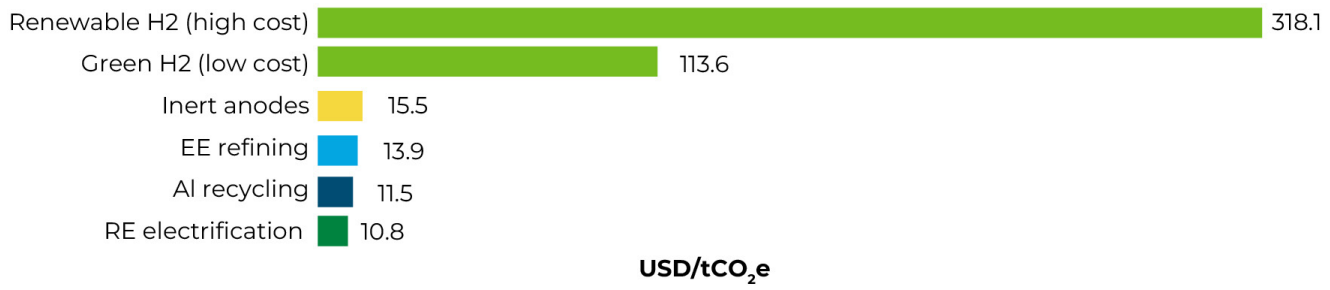
Table 7. Operating Costs and Annual Benefits from Investments

		Benefits (million USD/year)			
Measures	Operating Costs	Energy Savings/ Operation	Avoided CO2 Emissions	Total	Cost/Benefit Difference
Green hydrogen (low cost)	1,168	400	69	469	-699
Green hydrogen (high cost)	3,312	400	69	469	-2,843
Refining energy efficiency	0	78	10	88	88
Inert anodes	153	307	77	384	231
Electrification with renewable energy	80	403	128	530	451
Aluminum recycling	459	458	222	681	222

Source: Produced in-house

With the exception of renewable hydrogen, the measures achieve a levelized cost of GHG emissions reduction of USD 10-16/tCO_2e, with electrification from renewable energies (RE) having the lowest cost, followed in ascending order by aluminum recycling, refining efficiency, and inert anodes. In the low-cost hydrogen scenario, the emissions reduction cost is more than USD 100/tCO_2e, while it exceeds USD 300/tCO_2e in the high-cost scenario.

Figure 38. Levelized Cost of CO2e Reduction by Measure



Source: Produced in-house

Notably, aluminum recycling and electrification with renewable energies (RE) are the only measures that reduce the investment cost of inputs (energy + materials) in the BAU scenario. RE reduces the investment to meet electricity demand by USD 500/t. In contrast, recycling minimizes the investment by USD 812/t for energy consumption, enough to absorb the cost of materials (scrap) and remain below the current investment cost of BAU. The rest of the measures have higher investment costs than the BAU scenario, as shown below.

Table 8. Present Value of Investments (USD/t)

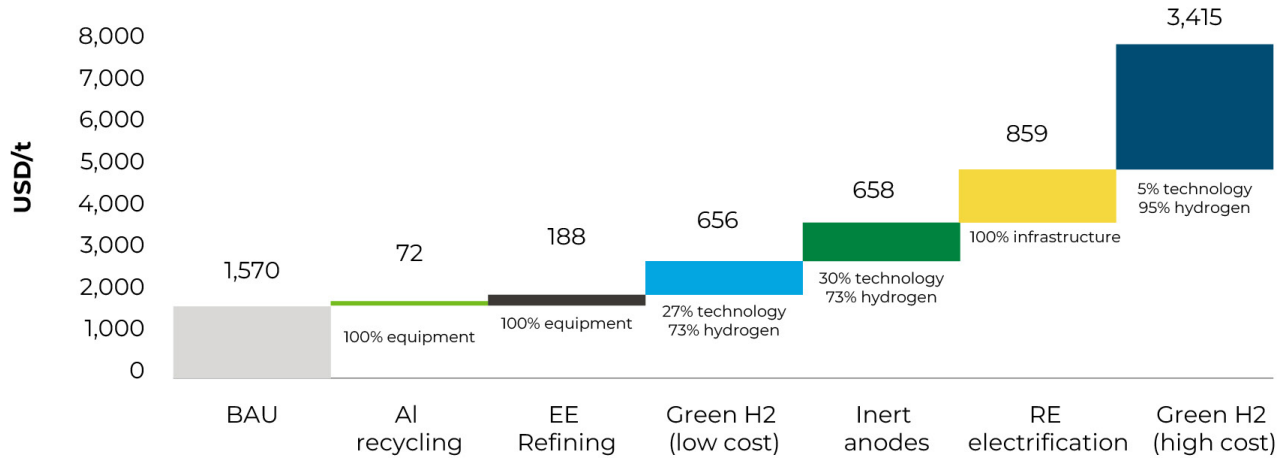
Measures	Inputs		Equipment/ Infrastructure	Total
	Energy	Materials		
Hydrogen (low cost)	1,503	-	177	1,680
Hydrogen (high cost)	4,262	-	177	4,439
Refining energy efficiency	-	-	188	188
Inert anodes	-	1,004	200	1,204
Electrification with renewable energy	524	-	859	1,383
Aluminum recycling	212	1,137	72	1,421
BAU	1,024	546	-	1,570

Source: Produced in-house

Low-cost and high-cost renewable hydrogen investment values differ the most from the BAU scenario mainly due to the hydrogen purchase costs of USD 479/t and USD 3,238/t, respectively. To this value USD 177/t is added for technology upgrading, totaling USD 656/t (low-cost hydrogen) and USD 3,415/t (high-cost hydrogen). The investment in inert anodes generates an incremental value of USD 658/t, some 70% of which is for anode (input) purchase and the remaining 30%

for technological changes. The rest of the measures involve incremental costs associated with new equipment purchases, technology upgrades, or new infrastructure construction (electricity generation from renewable energy). To sum up, an additional investment (compared to BAU) of USD 2,432/t is needed to decarbonize primary aluminum production by 2050 due to low-cost hydrogen purchases. For high-cost hydrogen investments, the investment in decarbonization would increase to USD 6,761/t. The figure below shows the incremental decarbonization costs for each measure.

Figure 39. Cost of Zero-emission Primary Aluminum in LAC by 2050



Source: Produced in-house

6. Aligning Aluminum Industry Investments with the Paris Agreement

Aligning aluminum industry investments with PA mitigation goals requires operations consistent with each country's low-GHG-emission development strategy. One approach to evaluating investment alignment looks at whether investments are "universally aligned" or "universally non-aligned" with PA mitigation goals. For those not falling into either category, a detailed analysis is required to evaluate the project against specific criteria.

This ensures that investments:

i. Do not contradict each country's Nationally Determined Contributions (NDCs), GHG emission reduction plans, or sectoral pathways;

ii. Do not "lock in" GHG emissions levels that are likely incompatible with 2050 net-zero emissions targets by ensuring that all technical and financially feasible alternatives with lower GHGs are evaluated; and

iii. Where appropriate, include strategies to manage climate transition risks that may jeopardize the investment's economic viability and/or result in locked-in or stranded assets.

Paths to decarbonizing the aluminum industry that are universally aligned with the Paris Agreement include: (i) anticipated, planned, and organized replacement of carbon-intensive production processes; (ii) renewable or low-emission electrification to supply the energy demand of the aluminum electrolysis process and use of alternative fuels such as bioenergy and hydrogen for heat generation in refining processes; iii) implementation of efficiency measures to reduce process energy intensity, including the use of more efficient equipment and aluminum recycling; and iv) introduction of new technologies to reduce direct process emissions, such as the use of inert anodes and carbon capture and storage (CCUS) (IDB, 2019; IEA, 2022b).

Investment measures that are considered universally aligned with the PA thus include those where: i) their economic feasibility does not depend on fossil fuel consumption, processing, or transportation; ii) their economic feasibility does not depend on fossil fuel subsidies; and iii) the operation does not significantly depend on the direct use of fossil fuels. The table below shows aluminum industry measures universally aligned with the PA.

Table 9. Measures Applicable to the Aluminum Industry that are Universally Aligned with the PA

Measures	Conditions and Guidelines
Replacing carbon anodes with inert anodes for aluminum smelting (electrolysis)	Inert anodes are universally aligned with the PA. Replacing conventional anodes with inert anodes reduces 100%of the direct CO2 emissions generated by carbon oxidation in the aluminum electrolysis process.
Implementing energy efficiency improvements in tube digesters, fluidized bed calciners, bauxite digestion and alumina calcination	Using higher energy performance technologies reduces the energy intensity of the processes and are therefore universally aligned with the PA. They are mature technologies in the aluminum industry proven to reduce fossil fuel and electricity consumption.
Displacing conventional fuels with green hydrogen to generate heat for refining processes (bauxite digestion and alumina calcination)	Green hydrogen is universally aligned with the PA because it displaces fossil fuel consumption. Producing hydrogen with renewable electricity maximizes emission reductions.
Electrifying refining and electrolysis using renewable electricity	Electrifying energy demand with renewable energy is universally aligned with the PA. Implementing renewable electrification displaces fossil fuel use and related emissions.
Producing renewable electricity for self-consumption	Producing renewable electricity is universally aligned with the PA. Implementing renewable electricity can mitigate 100%of the indirect emissions associated aluminum industry electricity consumption.
Recycling aluminum using zero-emission processes and transportation	Recycled aluminum's carbon footprint is 6% that of primary aluminum. Recycling with electricity from renewable energy and electric transport is universally aligned with the PA.

Source: Produced in-house

According to the IDB Group Sustainable Energy Sector Guidelines (GN-2613-1), the IDB Exclusion List of the Environmental and Social Policy Framework (ESPF)[129], and the IDB Invest Environmental and Social Sustainability Policy (ESSP), investments inconsistent with the PA include activities related to the exploration and production of coal, oil, and gas.

For the aluminum industry this includes consuming energy from fossil fuels and processes that release carbon when treating raw materials. Measures applicable to the aluminum industry that are not considered universally aligned with the PA are shown below.

[129] The Exclusion List contains activities that are incompatible with the IDB Group's commitments to address climate change in coal, oil and gas issues.

Table 10. Measures Applicable to the Aluminum Industry that are Not Aligned with the PA

Measures	Conditions and Guidelines
Infrastructure for carbon cathode production	Using carbon cathodes is not aligned with the PA. Producing carbon anodes (generally done by the aluminum industry itself) is energy intensive. Carbon anodes also produce CO2 as they degrade with use.
Replacing calciners and furnaces with technologies that consume fossil fuels	Modernizing equipment to use fossil fuels more efficiently, while reducing emissions, extends the period of time in which carbon-emitting technologies are used. Therefore, their implementation is not aligned with the PA.
Fossil fuel-based power generation plants	Electricity generation plants based on fossil fuels are not aligned with the PA. Developing this infrastructure supports continued carbon emissions.

Source: Produced in-house

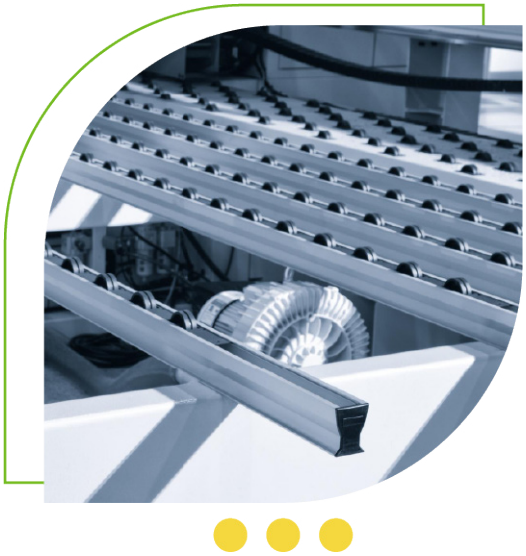
Other investments have the potential to align with the PA. These investments must demonstrate tangible changes and benefits in displacing carbon-intensive production processes in alignment with industry policies and national climate change goals. For the aluminum industry, this implies implementing measures that reduce energy intensity or displace or replace traditional processes. Measures that require validation to be universally aligned with the PA are given below.

Table 11. Aluminum Industry Activities Requiring Validation of Alignment with the PA

Measures	Conditions and Guidelines
Blue hydrogen	Blue hydrogen is extracted from natural gas fields. If it can be produced without also releasing underground CO_2 it would be in line with the PA. Producing blue hydrogen under zero-emission conditions raises costs, and is thus not competitive for industry project developers.
Hybrid generation systems	Installing systems that combine renewable and natural gas-based electricity generation plants can significantly reduce emissions by displacing electricity generation from bunker or diesel.
Improving aluminum recycling processes efficiency	For existing facilities, new investments should integrate PA-aligned measures, such as using renewable electric power and alternative low-emission fuels, to reduce aluminum remelting and casting emissions.

Source: Produced in-house

7. Policy Roadmap for Individual Countries



The aluminum industry is essential to modern economies, driving transport, machinery and equipment, packaging, construction, and consumer goods. Its competitiveness, however, will increasingly depend on its ability to transition toward low-carbon aluminum production. Decarbonization is especially relevant given the high energy intensity of aluminum smelting and high emissions of the whole process. However, large-scale investment, strong policy frameworks, and funding for research and development are needed to enable technological transition.

In this context, this section presents a roadmap, summarized in the table below, that governments can follow to decarbonize the aluminum industry. The policy recommendations are based on technological pathways identified in this chapter for aluminum decarbonization, which include energy efficiency measures, replacing fossil fuels electricity with renewable energy sources, generating process heat with renewable hydrogen, recycling aluminum for secondary production, deploying CCUS in refining and smelting, and producing and using inert anodes.

Table 12. Summary of Aluminum Decarbonization Roadmap for LAC Countries

Period	Goals
2025–2030	Define national aluminum decarbonization strategies to 2050; adapt regulations to enable low-carbon production; identify champion smelters and refineries for early deployment; design and launch demonstration projects in Brazil with CIF and in other producing countries with concessional finance; expand scrap collection and recycling programs; encourage industrial symbiosis initiatives that valorize by-products such as red mud and spent pot lining; begin regional cooperation, and coordinate with the EU on CBAM.
2031–2037	Introduce embodied-carbon standards in public procurement; apply carbon pricing to aluminum production and imports; prioritize industrial decarbonization loads in electricity planning; mandate emissions-intensity disclosure and scrap reporting; expand recycling systems; scale proven solutions; launch demonstrations for inert anodes, hydrogen, and CCS; develop industrial hubs and recycling hubs; expand concessional lending, green bonds, and tax incentives; harmonize certification and recycling rules; build regional scrap markets; and share lessons from demonstration projects.
2038–2045	Mandate emissions-intensity performance standards; set minimum recycled-content rules; begin retrofitting smelters for inert-anode readiness; scale CCS and inert-anode technology; support workers and communities with transition packages; expand industrial symbiosis and next-generation pilots; shift to blended/private finance; and deepen regional cooperation on recycling, hydrogen, and CO_2 logistics.
2046–2050	Tighten performance standards to near-zero; mandate high recycled-content thresholds and full recovery of packaging, vehicles, and construction scrap; deploy large-scale inert-anode smelting powered by renewables; focus finance on O&M optimization, reinvestment, and competitive renewable electricity pricing; and position LAC as a global hub for sustainable aluminum.

7.1 Vision and Baseline

Aluminum production in Latin America varies widely in plant age, energy supply, integration with bauxite mining and alumina refining, and market orientation. For governments seeking to draft effective aluminum decarbonization strategies, the first step is to establish their national position within the global and regional aluminum value chain—whether as bauxite producers, alumina refiners, aluminum smelters, importers, exporters, recyclers, or end-use consumers—and to articulate the role they aspire to play in a low-carbon aluminum value chain. This includes identifying the relevant stakeholders that can be affected by the policies implemented by the government.

Producing countries must carry out detailed mapping of existing production pathways, including bauxite mining, refining, and smelting, and assess the GHG emissions to establish a baseline and evaluate the resilience of their operations and supply chains. Exporting countries must analyze the evolving requirements of importing countries and the implications of carbon border adjustment mechanisms such as the one adopted by the EU.

Non-producing countries, meanwhile, should focus on their role as importers, consumers, recyclers, and traders within the aluminum value chain. Even if a country doesn't mine bauxite, refine alumina, or operate smelters, it will import and use aluminum in transport, construction, and packaging. To meet their decarbonization plans, non-producing countries should consider the carbon footprint of imported aluminum. Additionally, they can also increase their recycling and scrap recovery, either for export or for secondary aluminum plants, which are much cheaper to build.

This baseline analysis will enable governments to design tailored, pragmatic roadmaps that align industrial, energy, and trade policies to reduce GHG emissions and safeguard competitiveness and long-term industrial resilience.

7.2 2025–2030: Foundations and Early Demonstration Projects

7.2.1 Policies and Regulations

During this first phase, governments should design national aluminum decarbonization strategies to 2050 that establish their long-term emissions reductions goals. These can also reflect their natural resource availability, role in the low-carbon aluminum value chain, energy systems, industrial and labor structures, and financial capacity. They should include modeled scenarios of technology adoption, an emissions abatement curve to prioritize actions by cost-effectiveness, and an assessment of funding gaps. Policy cost curves can help identify the most appropriate measures, while just transition plans should address environmental and social considerations.

Countries should also conduct a comprehensive review of existing frameworks to ensure they enable the deployment of early decarbonization pathways, including standards for safe reuse and management of red mud and spent pot lining, adapting strategic minerals regulations to check the role of bauxite and aluminum, or establishing rules for CCUS. Governments can also establish and actively promote industrial regulatory sandboxes for innovative technologies and business models in controlled conditions.

National recycling programs and targets should be introduced to stimulate demand and improve circularity. Government policy can advance aluminum circularity by mandating recycling in short-lifecycle applications such as packaging, while promoting education, awareness, and investment in recovery and processing infrastructure to enable circular practices in long-lifecycle sectors such as construction.

7.2.2 Projects, Technologies and Infrastructure

Demonstration projects should be designed and launched in this period. Each country should identify champion companies, meaning large domestic or multinational smelters and refineries with the willingness and resources to advance decarbonization early and implement demonstration projects, such as deploying inert anodes or improving aluminum recycling process efficiency, among others. Successful demonstration projects will be critical to validating new technologies in the LAC context.

Governments should promote early adoption of no-regrets measures such as energy efficiency measures (tube digestion, fluidized bed calcination, and magnetic compensation), optimization of refining and smelting processes, and renewable and hybrid generation systems for electricity-intensive operations, such as partial substitution of fossil fuels in refining or integration of renewable-based PPAs into smelting operations. Pre-development studies for renewable grid expansion, CO_2 storage capacity, recycling hubs and advanced sorting and shredding facilities, and inert anode demonstration plants should be initiated to prepare the ground for scaling in later phases.

7.2.3 Funding and Incentives

On the financing side, Brazil is positioned to lead with the support of the CIF Industry Decarbonization Investment Program. Other producing countries, such as Argentina, can access concessional loans, blended finance structures, and guarantees to advance their own demonstration projects. MDBs can design country-specific instruments to de-risk investment such as guarantees, low-interest loans, and results-based grants tied to verified emission reductions.

Scrap recycling programs can be incentivized in both producing and non-producing countries to strengthen national and regional supply chains and reduce reliance on imported scrap. National scrap collection and recycling programs should align with ISO 59000 circularity standards, while circularity can be encouraged by industrial symbiosis initiatives that valorize by-products such as red mud and spent pot lining for cement production. Creating market incentives for recycled content in construction, packaging, and infrastructure projects will further stimulate demand for circular aluminum.

7.2.4 Capacity Building and Regional Cooperation

MDBs can facilitate knowledge exchange and support the development of regional standards and certification schemes, as well as early coordination with the EU on CBAM. Countries should harmonize definitions of recycling and waste management, create common measurement tools, and enable cross-border trade in scrap. Capacity building should also include training in circular economy and aluminum recycling, inert anode technologies, CCUS, certification processes, and monitoring, reporting and verification processes.

7.3 2031–2037: Scaling and Infrastructure

7.3.1 Policies and Regulations

In this phase, governments should introduce embodied-carbon standards in public procurement to create stable demand for low-carbon aluminum. In parallel, carbon pricing mechanisms, such as carbon taxes or cap-and-trade programs, should be applied to the aluminum industry and imports.

Electricity planning should prioritize industrial decarbonization loads, provided these do not compete with residential needs. Establishing permitting frameworks for CO_2 transport and storage infrastructure should be planned.

Regulations can mandate emissions-intensity disclosure from both domestic producers and importers. Reporting of scrap generation and recovery rates from industries can also be introduced.

Finally, governments can expand advanced scrap recycling systems by mandating separate collection, extended producer responsibility, and clear labeling to ensure high recovery rates. They can also introduce minimum percentages of recycled aluminum in new packaging and vehicles.

7.3.2 Projects, Technologies and Infrastructure

During this phase, scaling proven solutions should be prioritized while continuing demonstrative projects in new technologies. Large-scale demonstration projects should be launched in regions with abundant renewable resources. Producing countries should continue energy efficiency measures and prioritize decarbonization of heat production and the introduction of co-generation systems that reuse process heat for electricity generation. Inert-anode, renewable hydrogen, use of refuse-derived fuels, and CCUS demonstration projects should be deployed, with shared CO_2 hubs beginning development near plants with suitable geological conditions. Governments should promote the development of recycling hubs equipped with advanced sorting and shredding facilities, leveraging public–private partnerships to mobilize investment.

7.3.3 Funding and Incentives

Governments and MDBs should broaden concessional lending, expand green bond frameworks, and co-finance renewable energy, transmission, low-carbon industrial hubs in strategic regions, and recycling hubs. They can also provide grants or tax incentives for companies adopting secondary aluminum processing technologies and new technologies. Instruments such as contracts for difference (CfDs) can de-risk high-cost projects such as inert anode deployment and CCUS, provided they are fiscally sustainable and time-bound. Public–private partnerships for industrial infrastructure such as renewable-powered smelting clusters and CO_2 networks should also be promoted.

7.3.4 Capacity Building and Regional Cooperation

Countries should harmonize certification schemes, monitoring standards, and recycling and waste reuse and management rules to enable regional integration. Cooperation should focus on creating regional scrap markets, coordinating logistics for hydrogen and CO_2, and sharing lessons from early demonstration projects. Capacity building for recycling operations and new technologies is also encouraged.

7.4 2038–2045: Transformation and Deployment

7.4.1 Policies and Regulations

By the late 2030s, governments should mandate emissions-intensity performance standards for aluminum, introduce minimum recycled-content requirements in key end uses such as construction, packaging, and transport, and align trade policies with global low-carbon standards. Non-producing countries should strengthen their role as enablers by scaling procurement of low-carbon aluminum for infrastructure and facilitating regional logistics for scrap.

7.4.2 Projects, Technologies and Infrastructure

By this phase, producing countries must move to the deployment of transformative technologies, such as renewable hydrogen and proven inert-anode technologies. CCUS should be scaled in regions where renewables and hydrogen are not widely available. Industrial symbiosis projects can be expanded, particularly for the use of red mud and spent pot lining in cement and other industries. Governments should continue to support next-generation pilots to keep future technology options open. Transition packages should accompany the retirement of stranded assets to protect communities.

7.4.3 Funding and Incentives

Funding will increasingly come from private capital as technologies mature, with concessional support tapering off for well-established technologies. Public incentives should focus on transition finance to convert existing assets and on just-transition funds to support affected workers and communities. International partnerships, anchored by MDBs, will remain essential for financing large-scale infrastructure projects.

7.4.4 Capacity Building and Regional Cooperation

Reskilling programs, community engagement initiatives, and harmonized regional safety protocols for waste, hydrogen and CO_2 should be scaled up to manage risks and build trust.

7.5 2046–2050: Consolidation to Net-Zero

7.5.1 Policies and Regulations

In the final phase, performance standards should be tightened to near-zero emissions. Governments should mandate high recycled-content thresholds and enforce full recovery of end-of-life aluminum products across packaging, transport, and construction. Trade and customs policies should be aligned with global carbon requirements, with countries consolidating their own carbon adjustment mechanisms that are consistent with international standards.

7.5.2 Projects, Technologies, and Infrastructure

By this stage, inefficient fossil-based smelters can begin to be retired and replaced with proven low-carbon technologies, such as large-scale inert-anode smelting powered by renewables. Residual emissions should be offset through CCUS-equipped facilities and carbon removals, where necessary, and supply chains should be optimized through regional integration of scrap, alumina, and aluminum flows.

7.5.3 Funding and Incentives

Financing will focus on maintaining competitiveness through O&M optimization, reinvestment cycles, grants for new technologies, and continued just-transition support for affected regions. Ensuring competitive renewable electricity pricing through regulatory reforms will be critical for long-term viability.

7.5.4 Capacity Building and Regional Cooperation

Regional governance of standards and certification systems should continue alongside benchmarking and data sharing to ensure continuous improvement. Latin America should also position itself as a global knowledge hub for sustainable aluminum production, exporting expertise to other regions.

By 2050, emissions from electricity consumption should be substantially reduced through the progressive replacement of fossil fuels with renewable energy. Latin America's major aluminum producers should establish themselves as global leaders in low-carbon aluminum while preserving economic competitiveness, while non-producing countries should align with regional net-zero aluminum value chains by ensuring that their procurement, recycling, and trade policies strengthen the sector's competitiveness.

8. Next Steps for LAC

Decarbonizing the LAC aluminum industry requires support for pilot programs with emerging technologies, investment in renewable energy capacity, expanded access to climate finance funds, and further studies to inform investment decision-making.

New analyses would be particularly beneficial in the following five key areas:

1. **Decarbonization scenarios for the aluminum industry in LAC.** This consists of modeling potential technology adoption strategies to identify their impact on reducing regional direct and indirect aluminum industry emissions. The LAC aluminum industry's current scope 1 and scope 2 mitigation trajectory must first be defined within the Paris Accord framework. Then the contributions of identified decarbonization alternatives, including their technical and commercial development trajectories, must be evaluated against the BAU baseline scenario to identify their potential impacts on the industry's emissions reduction by mid-century.

2. **Economic valuation of the measures to construct an emissions abatement curve.** The economic benefits of implementing the identified decarbonization alternatives need to be assessed by compiling and evaluating the costs associated with adopting each technology in LAC, including initial investment and operating costs. The benefits of fuel cost savings and carbon offsets are then estimated. This economic valuation will help identify the most cost-efficient alternatives for decarbonizing the LAC aluminum industry and options for improving the economic performance of technically feasible alternatives, including synergies with other sectors. It will also determine the impact of the evaluated decarbonization alternatives on aluminum costs. The assessment will be the primary input for an emissions abatement curve showing each measure's cost and impact on emissions reduction to 2050.

3. **Calculation of the funding gap.** Estimating the financing needed to implement the decarbonization alternatives is key to an understanding of financial needs, strategic planning, fundraising, and informed decision-making. An assessment is made of currently available financing and the aggregate financing needed to decarbonize the entire aluminum industry in the region by 2050 to determine the resulting gap. The possible causes of these gaps should be identified and routes to close them must be defined. The Decarbonization Roadmap Report of the Aluminum Association of North America calls for making capital available to help the aluminum industry achieve its emissions reduction goals, especially through technological options that are still in the R&D stage and therefore require time to mature and deploy.[130]

4. **Business synergies.** Identifying common decarbonization efforts across businesses and across the region can improve the economic performance of mitigation measures and expand access to key resources or infrastructure. To this end, the value chains of aluminum and related companies must be analyzed to link and identify synergies between their operational and productive ecosystems. Potential partners include producers, input and technology suppliers, distributors, and customers, among others.

[130] ICF. (2024). North American Aluminum Industry Decarbonization Roadmap. Aluminum Association.

CEMENT

1. INTRODUCTION

Though the cement industry plays a key role in building the infrastructure required for global development, it is a significant contributor to global carbon dioxide emissions (CO_2), accounting for approximately 7% of total emissions generated by human activities. Approximately 95% of emissions from cement production occur during clinker production through chemical reactions that release CO_2 and fuel-burning to heat calcination kilns to high temperatures. These physical realities of cement production make decarbonizing the cement industry particularly challenging.

At the global level, initiatives to address this challenge include the Paris Agreement (PA), the Low Carbon Technology Partnership Initiative (LCTPi), Race to Zero (UNFCCC), the Cement Sustainability Initiative (CSI), and the Science Based Targets Initiative. In Latin America and the Caribbean (LAC), the *Federación Interamericana del Cemento* (FICEM) is developing country-level decarbonization roadmaps. These efforts reflect a global and regional commitment to transform the industry that is fundamental to building a sustainable future.

This chapter analyzes decarbonization options for the cement sector in LAC. It first provides an overview of cement production, its lifecycle, and end uses. Next, it describes the global and regional cement market, examining the industry's energy and emissions intensities. It goes on to describe the industry's main decarbonization initiatives and then proposes concrete actions to increase cement production's sustainability in LAC, after which it describes potential pathways and investments needed to implement the proposed actions. Finally, it provides recommendations for next steps.

2. Production Processes

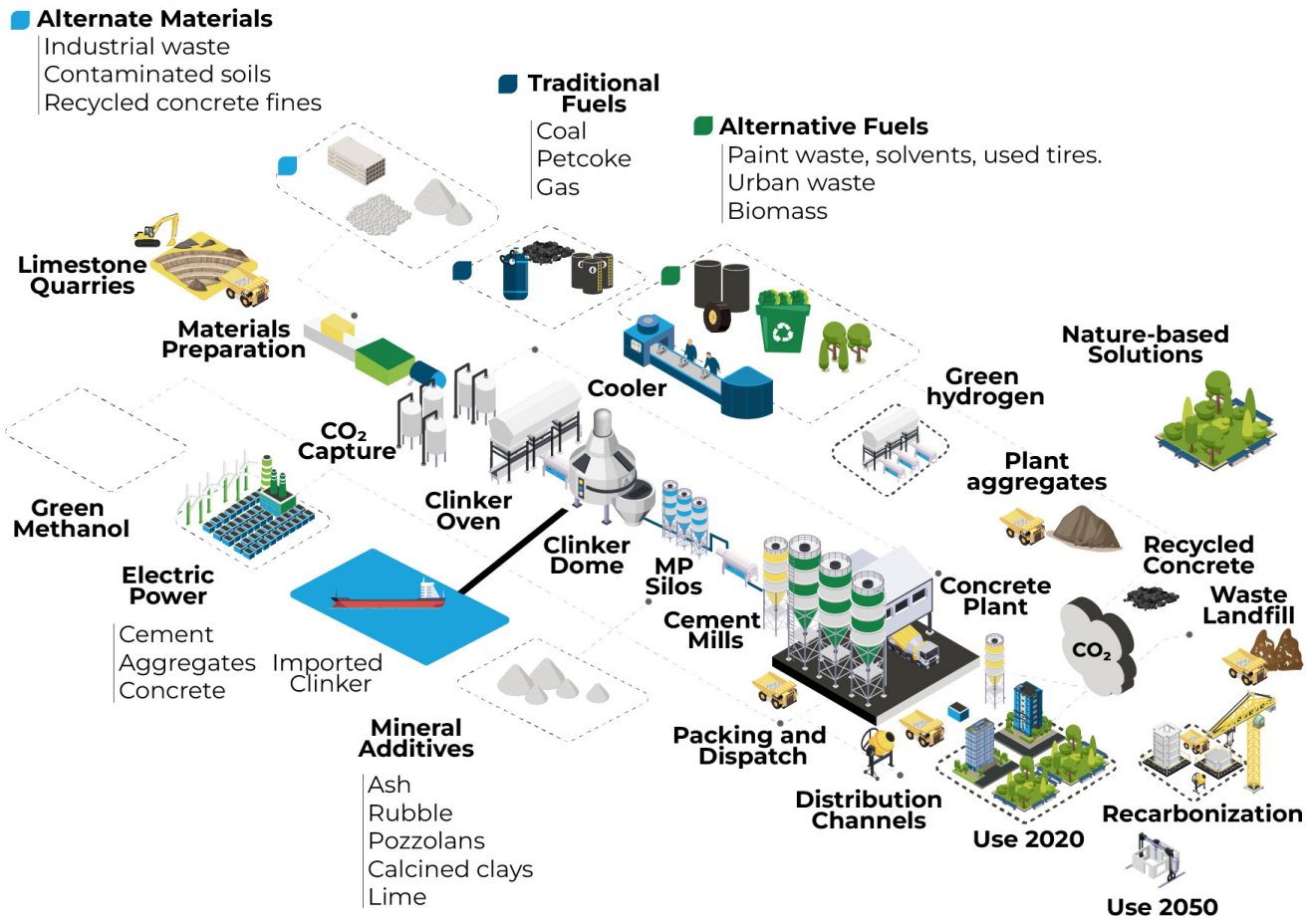
Cement is a powdered binding material composed of finely ground minerals that, when mixed with water, forms a paste capable of setting and hardening through multiple exothermic hydration reactions. This allows it to bind together fragments of solid matter to create a compact, hardened structure. After the hardening process, cement maintains its strength and stability even when exposed to water.

Historically, cement-based materials have been essential for construction and civil engineering. Cement has become the most widely used material and the second most consumed resource globally (Gagg, 2014). Globally, the most widely used type of cement is Portland cement, which is manufactured by mixing lime, silica, alumina, and iron in controlled quantities. This mixture is subjected to high temperatures in a kiln and then pulverized for storage or final use in the construction industry (Saleh & Eskander, 2020).

2.1 Manufacturing Process

Standard cement is manufactured in three stages: raw material preparation, clinker production, and cement grinding. The figure below shows the steps within each stage of the cement manufacturing process, and introduces areas where decarbonization could occur.

Figure 1. Cement Manufacturing Process



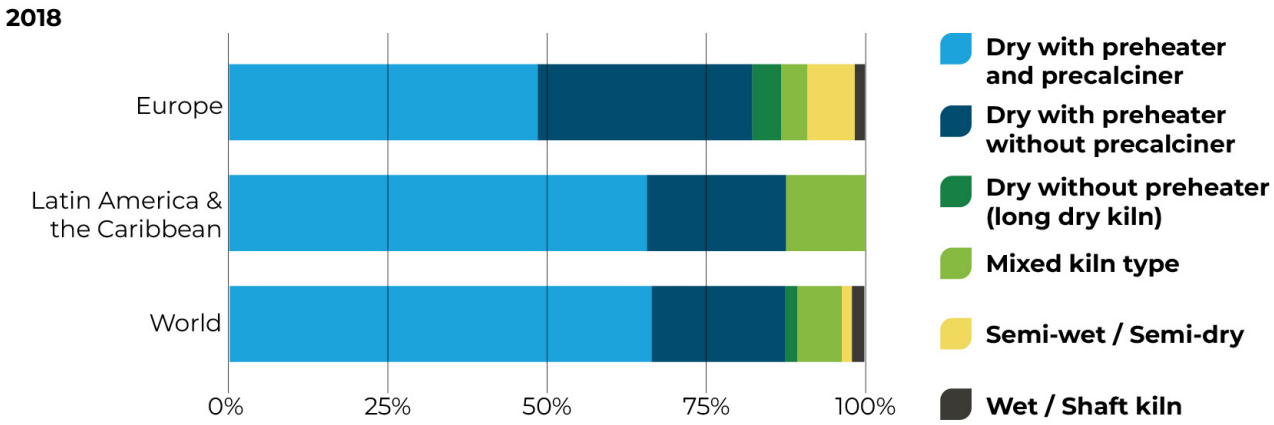
Source: Elaboration based on LAC Roadmap to Carbon Neutrality, FICEM 2050 (Pareja, 2024).

In stage 1, the raw materials used for cement manufacturing include limestone, which provides calcium carbonate ($CaCO_3$); iron ore, which provides iron oxide (Fe_2O_3); clay, which provides alumina (Al_2O_3); and, sand, which provides silica (SiO_2). These raw materials are first ground separately to pieces approximately 10 cm in diameter. Next, different raw materials are ground together in the required ratios to create a product known as “crude” (FICEM, 2023a).

The second stage begins with preheating the crude to approximately 600-650°C by passing it through a series of cyclones to facilitate the crude’s subsequent precalcination. This precalcining takes place in a combustion chamber in the lower part of the preheater where the limestone is chemically decomposed at temperatures of between approximately 750°C and 1,000°C. The precalcined raw material then enters a kiln, generally of the rotary type, where it is subjected to a gradual and continuous temperature increase. This progressive increase in temperature throughout the kiln causes the raw materials to decompose and the lime and clay oxides to combine. The process culminates in calcination and sintering that produces clinker at temperatures close to 1,400°C (John, 2020; Marenco et al., 2023).

This thermal treatment can be made through dry or wet processes or an in-between variant (semi-dry and semi-wet). Wet processes consume more energy than dry processes as water in the raw materials must be evaporated. This translates into higher emissions and higher operating costs (John, 2020). In Latin America and the rest of the world, dry process kilns with a preheater and a precalciner prevail, followed by dry process kilns with a preheater but without a precalciner, as illustrated in the figure below.

Figure 2: Crude Thermal Treatment for Clinker Production by Type



Source: Elaboration based on FICEM based on data from *Getting the Numbers Right* (GNR).

Once the clinker leaves the kiln, it is cooled to approximately 100°C. The hot air produced from the cooling process is recirculated back to the kiln to promote combustion and improve energy efficiency (Viñas, 2023).

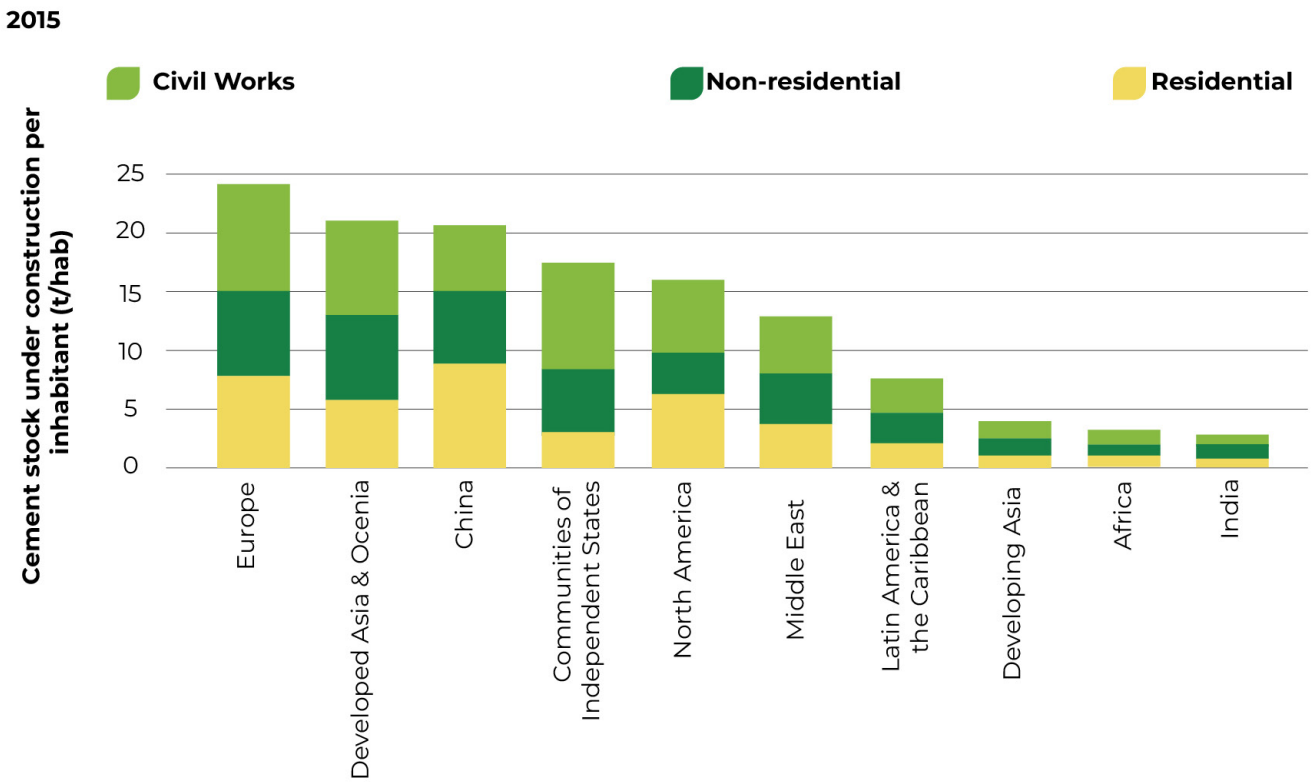
The third stage, cement grinding, starts with combining the clinker with gypsum in a roughly 19:1 ratio to control the cement's setting time. This mixture of clinker and gypsum is then ground to make ordinary Portland cement or other mineral components can be incorporated to produce compound Portland cement. Ball mills are the traditional choice for grinding, but other technological alternatives include roller presses and vertical mills. The cement is then stored in silos before being sent to a packing station and transported and distributed (FICEM, 2023a).

Cement can be produced in an integrated plant that incorporates all stages from limestone extraction to clinker production to grinding, or in a grinding plant that acquires clinker from an external supplier and then mixes and grinds it with gypsum and other inputs to produce cement.

2.2 End Uses and Lifecycle

Cement is an essential material with end-use applications ranging from building construction to road paving and precast concrete. Cement's end-use is almost evenly distributed across the residential, non-residential, and civil works sectors, as illustrated in the figure below.

Figure 3. Cement Stock in Use Per Capita by Application Sector (2015)

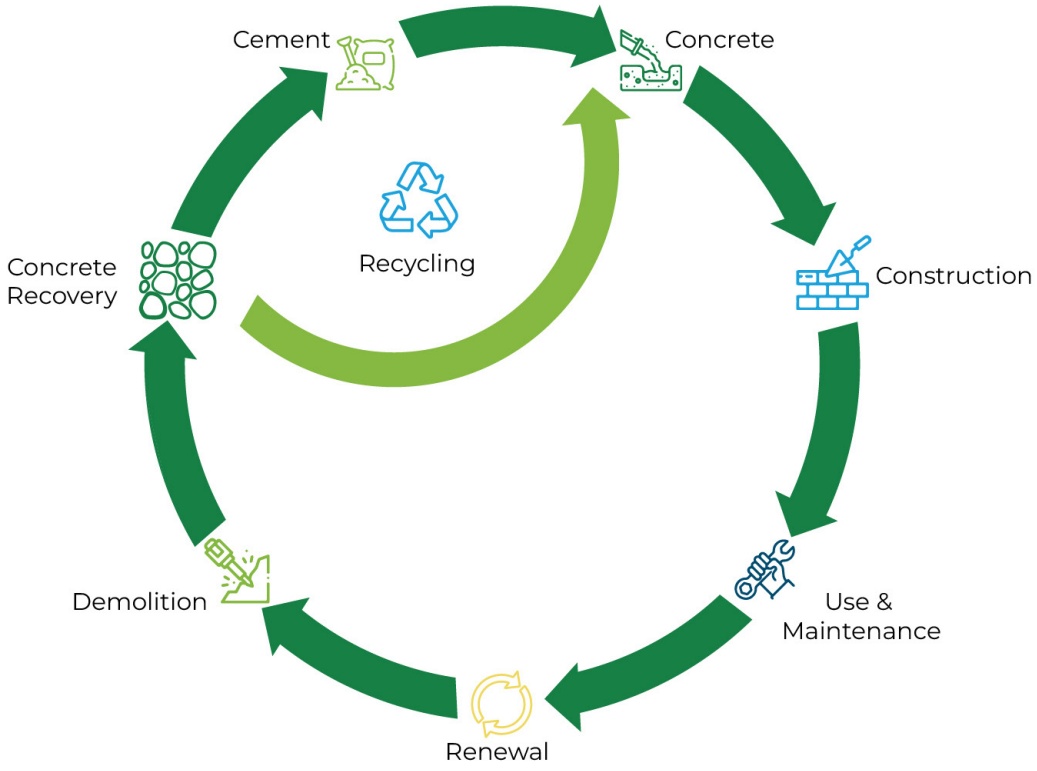


Source: Elaboration based on FICEM, Potential Value of Cement Industry Residuals in LAC in 2030. (Pinilla C., 2021)

Europe had the largest cement stock in use per capita in 2015, followed by Developed Asia and Oceania and China. LAC is a growing market for cement end-use owing to economic growth, increasing urbanization, and the need to modernize infrastructure.

As a fundamental component of concrete, cement has remarkable durability regardless of its final application. Most building regulations establish a 50-year-design economic life for conventional reinforced concrete structures (Medeiros et al., 2015), while for critical infrastructures such as tunnels and dams, this service life can extend to 100-120 years (Nilsson, 2019). Under favorable environmental conditions, it is possible to extend concrete's useful life even further through appropriate maintenance. This implies considerable extending of the intervals for infrastructure decommissioning and concrete (cement + aggregates) recovery and reuse. The figure below simplifies the lifecycle of cement in construction applications.

Figure 4. Cement Lifecycle



Source: Prepared in-house.

Once concrete reaches the end of its useful life, it undergoes a recycling process that involves removing unwanted materials such as impurities and steel reinforcements and crushing the resulting mix until it meets the required specifications. This recycled concrete aggregate (RCA), which contains coarse aggregates (stone and gravel), fine aggregates (sand), and 5-20% cement (WBCSD, 2009), can be used to manufacture new concrete products (CEMEX, 2023). This approach reduces construction and demolition waste and the need to extract new raw materials.

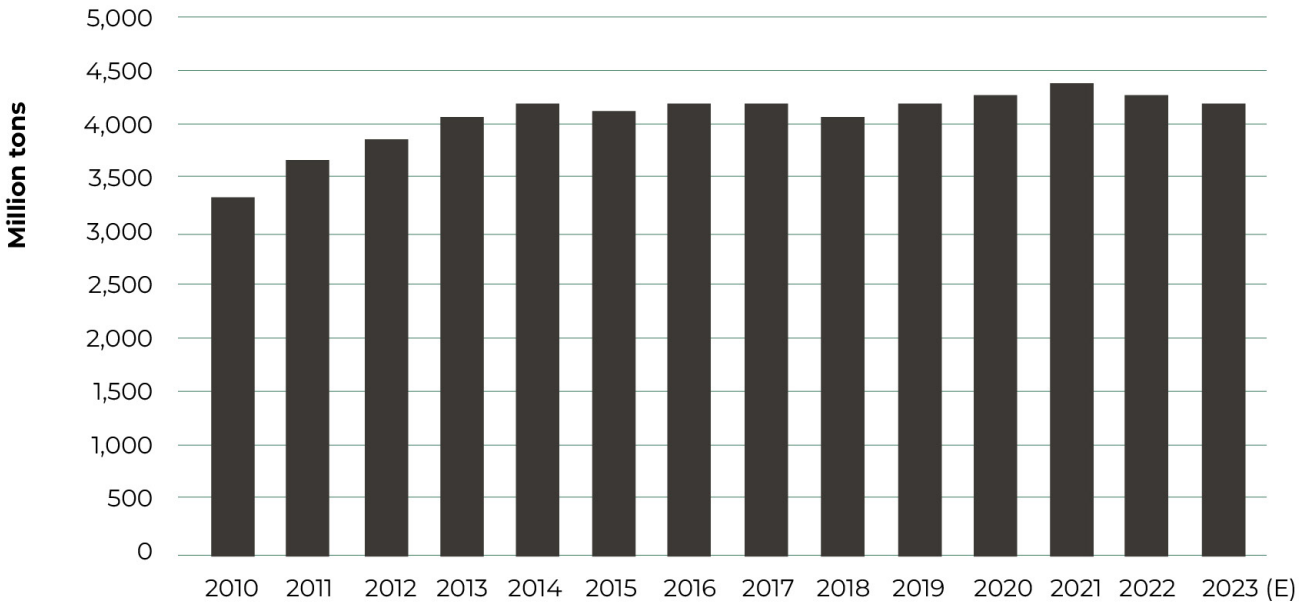
With this in mind, several countries have established standards to include RCA in the manufacturing of structural and non-structural concrete. For example, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) allows up to 100% RCA in the manufacturing of structural concrete. Countries have also set standards for the percentage of RCA that can be used according to the required concrete strength. For example, Portugal allows 25% RCA, while China, Spain, the United Kingdom, and the Netherlands allow up to 20% RCA in structural concrete. Canadian and Brazilian regulations limit RCA exclusively to non-structural concrete, allowing 100% and 20%, respectively (Ahmed et al., 2020).

3. Global and Regional Cement Markets

3.1 Production and Consumption

Between 2010 and 2014, world cement production grew by 27.4 %, reaching a total of 4,190 million tons (Mt). Since 2014, production has been level (see figure below).

Figure 5. World Cement Production (2010 - 2023)

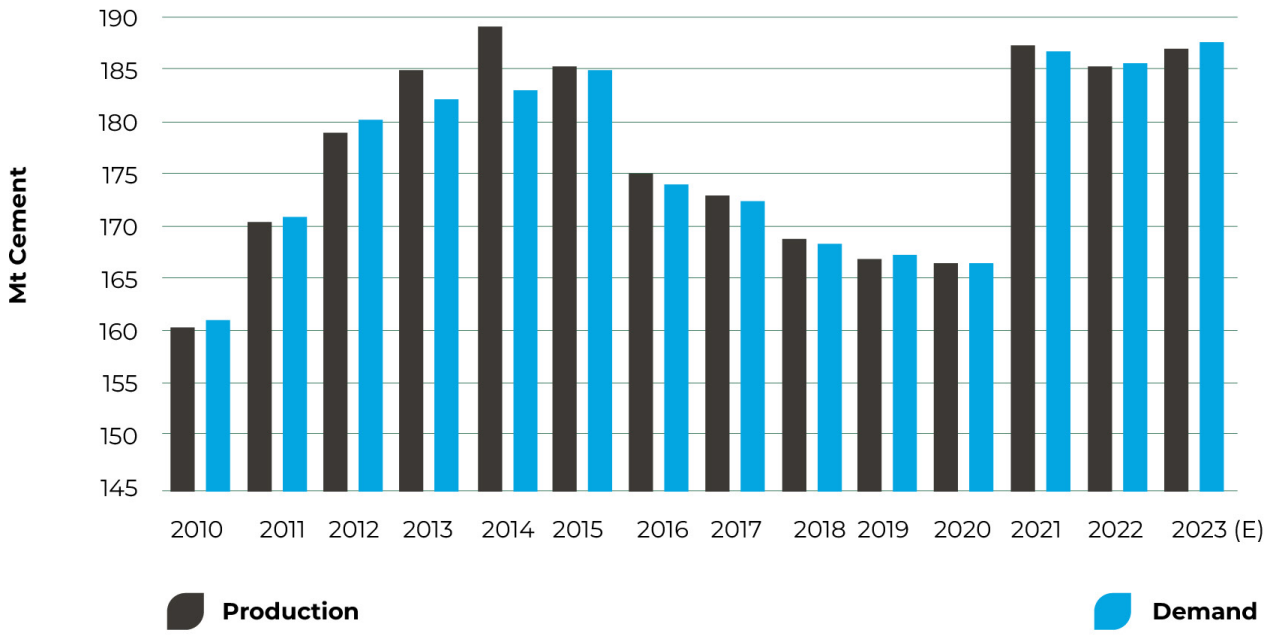


Source: Prepared in-house based on USGS statistics.[131]

[131] https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

During this period, LAC contributed, on average, 4.4% of global supply, equivalent to about 176 Mt per year. Similar to global cement production, LAC cement production grew rapidly between 2010 and 2015, increasing by 14.9% from 161 Mt in 2010 to approximately 185 Mt in 2015. LAC cement production fell to 174 Mt in 2016 and steadily declined to 166 Mt in 2020. The decline in 2016 was mainly due to economic contractions in the region's main producing countries as well as an increase in production prices (IADE, 2017; ODEB, 2016; INEI, 2016; Bermudez, 2016). Production increased dramatically in 2021 to nearly 187 Mt and has averaged over 186 Mt since then. This surge in cement production in recent years is largely driven by latent demand from projects delayed during the COVID-19 pandemic. LAC cement consumption has closely followed the trend in production, as shown in the figure below.

Figure 6. Cement Production and Consumption in LAC (2010 - 2023)



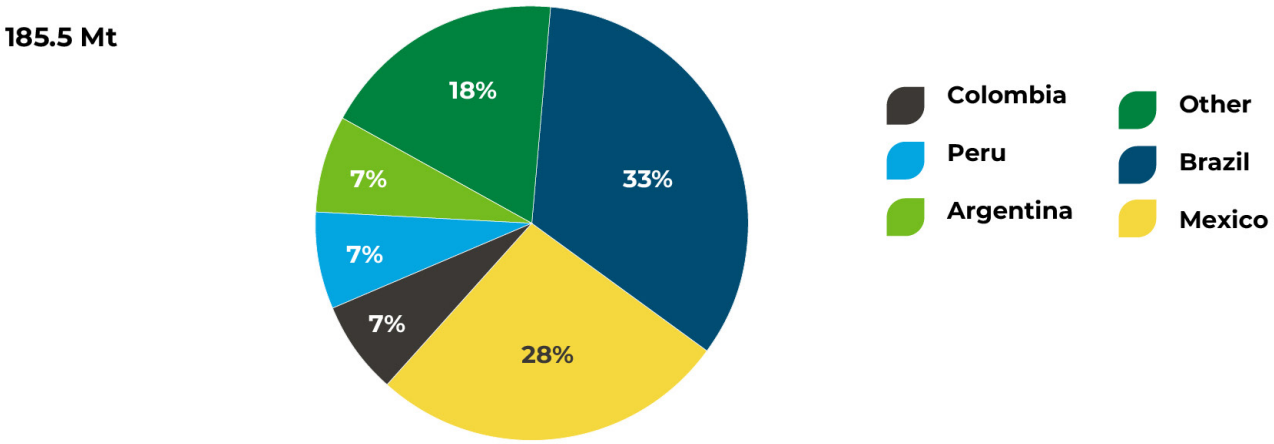
Source: Prepared in-house based on FICEM statistics.[132]

Medium- and long-term growth prospects in the region are uncertain. Residential construction and remodeling projects, along with mega infrastructure construction projects, are expected to drive cement demand in the near term.

Brazil, Mexico, Colombia, Argentina, and Peru account for 82% of LAC cement production. In 2021, Brazil produced 60.8 Mt of cement, Mexico 51.7 Mt, Colombia 13.8 Mt, Peru 12.9 Mt, and Argentina 12.1 Mt. The figure below shows each country's share of regional cement production for 2021.

[132] https://ficem.org/uso-estadisticas/

Figure 7. Share of the Main Cement-Producing Countries in LAC in 2021

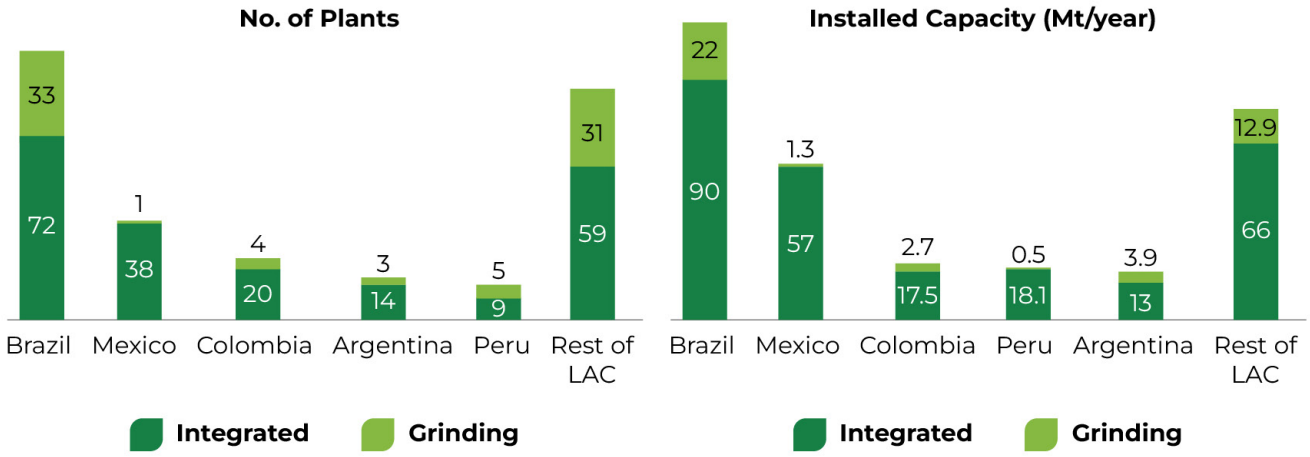


Source: Prepared in-house based on FICEM statistics.[133]

Approximately 289 plants produce cement in LAC. Of these, 212 are integrated plants, while the remaining 77 are grinding mills. The integrated plants have a combined installed capacity of 261 million tons of cement per year, while the mills have a capacity of 43 million tons (Villagrán et al., 2022).

Brazil and Mexico are the largest producers with more than 15 Mt/year of production each. These two countries alone comprise 50% of the region's cement plants and 56% of the region's installed capacity. Second-tier countries that produce between 5 and 15 Mt/year include Argentina, Colombia, Ecuador, and Peru. Third-tier countries with between 1 and 5 Mt/year of production include Bolivia, Chile, Costa Rica, El Salvador, Guatemala, Honduras, Panama, Paraguay, Uruguay, and Venezuela. Finally, those countries with less than 1 Mt/year of production include Cuba, Nicaragua, and Puerto Rico. The figure below shows the number of plants and installed capacity for the region's main cement-producing countries.

Figure 8. Number of Plants and Installed Capacity of the Main Cement-Producing Countries in LAC



Source: Elaboration based on No. of Plants, FICEM (2023b). Cement Industry Map of the Region,[134] CEMNET (2022). World Cement Report: Online Database of Cement Plants.[135] Installed Capacity, Villagrán et al. (2022).

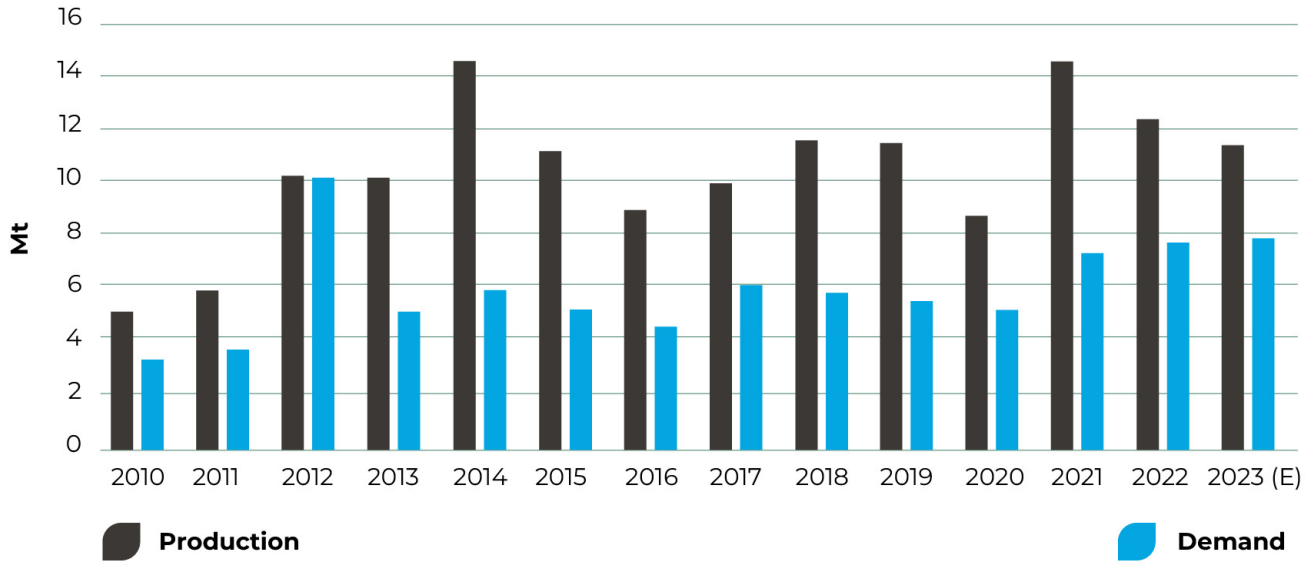
[133] https://ficem.org/uso-estadisticas/
[134] https://ficem.org/mapa-industria-de-la-region/
[135] https://www.cemnet.com/global-cement-report/

LAC's current cement production represents approximately 70% of the region's installed capacity. This suggests that future demand growth can be met without investing in new production capacity for many years. The available excess capacity could slow the adoption of cleaner and more efficient technologies, suggesting that efforts to decarbonize the LAC cement industry should focus on upgrading current facilities rather than investing in new mills.

3.2 Import and Export

LAC cement trade constitutes a small fraction of its annual production. Between 2010 and 2023, LAC imported an average of 10.5 million tons of cement per year (roughly 5% of annual demand), while exports averaged 6 million tons per year (3% of annual production). The figure below shows LAC historical cement import and export volumes.

Figure 9. LAC Cement Imports and Exports (2010 - 2023)



Source: Prepared in-house based on FICEM statistics.[136]

LAC's status as a net importer while not fully utilizing its regional cement manufacturing capacity reflect regional variations in the cost of production and the integrated nature of international cement markets. For example, cement production is estimated to be 30% more expensive in Argentina than in Brazil (Velázquez, 2019). Chile, Peru, Guatemala, Colombia, El Salvador, Brazil, and Guyana are the region's main cement importers with suppliers that include Turkey, China, Algeria, Spain, Japan, South Korea, and Vietnam.[137]

The availability of cement imports poses a challenge to decarbonizing the sector in LAC. Measures that significantly increase the price of cement relative to global competitors may cause import volumes to rise. Although cement is easily shipped, it is also very heavy. Importing cement from distant, higher emitting markets, mainly in Asia, could add between 70 and 120 $kgCO_2/t$ of product (Villagrán et al., 2022). Strengthening local cement production and reducing imports would in turn minimize the carbon footprint of the LAC cement supply chain.

[136] https://ficem.org/uso-estadisticas/
[137] https://oec.world/es/profile/bilateral-product/cement/reporter/

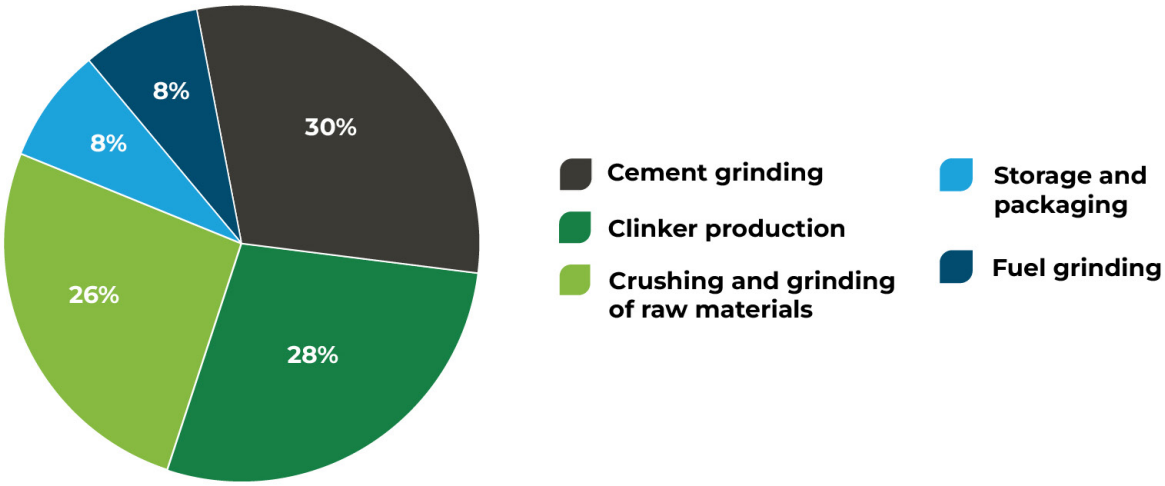
4. Environmental Impact of the Industry

The cement industry is characterized by its high energy intensity and high carbon dioxide emissions, making it a key sector for global industrial decarbonization. Cement production is estimated to contribute 6-7% of anthropogenic CO_2 emissions worldwide, ranking second only to the steel industry (GCCA, 2021; Bataille, 2019). This section details energy consumption and CO_2 emissions at each stage of cement production.

4.1 Energy Consumption

Approximately 92% of the energy used to produce cement is employed in the thermal processes associated with clinker production, which include preheating, pre-calcining, and calcining. The remaining energy use is divided equally between raw material preparation and cement grinding (Aristizábal and González, 2021). Cement facilities use fuels to activate the kiln burners and generate thermal energy for clinker production and they use electricity for raw material crushing and grinding, fuel preparation, kiln ventilation and cooling, cement grinding, and storage and packaging. The figure below shows electricity use in cement production.

Figure 10. Electricity Use in Cement Production

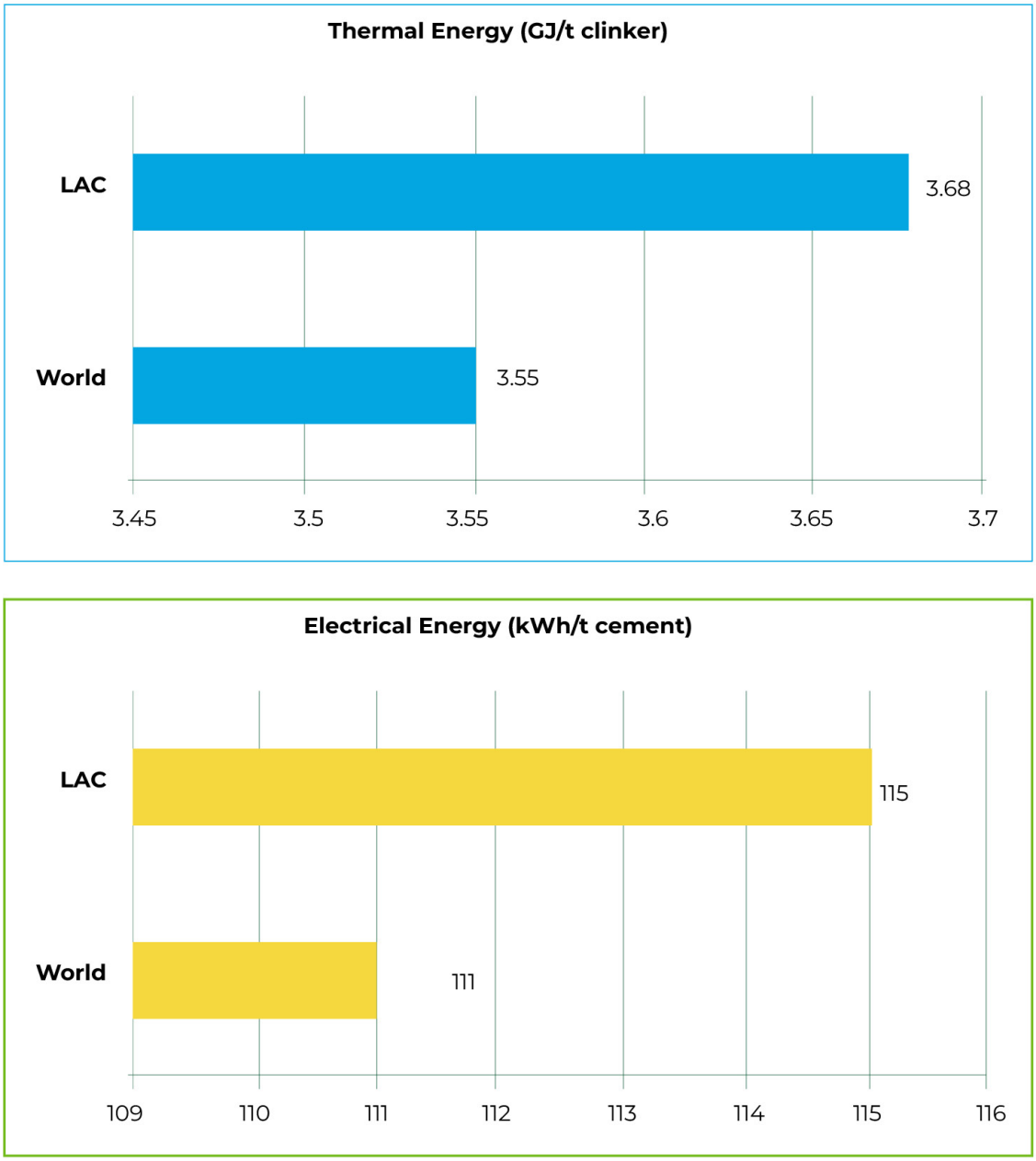


Source: Prepared in-house based on data from IEA (2018).

A cement plant operating with highly efficient kilns consumes approximately 2.95 gigajoules (GJ) of energy per ton of clinker produced. Less efficient plants can consume more than 5 GJ/t (Aristizábal and González, 2021). Electricity consumption may also vary significantly, ranging from 70 to 140 kilowatt-hours (kWh) per ton of cement produced (IEA, 2021). Energy consumption can also be affected by fuel quality and type and the mineral raw materials' hardness and composition.

Cement industry energy consumption in LAC is above the world average. In 2022, the region exceeded the global thermal intensity by 3.6%, reaching 3.68 GJ per ton of clinker. LAC electricity intensity was 115 kWh per ton of cement, also 3.6 % above the world average, as illustrated in the figure below.

Figure 11. Energy Intensity of Cement Production in LAC and the World for 2022



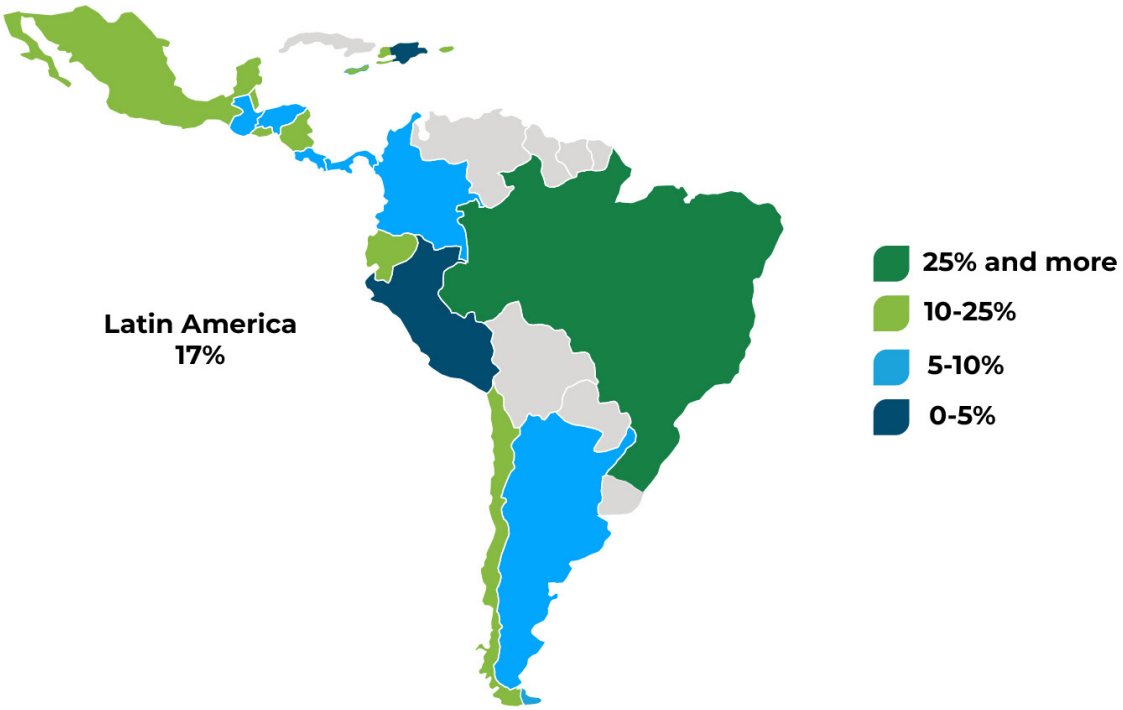
Source: Prepared in-house based on FICEM statistics.[138]

[138] https://ficem.org/uso-estadisticas/

Clinker production uses fossil fuels such as coal and petroleum coke and alternative energy sources, including solid waste (such as tires, plastics, textiles, sawdust and wood, and paper industry waste) and liquid waste (such as used mineral oils, solvents, paints, varnishes, and hydrocarbon residues). The industry has also used biomass as an energy source, incorporating materials such as rice husks, peanut or sunflower shells, bagasse from the sugar industry, and African palm kernel residues, as well as other materials. Using biomass can reduce dependence on fossil fuels and provide thermal energy without generating new waste, ash, or emissions.

The amount of waste co-processed in the cement industry varies significantly by country. For example, Germany, Poland, Czech Republic, and Austria have achieved processing levels above 70%. LAC averages 17%, with Brazil using waste for more than 25% of the energy used for cement production, as shown in the figure below.

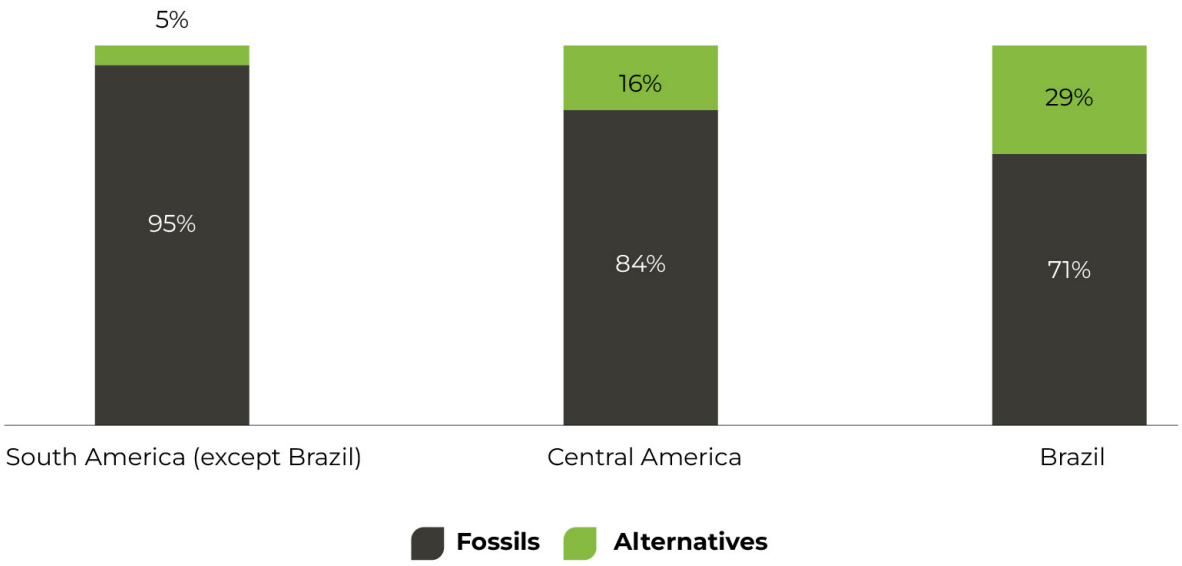
Figure 12. Co-processing Rate in LAC Countries



Source: Elaboration based on FICEM Data Report (2023c).

The weighted average co-processing practice in the region is approximately 17%, although in several cement producing countries the practice is close to 0 %. In South America, the average is mainly driven by Brazil's waste co-processing. Excluding Brazil, South American producer countries average 5% in co-processing. In Central America, the average share of alternative fuels in clinker production is 16%, as shown in the figure below.

Figure 13. Share of Fuel Consumption in Clinker Production in LAC Subregions and Countries



Source: Prepared in-house based on IEA data (2021).

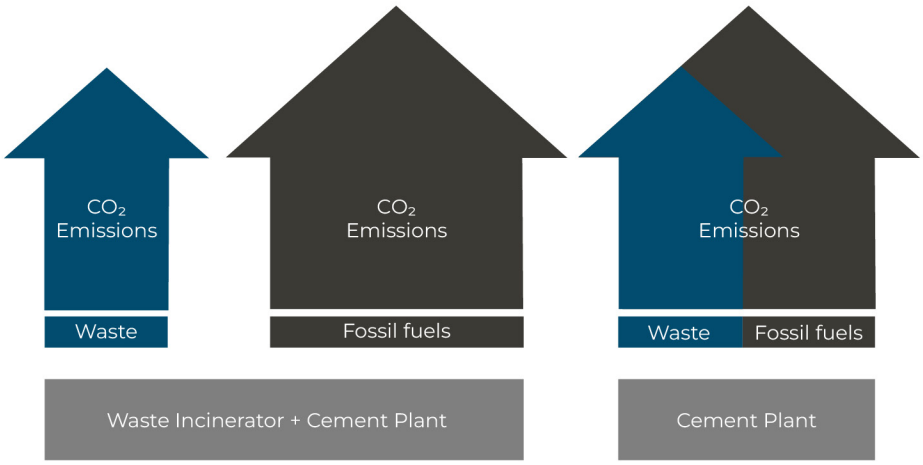
The LAC cement industry uses alternative fuels from a wide variety of sources: agricultural residues, scrap tires, mixed industrial residues, industrial fossil waste, and, to a lesser extent, sludge from wastewater treatment plants, solvents, plastics, wood, and waste from the paper industry.

Co-processing leads to indirect CO_2 emission reductions. Burning the waste produces CO_2, but CO_2 and other emissions would be produced even if the waste were disposed of in landfills and incinerators. Using the waste to produce heat for cement production, instead, partially or completely offsets the direct CO_2 emissions that would result from burning conventional fossil fuels.

Cement industry CO_2 emissions can therefore be quantified in two ways: gross emissions, which encompass all emissions, including those from alternative fuels (AF), and net emissions, which exclude emissions from AF. However, for net emissions to be valid, AF credits must be approved and certified. This is determined by specific local circumstances (such as national agreements or lifecycle analysis of local AF use) and verified through third-party reporting, as necessary.

By default, the protocol assumes that indirect savings credits are equivalent to direct CO_2 emissions from the use of AF. The figure below illustrates how indirect savings in CO_2 emissions are achieved by using waste as an alternative fuel in a cement production plant.

Figure 14. Indirect Savings in CO_2 Emissions by Using Waste as an Alternative Fuel in a Cement Plant



Source: WBCSD (2011).

4.2 CO_2 Emissions

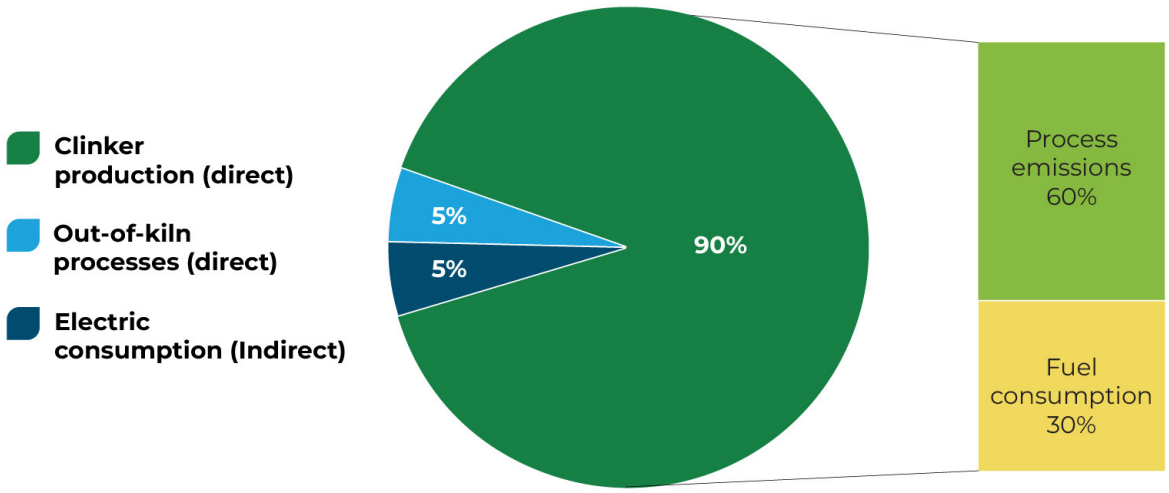
Cement industry CO_2 emissions include direct emissions from the process, direct emissions from burning fossil fuels, and indirect emissions from consuming electricity from the electrical grid. The figure below identifies where each of these different emission sources occurs during cement manufacturing.

Figure 15. Sources of CO_2 Emissions from the Cement Manufacturing Process

Source: Prepared in-house.

Clinker production accounts for about 90% of total emissions (Bosoaga et al., 2009). Of the remaining emissions, 5% correspond to direct emissions from fuels used to transport raw materials and electricity self-generation. The other 5% are indirect emissions from grid-supplied electricity. Within the clinker production process, chemical limestone decarbonation ($CaCO_3$ + heat → CaO + CO_2) accounts for about 60% of emissions and the remaining 30% is from in-kiln fossil fuel burning (John, 2020; Boyaghchi, 2014). The figure below disaggregates cement production CO_2 emissions.

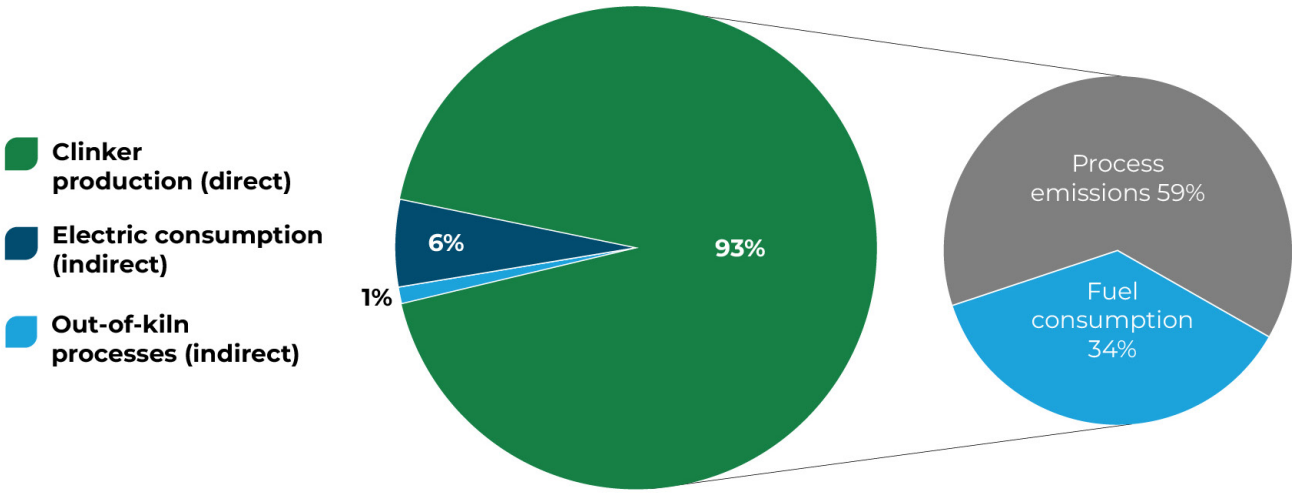
Figure 16. Share of CO_2 Emissions in Cement Production Worldwide



Source: Prepared in-house based on John (2020), Boyaghchi (2014), Bosoaga et al. (2009).

The figure below shows this same disaggregation for cement production in LAC.

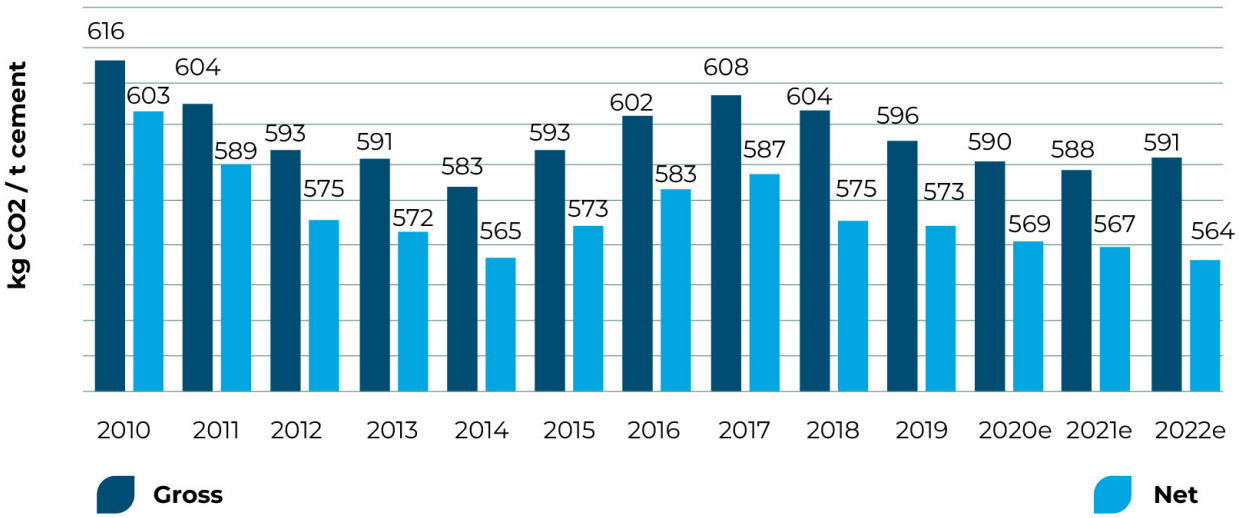
Figure 17. Share of CO_2 Emissions in LAC Cement Production



Source: Prepared in-house based on the FICEM calculator.

Co-processing waste with clinker production can reduce the share of fuel consumption emissions. Between 2010 and 2022, the LAC cement industry's gross CO_2 emission intensity averaged 597 kg per ton of cement manufactured while the net CO_2 emission intensity was 576.5 kg per ton of cement (see figure below). This represents a 3.4% reduction in carbon dioxide emission intensity from co-processing waste as an alternative fuel.[139] This reduction has also increased in recent years, reaching 4.5% in 2022.

Figure 18. Gross and Net CO_2 Emission Intensity of the LAC Cement Industry (2010 - 2022)



Source: Prepared in-house based on FICEM statistics.[140]

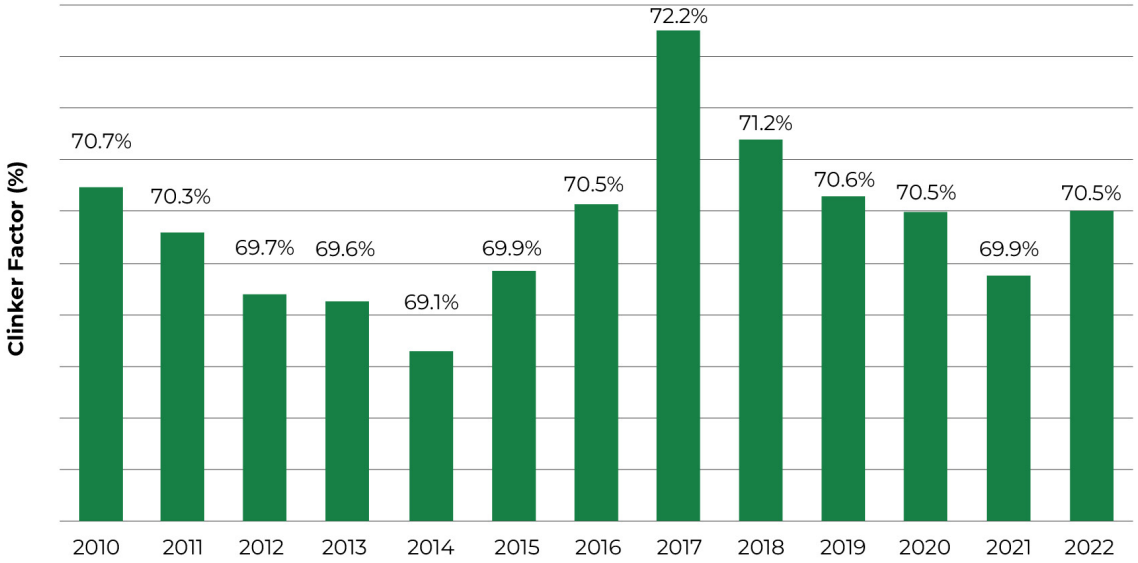
Both gross and net emissions declined between 2010 and 2014, increased from 2015 to 2017, and then again declined from 2017 to 2022. This fluctuation reflects changes in raw materials and cement production efficiency, particularly with regard to the clinker content used in cement production (clinker/cement ratio).

Because the chemical decarbonation reaction in clinker production produces such a large share of cement manufacturing CO_2 emissions, replacing fossil fuels with zero carbon alternatives can only mitigate a fraction of clinker production emissions. The clinker/cement ratio, which indicates the amount of clinker required to produce one ton of Portland cement, also influences CO_2 emissions. Reducing the clinker/cement ratio by optimizing the raw material mix, adopting advanced technologies, or reducing process losses reduces CO_2 emissions per ton of cement produced.

The figure below shows the LAC clinker/cement ratio between 2010 and 2022. The clinker/cement ratio trend matches the trend in CO_2 intensities shown in Figure 18 above.

[139] Gross emissions correspond to all emissions, including those from alternative fuels (AF), while net emissions exclude emissions from AF.
[140] https://ficem.org/uso-estadisticas/

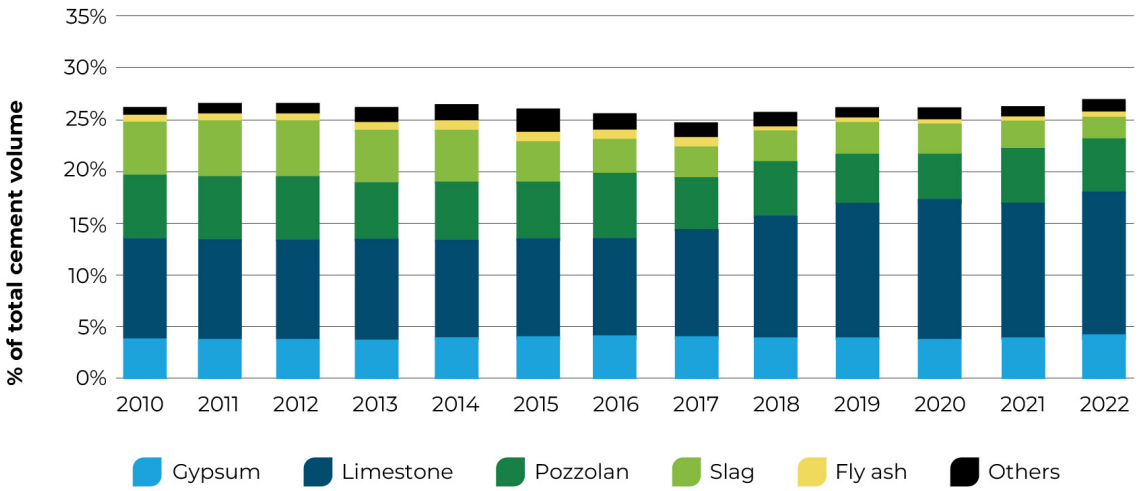
Figure 19. LAC Clinker/Cement Ratio (2010 - 2022)



Source: Prepared in-house based on FICEM statistics[141] and data provided by Villagrán et al. (2022).

The availability of supplementary cementitious materials (SCM) with the required quality helped improve the clinker/cement ratio. Between 2010 and 2014, the LAC cement industry increased the use of supplementary cementitious materials such as fly ash and slag, leading to a lower clinker/cement ratio while maintaining a steady amount of limestone as a filler material through proper blending. In 2017, the region began using more limestone for clinker production and the use of ash and slag decreased owing to its scarcity (Villagrán et al., 2022). This change in the raw material composition affected the clinker/cement ratio and the resulting CO_2 emissions. The figure below shows the share of mineral components used to produce clinker-based cement in LAC.

Figure 20. Mineral Components Used to Produce Clinker-Based Cement in LAC (2010 - 2022)



Source: Elaboration based on Villagrán et al. (2022).

This suggests that regional availability of supplementary cementitious materials is a fundamental factor in reducing the clinker/cement ratio and mitigating CO_2 emissions from clinker production. (Rosković & Bjegović, 2005; Scrivener et al., 2018).

[141] https://ficem.org/uso-estadisticas/

5. Decarbonization in LAC

This section presents global and regional initiatives related to decarbonizing the cement industry.

5.1 International Context

5.1.1 Paris Agreement

The Paris Agreement (PA) was adopted during the COP21 meeting of the UNFCCC in Paris on December 12, 2015, and entered into force on November 4, 2016. Its fundamental goal is to limit increased global temperatures to less than 2 degrees Celsius, preferably 1.5 degrees Celsius, compared to pre-industrial levels (UNCC, 2023).

The PA promotes cement industry decarbonization through several mechanisms. First, it advocates the development and implementation of clean and low-carbon technologies. Second, it encourages countries to adopt policies and regulations that help the transition to more sustainable cement production. Finally, it attracts funds that facilitate sustainable financing.

The PA operates in five-year cycles in which countries undertake increasingly ambitious climate actions. Each state submits its climate action plans, known as Nationally Determined Contributions (NDCs),[142] detailing the actions it will take to reduce greenhouse gas emissions and achieve the PA's goals. These contributions include building resilience and adapting to the effects of rising temperatures.

In addition, the PA encourages countries to design and present long-term low-carbon development strategies. This provides a long-term horizon for NDCs within each country's planning priorities, offering a vision and direction for future low-carbon development.

In line with the PA's targets, in 2018 the cement industry updated its first global roadmap for CO_2 emissions reduction in close collaboration with the International Energy Agency (IEA).[143] Carbon mitigation strategies in the roadmap include improving energy efficiency, transitioning to less carbon-intensive alternative fuels, reducing the share of clinker in cement production, and integrating carbon capture technologies. The roadmap has been continuously updated at the global and regional levels with the support of the Global Cement and Concrete Association (GCCA) and regional cement industry associations such as the Inter-American Cement Association (FICEM) in LAC.

[142] https://unfccc.int/es/acerca-de-las-ndc/contribuciones-determinadas-a-nivel-nacional-ndc
[143] https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

5.1.2 Low Carbon Technology Partnership Initiative (LCTPi)

The LCTPi includes more than 200 companies and 70 partners committed to accelerating the transition to a low-carbon economy aligned with the Paris Agreement goals. The World Business Council for Sustainable Development (WBCSD) leads the effort with support from *We Mean Business* partners. LCTPi provides a collaborative platform for businesses and policymakers to expand the implementation of business solutions. LCTPi's efforts can potentially contribute 65% of the emissions reductions required to keep global warming below the 2°C limit.[144]

LCTPi encompasses nine sub-initiatives: carbon capture and storage, cement industry sustainability, chemicals, climate-smart agriculture, energy efficiency in buildings, forestry, low-carbon transport, low-carbon transport fuels, and renewable energy.

Within the cement sustainability sub-initiative, LCTPi aims to reduce emissions by 20% to 25% relative to the business as usual scenario by 2030. The action agenda includes the following: i) improving the sector's CO_2 and energy consumption database, with a specific focus on China; ii) improving cement manufacturing energy efficiency; iii) increasing the collection, availability and use of good quality alternative fuels and raw materials; iv) further reducing the clinker content in cement; v) developing new cement with lower energy and calcination requirements; vi) engaging the entire construction and infrastructure value chain in local markets to identify and maximize avoided emissions from the use of cement and concrete products; and vii) evaluating cross-sectoral initiatives, particularly related to capturing, using and storing carbon at scale.[145]

5.1.3 Race to Zero (UNFCCC)

Race to Zero is a global campaign led by the United Nations Framework Convention on Climate Change (UNFCCC) that brings together non-state actors (including businesses, cities, regions, and financial, educational and healthcare institutions) to take rigorous and immediate action to help halve global emissions by 2030 and achieve a healthier and fairer zero-carbon world. As of June 2020, more than 11,000 members in 116 countries have joined the campaign and are committed to reducing emissions in line with the Paris Agreement with transparent action plans and robust short-term targets.[146]

The campaign has 20 accelerators to drive the Race to Zero emissions, including the Global Cement and Concrete Association, whose members accounts for around 80% of the world's total cement and concrete industry production (Race to Zero, 2022).

5.1.4 Cement Sustainability Initiative

The WBCSD established the Cement Sustainability Initiative in 1999 to address the cement industry's CO_2 emissions (Nunes & Costa, 2021). CSI's objectives focused on defining sustainable development within the cement industry, identifying actions and facilitating steps that cement companies can take to accelerate progress towards sustainable development, establishing a framework for companies in the sector to participate, and creating the content and environment necessary for greater stakeholder involvement (Schumacher & Juniper, 2023).

CSI has been instrumental in developing a standardized methodology known as The Cement CO_2 and Energy Protocol to measure, record, and verify cement industry CO_2 emissions and energy performance.[147] It has also created a global database of cement industry CO_2 and energy. Known as

[144] https://climateinitiativesplatform.org/index.php/LCTPI_Low_Carbon_Technology_Partnership_initiative_(Main)
[145] https://docs.wbcsd.org/2015/11/LCTPi-Cement-Report.pdf
[146] https://racetozero.unfccc.int/system/race-to-zero/
[147] https://docs.wbcsd.org/2011/05/CSI-CO2-Protocol.pdf

the Getting the Numbers Right, or GNR, database,[148] it covers approximately 60% of global cement production and has a higher than 80% level of data verification (Schumacher & Juniper, 2023).

In 2019, WBCSD transferred CSI's activities to the Global Cement and Concrete Association as part of a strategic alliance between the two organizations.[149] Established in January 2018, the GCCA focuses on promoting innovation along the entire construction value chain in collaboration with industry associations.

5.1.5 Science Based Targets

The Science Based Targets initiative (SBTi) drives ambitious private sector climate action by helping organizations set science-based emissions reduction targets. The SBTi, launched in 2014 as a partnership between CDP, the UN Global Compact, the World Resources Institute (WRI), and the World Wildlife Fund (WWF), defines and promotes emissions reduction and net zero target best practices in line with climate science and provides technical and scientific assistance and expert resources to companies setting targets in line with the latest climate science.[150]

In 2022, the SBTi released a *Cement Science Based Target Setting Guidance*[151] for the cement sector that provides cement companies with resources to set short- and long-term climate targets consistent with the principles of the Paris Agreement. This guide offers a science-backed approach, providing concrete pathways for decarbonization that are in line with the goals of limiting the global temperature rise to 1.5 degrees Celsius. It also provides detailed guidance for defining specific targets and addressing cement and concrete industry process characteristics and gives criteria and recommendations for accurately recording the sector's greenhouse gas emissions. Finally, it provides illustrative examples of how companies can use these tools, in addition to providing guidelines for submitting targets for validation.

5.2 Regional Context (LAC)

5.2.1 FICEM Roadmap

The FICEM Roadmap represents a set of tools designed to contribute to Co_2 emission mitigation, promote energy efficiency, and respond to regional climate impact adaptation needs. This approach is achieved through analyzing current and future scenarios related to greenhouse gas (GHG) emissions throughout the cement lifecycle in Latin America (Pareja, 2017).

This FICEM Roadmap is structured around six goals (FICEM, 2018b):

1. Contribute to meeting both global and regional climate change targets;
2. Establish a robust CO2 emission baseline;
3. Identify the potential for emissions reduction;
4. Thoroughly map the cement lifecycle and develop specific strategies to reduce CO_2 emissions;
5. Facilitate the creation of customized country roadmaps to address climate change in the local environment; and
6. Consolidate FICEM's position as a reference entity on climate change in the region's cement industry.

[148] https://docs.wbcsd.org/2016/12/GNR.pdf
[149] https://gccassociation.org/news/partnership-with-world-business-council-for-sustainable-development-work-of-cement-sustainability-initiative-to-transfer-to-gcca/
[150] https://sciencebasedtargets.org/about-us
[151] https://sciencebasedtargets.org/resources/files/SBTi-Cement-Guidance.pdf

At present, four LAC countries have completed and published their respective FICEM Roadmaps to reach net-zero carbon or achieve a 1.5 degree scenarios (Argentina, Brazil, Chile and Colombia) and Peru is in the process of finalizing its Roadmap. In addition, seven countries have completed roadmaps for a 2 degree scenario path through 2030:: Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, and Panama, while Bolivia, Paraguay, and Uruguay have made progress. The roadmaps identify reductions made to date and project future reductions in cement production CO2 emissions. The joint effort has also led to the creation of an FICEM calculator, an important source of data for cement industry actions related to climate change in LAC (Pareja, 2017).

5.3 Mitigation Trends

Measures to decarbonize the cement industry include replacing fossil fuels with low-emission alternative fuels and electrification, carbon capture, use and storage (CCUS), reducing the clinker/cement ratio by incorporating supplementary cementitious materials (SCM), increasing concrete recycling, and improving efficiency. Each of these strategies is described below.

5.3.1 Substitution of Fossil Fuels in Clinker Production

This section describes three options for producing clinker without using fossil fuels: co-processing municipal solid waste, using clean hydrogen (H2), and electrifying the clinker production process.

5.3.1.1 Co-processing of Municipal Solid Waste (MSW)

Co-processing—using waste as fuel in cement kilns—has been used in the industry for several decades. The Basel Convention, which issued the Technical Guidelines on Environmentally Responsible Co-Processing of Hazardous Wastes in Cement Kilns, explicitly recognized the environmental benefits of using both hazardous and non-hazardous wastes in cement kilns (UNEP, 2011).

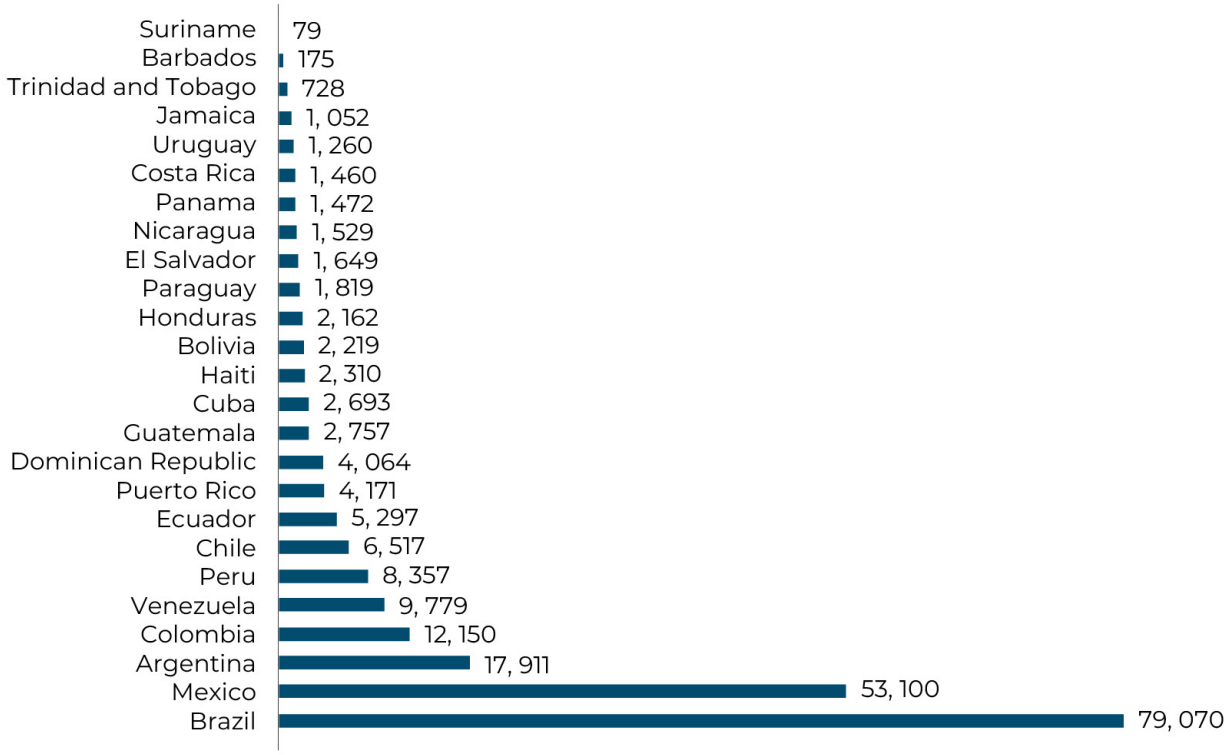
In LAC, many countries have co-processing standards that complement the Basel Convention, including Argentina (IRAM 29600 standard), Brazil (CONAMA resolution 264/99), Colombia (resolution 802 of 2014), Costa Rica (regulation 40557-S of 2017), Ecuador (Ministerial Agreement 48, official register 439 of May 3, 2011), Honduras (Regulation N1566-2010), Mexico (NOM-040-ECOL-2002 standard), and Peru (annex of Decree 1278). Despite these standards, MSW co-processing is less common in LAC than using agricultural and industrial waste.

This section evaluates the potential for MSW-based co-processing, considering its generation, composition and suitability as well as its technical and economic viability.

5.3.1.2 MSW Generation and Composition in LAC

The LAC region produces close to 223 million tons of MSW per year, some 0.96 kilograms per person per day on average. The five main cement-producing countries (Brazil, Mexico, Colombia, Argentina, and Peru) account for 76% of LAC's total waste generation. Brazil alone produces 79 million tons per year, as shown in the figure below.

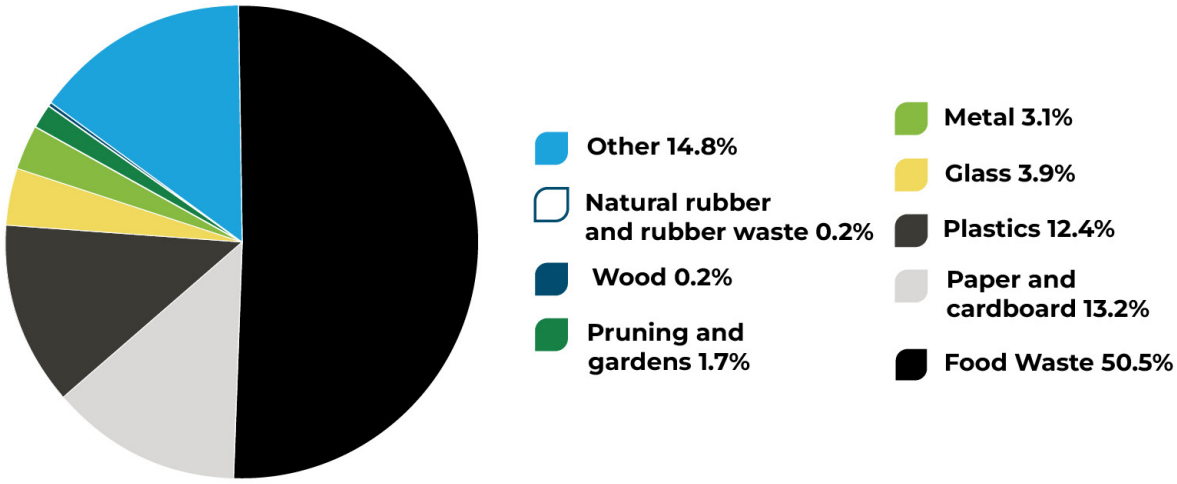
Figure 21. Volume of MSW Generated in LAC Countries (Thousands of Tons/Year)



Source: Prepared in-house based on FICEM Potential Value of Cement Industry Residuals in LAC to 2030 (Pinilla, C., 2021).

Approximately half of LAC MSW is food waste and a further third is made up of dry recyclable materials such as paper and cardboard, plastics, glass, metal, wood, and rubber (see figure below). About 15% is other types of waste that have not been characterized through formal systems but that are likely to be largely organic, given that areas outside the scope of municipal waste systems tend to be rural or lower income and generate more organic waste.

Figure 22. MSW Composition in LAC



Source: Prepared in-house based on Kaza et al. (2018).

5.3.1.3 MSW Co-Processing Potential

Approximately 25% of LAC's solid waste (56 million tons/year) could be co-processed by the cement industry. Organic waste, such as food waste or pruning and gardening waste, can also be used as an alternative fuel but would require substantial additional energy to dehydrate prior to use.

Waste for co-processing must be safe to use and have a high calorific value to effectively replace fossil fuels (GIZ, 2020). The MSW with the greatest potential are plastics and natural rubber and rubber waste since their calorific values are comparable to that of petroleum coke, as shown in the table below.

Table 1. Calorific Values for Different MSW Including Petroleum Coke

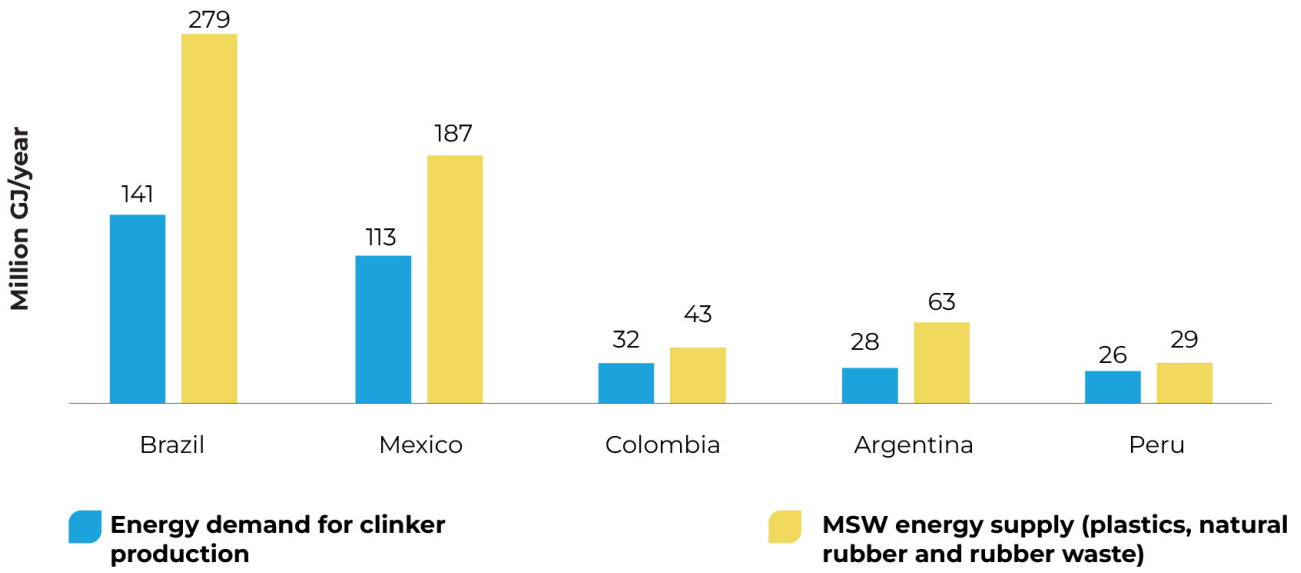
	Minimum (GJ/t)	Maximum (GJ/t)
Food waste	2	5
Plastics	21	42
Paper and cardboard	3	16
Natural rubber and rubber waste	25	31
Wood	16	18
Petroleum coke	32	35

Source: Prepared in-house based on data provided by GIZ (2020); FICEM (2021a).

Assuming a 70% clinker/cement ratio, LAC's annual clinker production is approximately 121 million tons, requiring roughly 432 million gigajoules of energy per year.

Recovering 80% of the region's plastics, natural rubber, and rubber waste for cement industry co-processing would provide 789 GJ per year at an average calorific value of 28 GJ per ton of waste. This suggests that availability would not limit the use of waste in co-processing. The figure below shows the current energy supply of MSW based solely on plastics, natural rubbers, and rubber waste (at an 80% recovery rate) and LAC's main cement producing countries' clinker production energy demand.

Figure 23. Current MSW Energy Supply and Clinker Production Energy Demand for Major Cement Producers in LAC

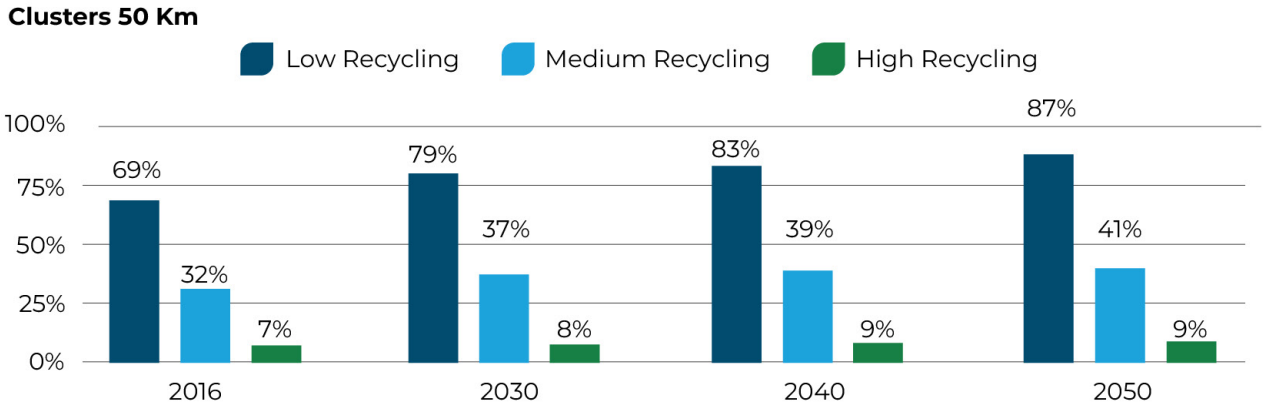


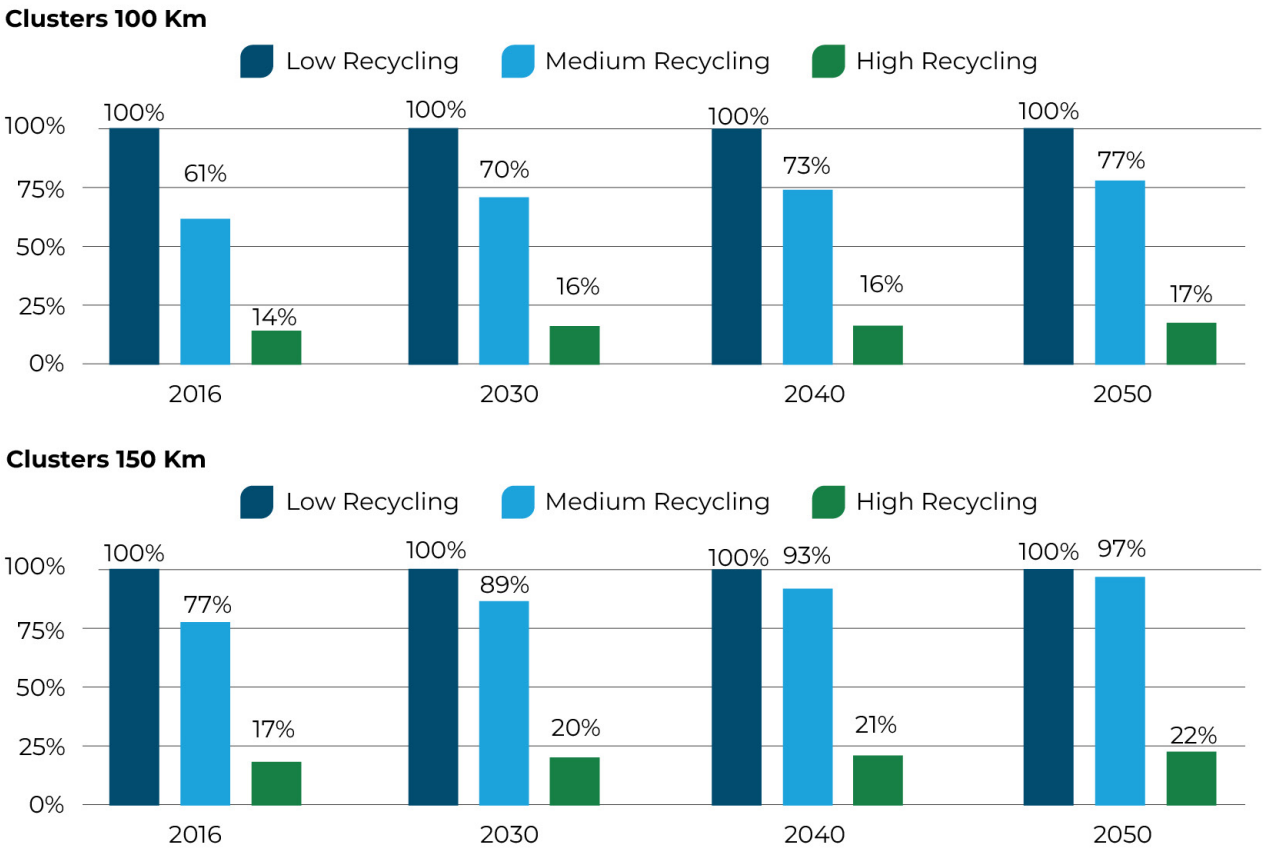
Source: Prepared in-house.

FICEM projected the availability of suitable MSW to 2050 based on the proximity of cement production plants to population clusters across LAC (FICEM 2021a). The assessment indicated cement plant energy requirements in 2050 could be 91% satisfied by MSW available within a 50-km radius and 100% satisfied for radii between 100 km and 150 km.

The rate at which plastic and rubber wastes are recycled can affect their availability for co-processing in the cement industry. The figure below shows the maximum co-processing potential for MSW (defined as the share of fossil fuel consumption that is replaced) for MSW collected within different radii around cement plants for three recycling rates: low (4%), medium (55%) and high (90%).

Figure 24. Maximum Co-Processing Potential for Different LAC Recycling Clusters and Scenarios





Source: Elaboration based on FICEM Potential Value of Cement Industry Residuals in LAC to 2030. (Pinilla C., 2021).

The results reveal that by 2050, the cement industry could meet between 40 % and up to 100 % of the energy demand needed for clinker production, with moderate or low recycling rates, without using organic waste. These findings underline the significant contribution that the co-processing of wastes such as plastics, rubber, paper and cardboard can make to the cement sector on its path to sustainability.

5.3.1.4 Technical Viability

International experience has shown that fossil fuel substitution rates can reach 80-100% in precalciner processes and 50-60% in the calcination process (Sharma et al., 2022) using tailored pre-combustion technologies and advanced burner designs such as multichannel and satellite burners. Operational challenges to using alternative fuels include incomplete combustion of residues, increased specific heat consumption, reduced flame temperature, and coating buildup in the kiln.

Factors affecting the technical viability of co-processing include the following (Jensen in 2016):

1. **Calorific value:** While modern cement kiln precalciners can use relatively low calorific value fuels, fuels for main combustion must have a net calorific value greater than 20 GJ/t (ECRA, 2022). MSWs must therefore be selected and separated to provide a high energy content fuel.

2. **Moisture:** Fuels with moisture levels of more than 20% affect cement kiln heat consumption and reduce production efficiency. Some alternative materials, such as organic food waste, which have a high moisture content and low net calorific value, may be suitable after undergoing thermal drying and milling to increase their net calorific value. However, this approach requires pre-processing equipment, such as dryers and mills, along with additional systems such as filters to manage waste gases.

3. **Particle size:** Fuel particle size affects process performance and efficiency. Particles that are too large may have difficulty igniting and burning completely, which reduces efficiency and can result in unwanted emissions. Particles that are too small may burn too fast, which can also be inefficient and result in uncontrolled emissions.

4. **Ash content:** Ash composition can have a significant impact on clinker quality. To ensure optimal results, specific ash characterization and control measures must be implemented.

5. **Chlorine content:** Chlorine can clog ducts or cyclones due to salt precipitation. A chlorine bypass system at the kiln inlet is required to manage chlorine effectively. Separating out chlorine-rich materials during the pretreatment stage is also critical.

Experience to date supports the technical viability of using alternative fuels derived from solid wastes effectively in the cement industry.

5.3.1.5 Economic Viability

A number of factors influence the investment required for MSW pre-processing and co-processing, including the amount of waste to be treated, the types of alternative waste-derived fuels and feedstocks used, the degree of pre-processing required, and potential required upgrades to the cement kiln systems, as well as the required waste storage and handling systems (GIZ, 2020). Variables that determine the economic viability of co-processing include the following (Jensen, 2016):

1. **Conventional fuel costs:** the cost per unit of thermal energy to be replaced and, as a result, saved by using alternative fuels. The comparison takes into account the total cost up to the burner input, including all costs for procurement, transportation, storage, preparation, and delivery to the kiln.

2. **Waste management logistical costs:** the cost of transporting waste from its place of origin to the pretreatment facilities. These costs are directly proportional to transportation distances.

3. **Waste management costs and/or revenues:** the payment for waste treatment. Payment may constitute a cost when waste is purchased or a revenue if the cement facility is able to charge for waste management services such as collection, separation, and pretreatment services provided to the waste generators.

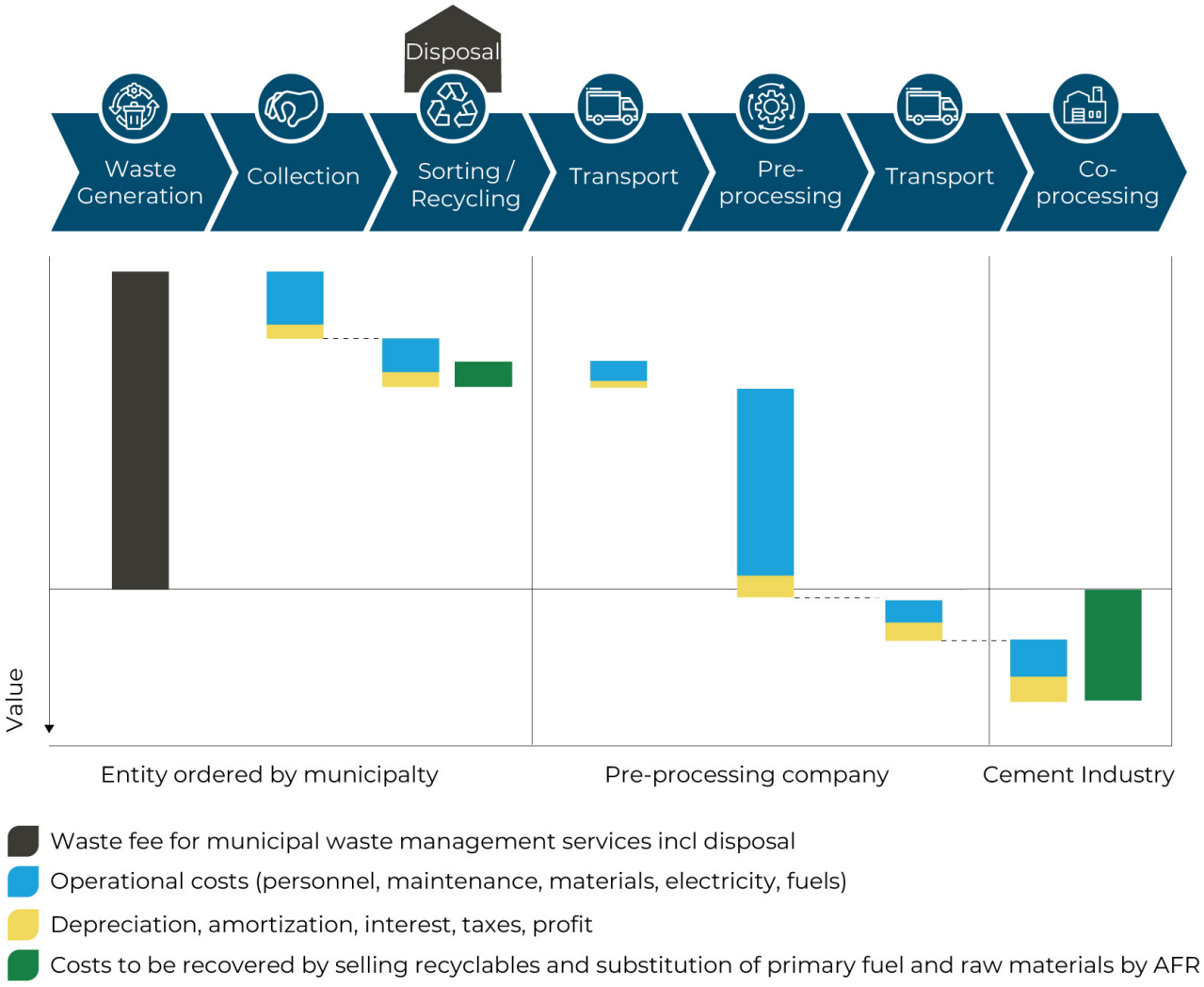
4. **Preprocessing costs:** the cost of sorting, shredding, and blending waste. Investment in facilities and equipment, as well as operating expenses, will vary according to the type and volume of materials subjected to pre-processing.

5. **Alternative fuel transportation costs:** costs derived from transporting pre-processed waste to the cement plant facilities.

6. **Receiving and kiln feed costs:** costs for the facilities and equipment that receive, store, transport, and supply alternative fuels to the cement kiln.

The figure below shows MSW costs and revenues along the value chain going from waste management at the municipal level to pre-processing and co-processing at the cement plant.

Figure 25. Costs and Revenues in the MSW Recovery and Pre- and Co-Processing Value Chain



Source: Elaboration based on GIZ (2020).

Revenues are generated from recycling and savings from primary fuel substitution. Costs include MSW collection, sorting, transportation, pre-processing, and co-processing, as well as equipment and facility related expenses.

In an ideal scenario, savings from substituting fossil fuels should cover the investment in the rest of the chain. In practice, though, this rarely happens. In many cases, those responsible for waste management and disposal are required to pay a management fee for the cement industry to take the waste.

To establish co-processing as a long-term waste management option, municipalities, waste management companies, and cement companies must understand the financial implications of pre- and co-processing. Charging waste generators a fee allows for cost-sharing of waste management with the municipal budget. Increasing this waste disposal fee may, in turn, make other waste management alternatives financially viable.

In middle- to low-income countries, local authorities generally avoid disposal fees that exceed landfill costs. This creates a challenge for municipalities, as it is difficult for them to generate sufficient revenues to compensate cement producers for managing municipal solid waste.

In some cases, authorities expect cement producers to pay for the waste because they believe it must have some value if it is used as fuel in cement kilns. This causes a dilemma, since cement producers consider the use of alternative fuels derived from waste a cost-control strategy. If they are willing to pay, the payment will probably not exceed preprocessing operating costs, implying that the main beneficiary could be the preprocessor rather than the municipality.

The costs associated with pre-processing must therefore be considered. If paying for this step (or purchasing waste at a price that includes preprocessing costs) is not viable for the cement producer, co-processing becomes an unviable option under typical financial conditions in most low- and middle-income countries. Simulations carried out in a Mexico case study (Jensen, 2016) suggested that the payment for waste management should reach US $20 per ton in order for MSW co-processing to be economically viable.

5.3.1.6 Hydrogen

Hydrogen can reduce cement industry CO_2 emissions as it releases only water (H_2O) when burned, thus producing no CO_2. The main challenge lies in ensuring sufficient carbon-neutral energy to produce H_2. Currently, H_2 use as kiln fuel is minimal. By 2050 it is projected to constitute up to 10% of the kiln energy matrix (ECRA, 2022).

Hydrogen and Municipal Solid Waste Synergies

Substituting fossil fuels with hydrogen or co-processing municipal solid waste (MSW) in clinker kilns can potentially play a key role in cement industry decarbonization. Burning hydrogen produces only water (H_2O), eliminating CO_2 emissions from fuels, while MSW is considered a carbon-neutral fuel. Burning MSW to produce clinker may also avoid methane generated in landfills, given that the biomass fraction available in these fuels does not decompose anaerobically at these sites.

Burning hydrogen and MSW together can also overcome the technical challenges posed by each when combusted separately. Hydrogen burns at more than twice the temperature required for clinker production. MSW can burn at a temperature that is too low, depending on its component materials. Combining the two fuels can allow the kiln operator to achieve the required temperature more easily.

Adopting either alternative fuel faces challenges. Hydrogen requires specialized infrastructure for its use and storage and is currently more expensive traditional and alternative fuels derivered form waste. For MSW, barriers include the logistics and commercial arrangements to collect and deliver adequate and consistent volumes at a resonable cost.

5.3.1.7 Technical viability

In 2022, the UK's *Fuel Switch* project (BEIS, Mineral Products Association) conducted the largest known kiln test of net zero carbon fuel blends in the primary burner. One of the trials included hydrogen/biomass blending, in which hydrogen achieved a 40% share of the thermal energy used in the kiln's primary burner (Mineral Products Association et al., 2022). This study concluded that using hydrogen in primary burners is technically feasible and that incorporating the required equipment does not pose a significant challenge.

Because hydrogen has low energy density per unit volume, it requires a considerable amount of space and specialized materials for safe storage. Hydrogen storage and distribution infrastructure is currently limited; large-scale hydrogen deployment will require significant investment.

The European Cement Research Academy (ECRA, 2022) has qualified the use of hydrogen in the cement industry as a developing technology, giving it a technology readiness level (TRL) of 6. This level indicates that the technology has been tested and validated in a relevant environment and shown to be feasible and effective under conditions that resemble operational conditions.

Looking ahead, ECRA predicts the use of hydrogen as a cement industry fuel could reach a TRL of more than 8 by 2040, meaning that by then the technology will have passed field trials and is implemented on a large scale, demonstrating its performance and reliability in normal cement industry operations.

5.3.1.8 Economic Viability

The Fuel Switch (BEIS, Mineral Products Association) project showed that adopting hydrogen as a fuel could cost €1,559 per avoided ton of CO_2. In this assessment, capital expenditure (CAPEX) turned out to be negligible compared to operating expenditure (OPEX), which encompasses the cost of hydrogen, its transport, storage, and use.

In the current context, using hydrogen-enriched net-zero carbon fuel blends is not economically attractive compared to implementing carbon capture, use, and storage (CCUS) measures. Even if renewable hydrogen were available at the current price of gray hydrogen, the cost-benefit ratio does not favor its adoption. Although the avoided cost of CO2 through CCUS is currently uncertain, previous research has indicated that it should be in the range of €55 to €170/tCO_2, provided certain technical and economic conditions are met and the entire CO_2 value chain is covered from capture to storage. This suggests that the cost of hydrogen at the burner tip would need to be twelve times lower in order to compete with the avoided cost of CO_2 through CCUS (Mineral Products Association et al., 2022).

5.3.1.9 Process Electrification

Electricity can generate heat for cement production through a variety of technologies, including plasma technology, induction heating, resistive electric heating, and microwave heating. Replacing fuel combustion with electricity can potentially remove 35% of cement manufacturing CO_2 emissions.

Cement industry electrification was deemed to have a TRL of 4 in 2022, indicating that it has been validated in laboratory environments. However, by 2030 it is projected to reach a TRL above 8, indicating that it would be tested, qualified, and ready to be implemented safely and competitively (ECRA, 2022).

In 2022, the Technical Research Centre (VTT) of Finland completed a series of experiments involving various raw materials in its electrically heated rotary kiln (VTT, 2022). A proof-of-concept for the electric kiln was performed at the precalcining stage, which allowed the raw material to reach an intermediate state in the thermal process. Although this achievement is significant, work still needs to be done to achieve higher temperatures for reaction with the silica and completion of the calcination process.

In addition, in 2022, CEMEX and the Finnish-Dutch company Coolbrook signed a memorandum of understanding to explore an innovative technology aimed at electrifying the cement kiln heating process (CEMEX, 2022). This technology, known as the roto dynamic heater (RDH), is able to achieve extremely high temperatures of around 1,700 degrees Celsius using electricity alone, a requirement for producing cement with state-of-the-art materials. The companies planned to have this revolutionary technology ready for industrial-scale implementation by 2024.

5.3.2 Carbon Capture

5.3.2.1 Technological Development

The cement industry has been investigating carbon capture technologies for approximately 15 years. Carbon capture's technical feasibility in the cement industry has been demonstrated at varying levels for different technologies. The table below gives the TRLs for nine cement industry carbon capture technologies.

Table 2. Technology Readiness Level (TRL) of Carbon Capture Technologies in the Cement Sector

Technology	TLR to 2022	Expected Applicability in Industry (TRL > 8)
Oxyfuel	6: Demonstrated in a relevant environment	2025
Absorption -Monoethanolamine (MEA)	8-9: Complete, qualified, and tested in a real environment	2022
Membranes	4-5: Validated in laboratory and in a relevant environment	2030-2040
Cryogenic capture combined with pressure swing adsorption	5-6: Validated and demonstrated in a relevant environment	2030
Adsorption by temperature change	6-7: Prototype demonstrated in a relevant environment	2030
Ca-Looping, tail end (CFD reactors)	7-8: Prototype demonstrated in a relevant, complete, and qualified environment	2025
Ca-Looping, integrated (built-in flow reactors)	6-7: Prototype demonstrated in a relevant environment	2030
Indirect calcination		2025
Mineral carbonation	5-6: Validated and proven in a relevant environment	2030

Source: Elaboration based on ECRA (2022)

Several industrial-scale projects are expected to be operational before 2030, paving the way towards commercialization (with TRL>8). The cement industry is expected to apply a combination of these technologies as carbon capture technology choice is highly site-specific. CO_2 emission reductions and carbon capture energy consumption are also site-specific. To illustrate this complexity, the table below summarizes the factors influencing CO_2 emission reductions and energy consumption, along with the expected capture rate for each technology.

Table 3. Factors Influencing CO_2 Capture and Energy Consumption

Technology	Factory Influencing CO_2 Reduction Potencial and Energy Consumption	Capture Rate
Oxyfuel	Oxidant purity (influences energy demand) Design (with or without exhaust gas recirculation, full or partial application) CO_2 processing unit power consumption and the oxygen supply system CO_2 purification separation ratio. Additional impurity removal Seals condition (air inlets to the system)	90-95
Absorption - Monoethanolamine (MEA)	Absorption process type. Amine scrubbing requires steam, while the SkyMine process requires a large amount of energy for chlor-alkali electrolysis. Steam availability and source. Use of waste heat to match regeneration energy demand boosts the capture rate by up to 50%. Acid gas load (SO_2 , NO_2).	>95
Membranes	Membrane properties Ignoring technologies to purify, process and transport the captured carbon dioxide	>80
Cryogenic capture combined with pressure swing adsorption	Process type, sorbent agent, and reactor affect energy demand. Impurity removal to meet downstream process requirements	>95
Adsorption by temperature change	Process type, sorbent agent, and reactor affect energy demand.	>90
Ca-Looping, tail end (CFD reactors) Ca-Looping, integrated (built-in flow reactors)	Absorbent agent type Degree of integration (amount of the CaO-rich purge stream used as raw material in the cement plant) CO_2 target purity Fuel type Tightness of the oxygen calciner and downstream equipment	>95
Indirect calcination	May need to add a CO2 purification step which would affect investment and operating costs. To achieve higher capture rates, additional capture of CO2 emissions from the main burner or carbon removal from fuels and electricity will be required.	>60
Mineral carbonation	Process type (direct/indirect carbonation) Raw material type Mineral pretreatment Capture rate depends on process conditions, such as exposure time, pressure and temperature. Additional electrical power is required for crushing and grinding, as well as for gas compression.	>90

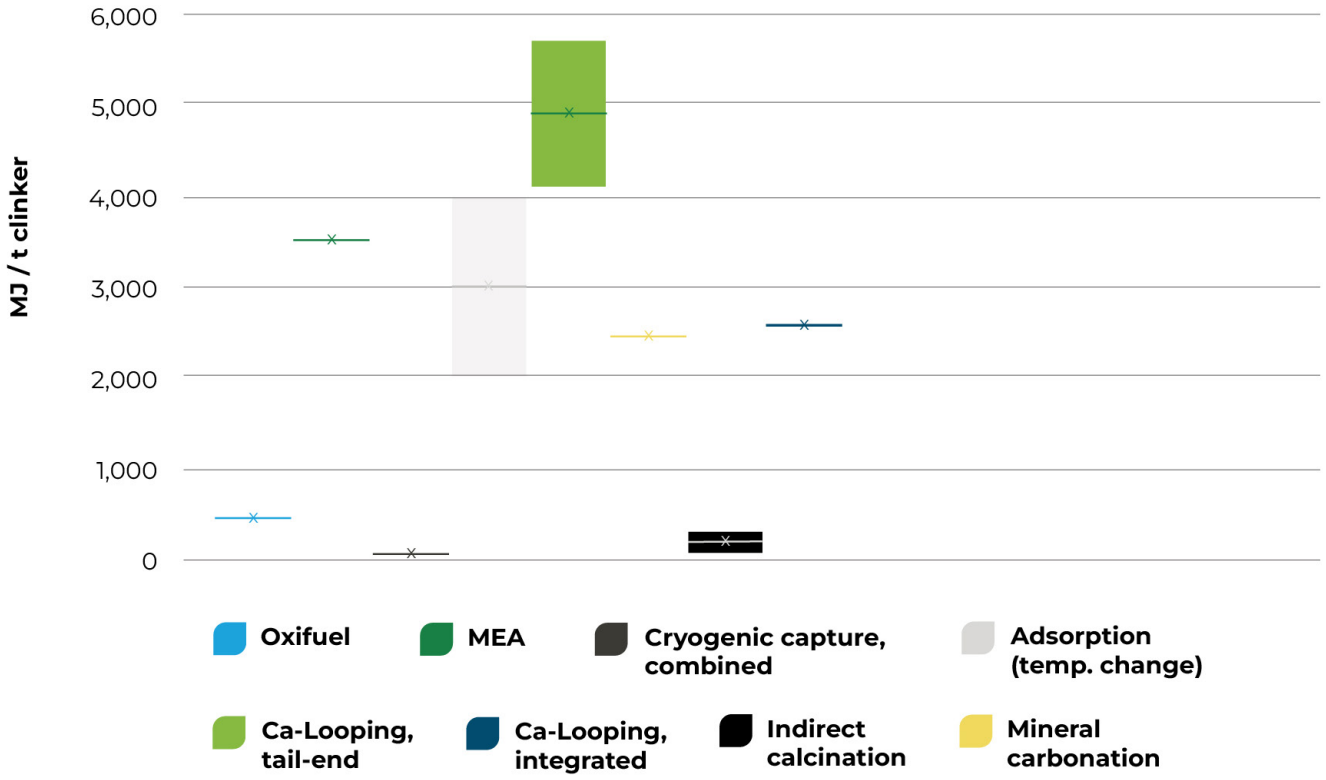
Source: Elaboration based on ECRA (2022).

5.3.2.2 Power Consumption

All carbon capture technologies require additional thermal and/or electrical energy to carry out processes such as CO_2 separation, purification, and compression/liquefaction. Oxyfuel, combined cryogenic capture, and indirect calcination technologies require less thermal energy compared to the other available alternatives.

Based on a global average energy consumption of 3,560 MJ/t of clinker, the carbon capture technologies with the lowest energy demand are estimated to increase thermal energy consumption by between 6% and 13%, on average. Technologies with higher energy demand could result in an average increase in energy demand ranging from 70% to 140%. The figure below illustrates the additional energy demand from implementing various carbon capture technologies in clinker production.

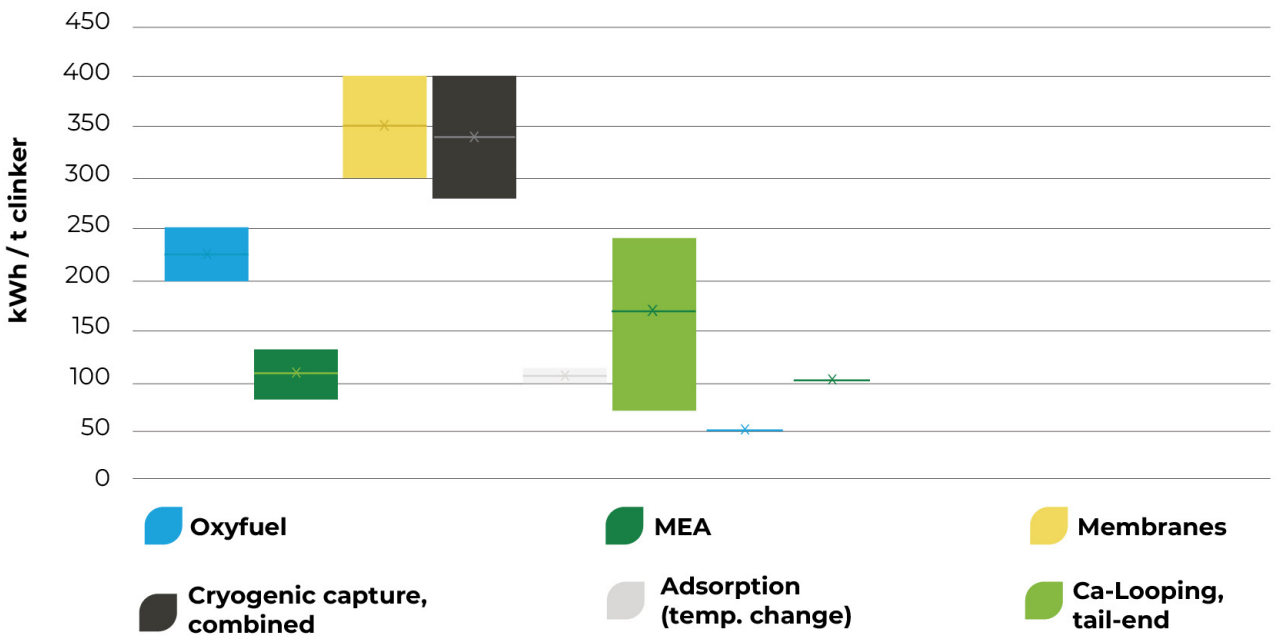
Figure 26. Thermal Energy Demand for Different Carbon Capture Technologies



Source: Prepared in-house based on data from ECRA (2022).

Similarly, electricity demand could increase significantly. Based on a global baseline electricity consumption of 102 kWh per ton in clinker production, energy demand linked to carbon capture would increase by an average of 100% to 300% for most technologies. This growth in energy demand would lead to a corresponding increase in indirect CO_2 emissions unless electricity is provided by carbon neutral sources. The figure below describes the electricity requirements for various carbon capture technologies.

Figure 27. Electrical Energy Demand for Different Carbon Capture Technologies



Source: Prepared in-house based on data taken from ECRA (2022).

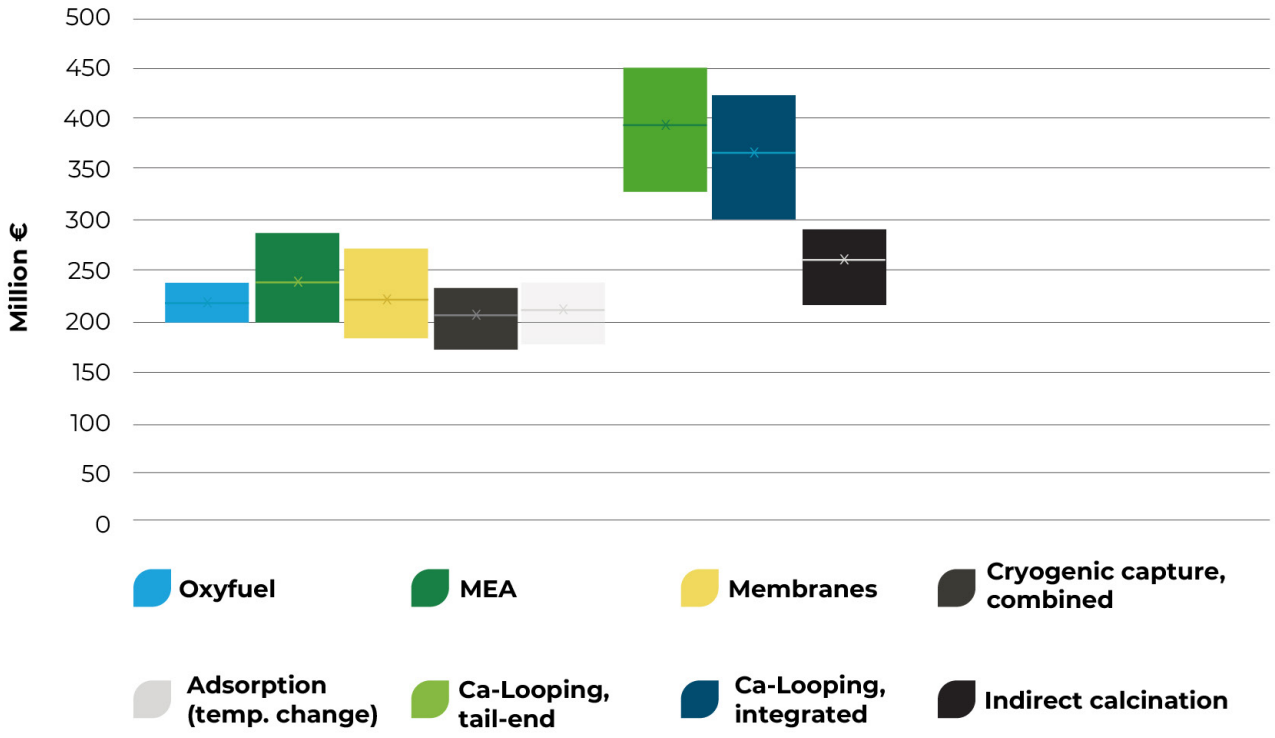
5.3.2.3 Investment and Operating Costs

Estimated investment and operating costs for various carbon capture technologies by 2050 are shown in Figure 28 below. This information was taken from ECRA (2022) and is based on the following: i) 6,000 tons per day production capacity; ii) investment figures and operating costs using 2020 as a reference point; and iii) investments focusing exclusively on the carbon capture process, excluding any site-specific investments such as temporary CO_2 storage, energy supply improvements, demolition of obsolete equipment, water treatment, or transport and storage.[152]

The carbon capture technologies with the highest required investment are Ca-looping technologies, which cost between 300 and 400 million euros for a new facility and roughly 15% more to renovate an existing facility. Other technologies require more moderate investments of 200 to 250 million euros for building a new facility, as shown in the figure below.

[152] These site-specific investments may require up to 100% additional investment compared to the figures for the capture plant.

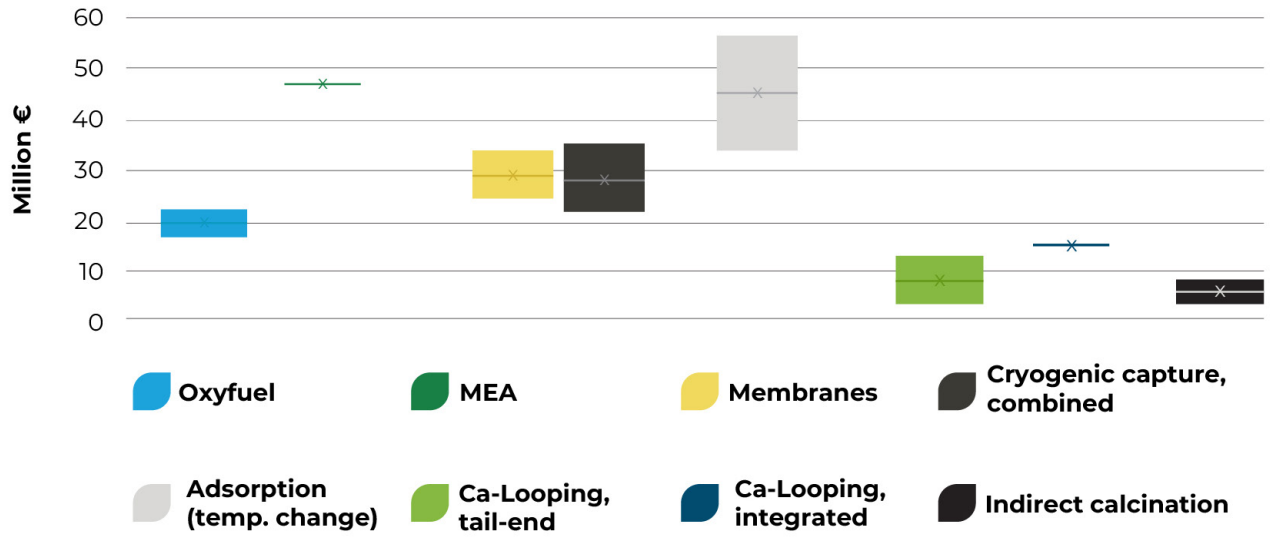
Figure 28. Investment Costs for Different Carbon Capture Technologies (New Installations)



Source: Prepared in-house based on data from ECRA (2022).

Each technology's operating costs also vary. Ca-looping and indirect calcination technologies offer lower incremental operating costs in clinker production, averaging less than 10 euros per ton. Technologies such as MEA and temperature exchange adsorption have higher operating costs, exceeding 40 euros per ton of clinker, as illustrated in the figure below.

Figure 29. Clinker Production Operating Cost Increase for Different Carbon Capture Technologies



Source: Prepared in-house based on data taken from ECRA (2022).

5.3.3 Supplementary Cementitious Materials

5.3.3.1 Development and Applicability

Incorporating supplementary cementitious materials (SCMs) instead of clinker leads to a proportional reduction of CO_2 emissions in cement manufacturing. SCMs have been extensively researched and are at a high level of technological development, generally exceeding TRL 8, especially for the industry's most commonly used SCMs. These include:

- **Fly ash:** produced by electrostatic or mechanical precipitation of dust-like particles from coal combustion gases.
- **Pozzolans:** siliceous or aluminum-silicate materials that naturally occur from volcanic eruptions.
- **Calcined clays:** Raw materials artificially produced through calcining clays (shales or sedimentary rocks).
- **Slag:** a solid by-product from manufacturing iron in iron and steel blast kilns.
- **Limestone:** a sedimentary rock, mainly composed of calcium carbonate, commonly used as a filler material, although its contribution to the strength of hardened cement paste is limited.

Integrating SCM depends on regional availability, national standards, material properties and prices, and the intended use of the concrete in which the cement is used. Among these factors, availability is typically the most critical. For example, slag availability depends on the location and power of iron blast kilns. However, steel industry decarbonization is shifting production from blast furnaces (BF) to direct reduced iron (DRI), which does not produce slag. This is expected to reduce both the amount of available slag and its suitability as a cement component.

Fly ash is generated in coal-fired power plants, although not all fly ash is suitable for cement or concrete production. Coal power plants are also significant carbon emitters and coal-fired power capacity is expected to decline as renewable energy sources increase, thereby also decreasing fly ash availability.

Natural pozzolans and clays for calcination are a common resource, although there is limited data on their future availability for the cement industry. Limestone, used in clinker production, is available to most cement plants and is expected to be available worldwide on a virtually unlimited basis, although pure, high-quality limestone may be limited in certain regions.

By 2050, average cement compositions are estimated to contain between 8% and 16% calcined clays or natural pozzolans and to possibly achieve 20% limestone (ECRA, 2022). Recent advances in determining the optimal combinations of these materials have led to a 50% reduction in clinker dependence and a 30% reduction in CO_2 emissions without sacrificing performance compared to conventional cement (Miller et al. in 2021). Using calcined clays and limestone produces "LC3" cement, which resembles current commercial cement and could therefore face fewer future distribution hurdles compared to other more innovative cement formulations (as mentioned by Fennel et al. in 2021).

Use of Granulated Blast Furnace Slag (GBFS) as a Raw Material in Cement

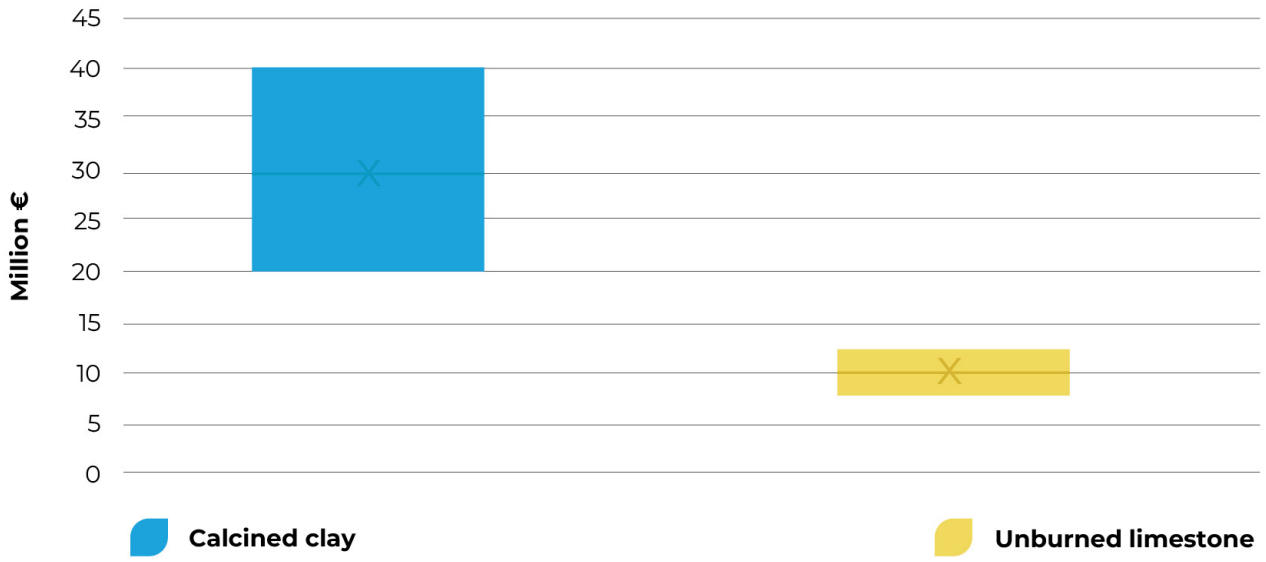
Using GBFS as a supplementary material in cement significantly reduces the carbon footprint of the production process. Since GBFS is a waste product from steel production, using it instead of clinker directly reduces the CO_2 emissions and energy consumption associated with clinker production. In practice, cement can reach up to 70% GBFS, improving its sustainability and resistance to sulfates and chlorides and reducing hydration heat, making it ideal for large infrastructure projects. GBFS quality and quantity available in the future, however, will depend on the steel industry's development as some more efficient steel production processes do not create GBFS waste.

5.3.3.2 Investment and Operating Costs

Cost projections to 2050 for calcined clay use and high limestone contents are presented below. The estimates are based on a 3% by mass of natural calcined pozzolan content compared to Portland cement with 95% by mass of clinker. For limestone use, a 95% by mass of clinker content reduction relative to Portland cement is assumed by using 0.45t of unburned limestone per ton of cement at 50% by mass in limestone-containing cement.

By 2050, cement industry investment to incorporate calcined clays as SCMs will range from 20 to 40 million euros. This budget will cover new facility costs and costs to expand clay storage capacity. Investment costs to increase limestone use will be lower since they will mainly require refurbishment to increase limestone storage and handling capacity. These costs are shown in the figure below.

Figure 30. Investment Costs for Use of Calcined Clays and Limestone as SCMs (New Facilities)



Source: Prepared in-house based on data taken from ECRA (2022).

Operating costs are expected to decrease when using both raw materials, driving clinker production costs lower. Calcined clay operating costs are expected to decrease by 3.6 euros per ton of product, while operating costs for substituting unburned limestone will decrease by 11 euros per ton of product.

5.3.4 Concrete Recycling

Recycled concrete fines, which are produced during the crushing process, have emerged as a promising source of material for cement manufacture. Crushed concrete fines can be used as a cement component and as raw meal in clinker production (Miller et al., 2021). These fines substitute for limestone in composite cement without requiring additional processing. Forced carbonation can be used to carbonate the residual $Ca(OH)_2$ and CSH phases present in recycled concrete fines, generating pozzolanic reactivity by forming an amorphous aluminum-silicate gel, which can be used as SCM to produce composite cements similar to fly ash (ECRA, 2022).

Approximately three tons of concrete are required to obtain one ton of recycled concrete fines. However, crushed concrete waste is rarely used to produce cement and concrete. Instead, virtually all of this crushed concrete waste is used in road substructures or mixed with soil material to improve its properties, such as providing frost resistance.

In 2022, using carbonated concrete fines reached a TRL of 6, indicating significant progress in their development and application while non-carbonated fines have reached a TRL of 9.

Challenges to increasing recycled concrete use in cement manufacturing include the following:

- **Product quality:** The process of transforming crushed concrete into recycled concrete fines, which involves separation, crushing, and fractionation, must be improved to obtain high-quality fines suitable as a cement component.
- **Transport and supply logistics:** A reliable and sustainable supply of recycled concrete needs to be established to ensure its availability. Long distances from the demolition site to the treatment and cement production facilities can be a significant barrier due to the costs and associated carbon footprint of transporting the concrete.
- **Limited forced carbonation system development:** Forced carbonation systems should be further developed, especially in existing cement plants. This involves improving flue gas CO2 capture and reducing the retention time needed to achieve efficient carbonation.
- **Dependence on calcium-rich phases:** Carbonation potential is mainly linked to calcium-rich phases in cement, such as clinker and slag. This may limit the applicability of recycled concrete fines in certain cement formulations.
- **Limited infrastructure development:** Recycled concrete processing requires adequate infrastructure development.

5.3.5 Electrical Efficiency in Cement Production

Approximately 70% of cement manufacturing electricity demand comes from raw material grinding and cement production itself. The following main factors influence electricity demand:

- **Grinding and separation technology:** Raw material crushing and cement production technologies are a major contributor to electricity consumption.
- **Cement quality and product portfolio:** The expected cement quality and the variety of products manufactured influence energy efficiency, as different formulations and processes may require different amounts of energy.
- **Emission reduction technologies:** Implementing emission reduction technologies such as carbon capture systems can affect electricity requirements.
- **Plant condition:** The condition and maintenance of the facilities can affect cement production energy efficiency.
- **Plant operation and flexibility:** The plants' operations and ability to adapt to demand fluctuations can impact energy efficiency.

Many cement-generating plants operate with 30-50 year-old equipment. Energy-saving measures are often not economically feasible in these older facilities. However, increasing the use of renewable energies and reducing the clinker/cement ratio in manufacturing will require additional grinding capacities for certain cement production lines. These anticipated upgrades will also create opportunities for the industry to move towards greater efficiency.

Specific electricity demand in cement processing (not including carbon capture) is projected to decrease from approximately 102 kWh per ton of cement in 2019 to around 100 kWh per ton of cement by 2030. This downward trend is projected to continue, reaching an average range of 90 to 95 kWh per ton of cement by 2050 (ECRA, 2022).

Two strategies to increase cement manufacturing energy efficiency (MGM International, 2018) include replacing standard motors with high efficiency motors and using vertical mills. These measures are described below.

- **Replacing standard motors with high-efficiency motors**

Cement plant electricity consumption is concentrated in the motors used for grinding, material conveyance, pumps, and fans. An estimated 500 to 700 motors, each with different capacities, operate in such a facility. Replacing old equipment (with 80% to 85% efficiency) with high-efficiency motors (with greater than 94% efficiency) could reduce motor energy consumption by 10-15%.

Motor modernization projects offer significant returns on investment with relatively short payback periods, generally 2-5 years, depending on the plant's energy costs and the size of the motor to be replaced. For motors with capacities above 300 kW, the specific investment is roughly US $75 per kW, while motors with capacities between 30 and 300 kW cost US $120 to $140 per kW. These investments translate into substantial improvements in energy efficiency and long-term savings for the plant.

- **Vertical mills**

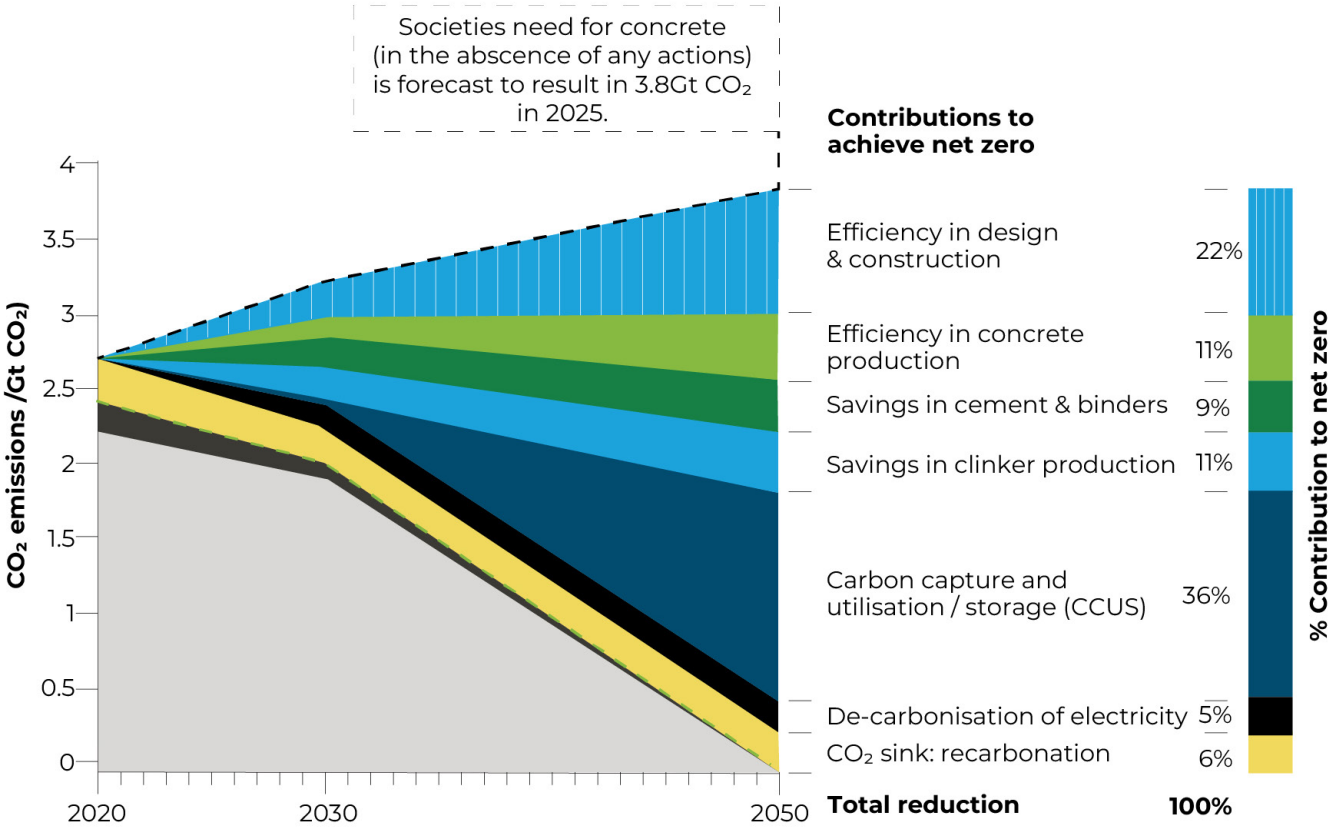
Implementing vertical mills instead of conventional ball mills can reduce the specific energy consumption for cement production grinding processes from a range of 55 to 70 kWh per ton to between 25 and 30 kWh per ton, depending on the desired size of the final grind. The required investment is estimated to range from US $2.5 to $8 per ton of annual cement production capacity. This initial expenditure typically has a 3 to 5 year payback period, depending on the plant's cost of electricity.

5.4 Decarbonization Pathways of the Cement Industry by 2050

5.4.1 Global Context

The Global Cement and Concrete Association (GCCA) has outlined a roadmap to align the cement industry with global targets in order to limit global warming to a 1.5 oC scenario. It presents seven measures to reduce CO_2 emissions across the cement and concrete lifecycle and evaluates their contribution to achieving zero emissions. According to the GCCA estimates, the cement industry's greatest impact on emissions reduction will come from implementing carbon capture technologies, closely followed by optimizing clinker production through incorporating alternative fuels and hydrogen and by using supplementary materials. The roadmap also highlights the value of electrification toward decarbonization. These contributions are shown in the figure below.

Figure 31. Zero-Emission Cement and Concrete, 2050



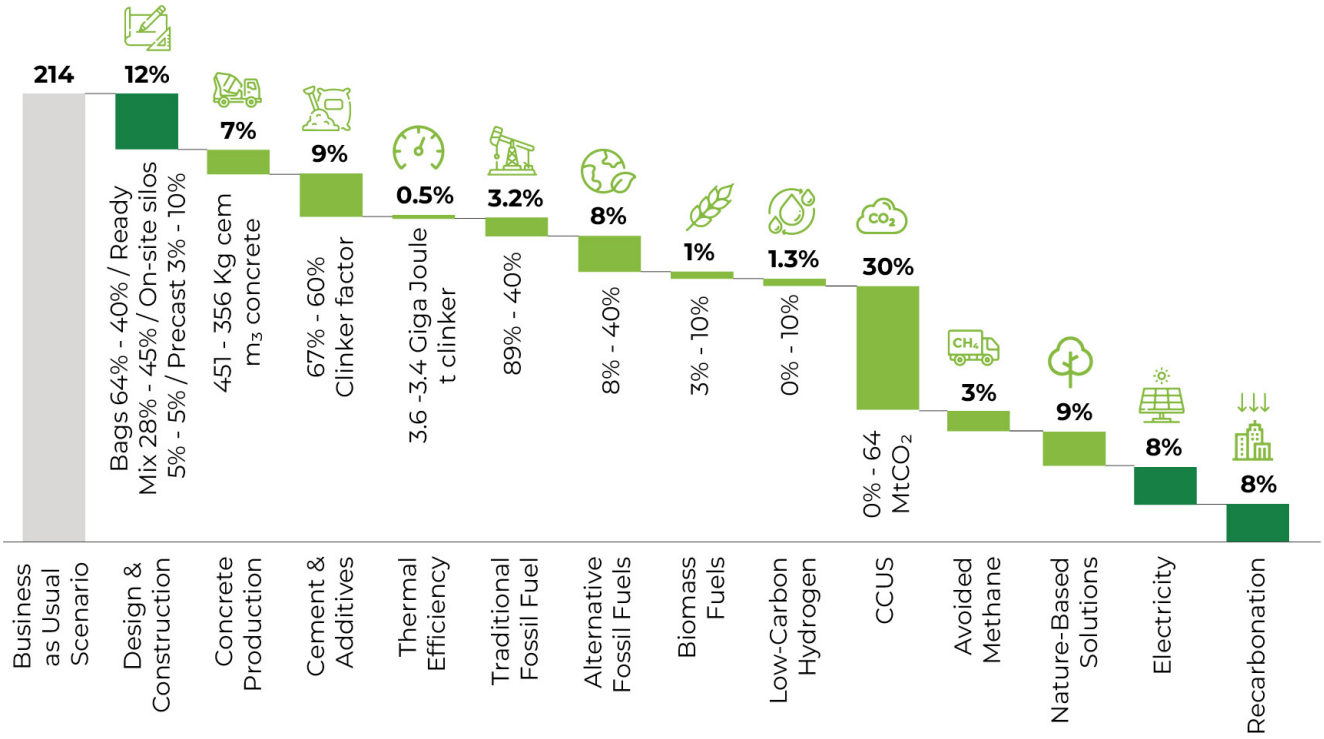
Source: Elaboration based on GCCA (2021).

In addition, the GCCA has launched the Net Zero Roadmap Accelerator Program to help national cement and ready-mix industries implement local decarbonization strategies and actions that are in line with the global roadmap.

5.4.2 Regional Context

FICEM has developed a decarbonization pathway approach for the LAC cement and concrete industry which is consistent with GCCA's global roadmap goals. This approach is illustrated in the figure below.

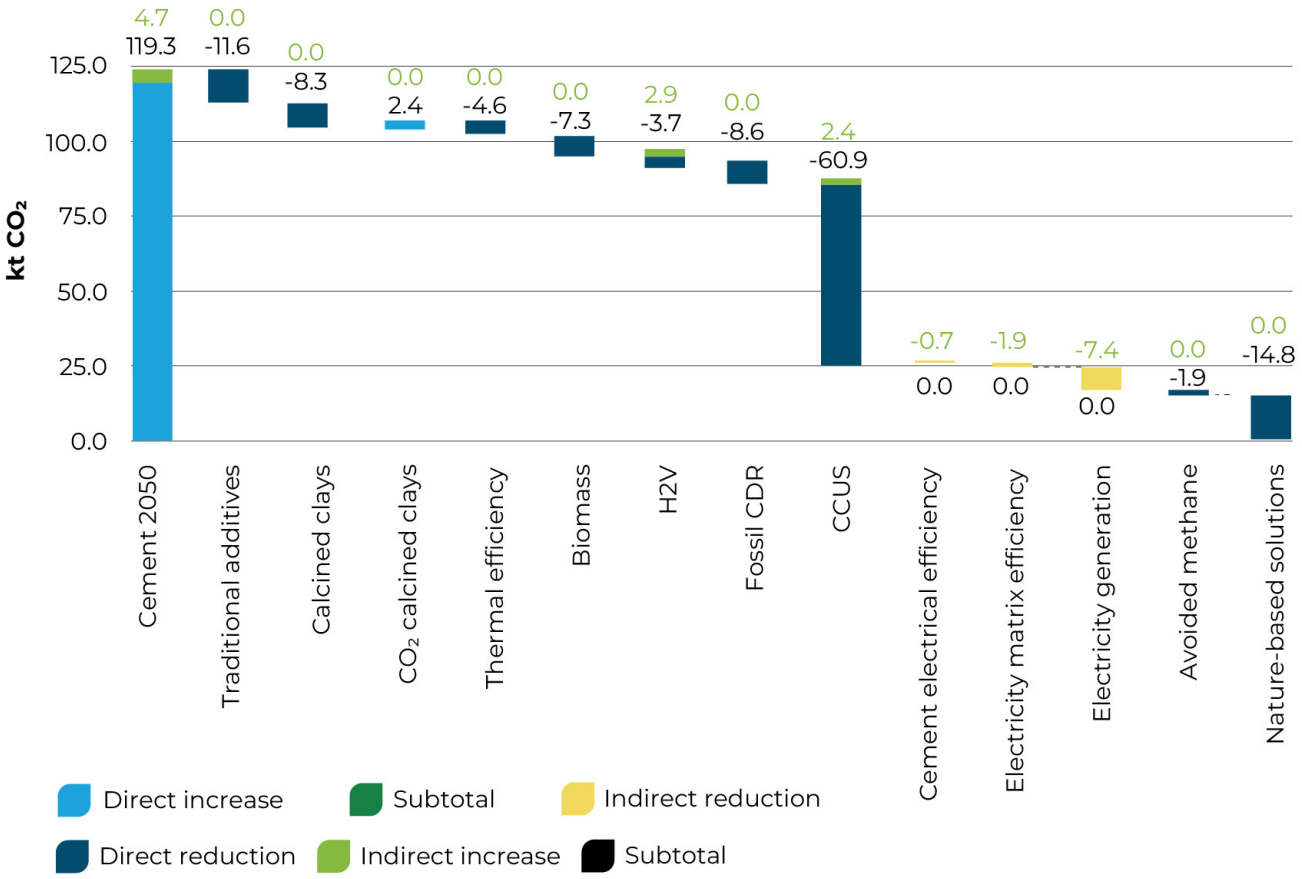
Figure 32. LAC Cement and Concrete Industry Decarbonization Pathway Approach



Source: Elaboration based on Pareja (2023).

The decarbonization pathways identify several measures to reduce cement industry emissions. Those with the greatest impact include CCUS (30% reduction), design and construction changes (12%), reduced clinker share in cement manufacturing (9%), and nature-based solutions to offset emissions (9%). Many of the proposed measures can reduce both direct and indirect cement industry emissions. The figure below shows the share that each measure would contribute to reducing cement industry direct and indirect emissions through 2050.

Figure 33. Zero Direct and Indirect Emissions for the LAC Cement Industry by 2050



Source: Prepared in-house.

5.5 Investments Under the Paris Agreement

5.5.1 UNIVERSALLY ALIGNED INVESTMENTS

Pathways to decarbonizing the cement industry that are universally aligned with the Paris Agreement (PA) include the following: (i) anticipated, planned, and organized replacement of carbon-intensive production processes; (ii) renewable or low-emission electrification of kilns or use of alternative fuels for heat generation in cement making processes; iii) efficiency measures to reduce process energy intensity, including the use of more efficient equipment and cement recycling; and iv) use of new technologies to reduce direct process emissions, such as carbon capture, use, and storage (CCUS) (IDB. 2019; IEA, 2022b).

Investment measures that are considered universally aligned with the PA therefore include those in which: i) their economic feasibility does not depend on fossil fuel consumption, processing, or transportation; ii) their economic feasibility does not depend on fossil fuel subsidies; and iii) the operation does not significantly depend on the direct use of fossil fuels. The table below shows cement industry measures that are universally aligned with the PA.

Table 4. Cement Industry Measures Universally Aligned with the PA

Measures	Conditions and Guidelines
Implementing energy efficiency improvements in cement manufacturing	Using higher energy performance technologies reduces the energy intensity of the processes and are therefore universally aligned with the PA. They are mature technologies in the cement industry proven to reduce fossil fuel and electricity consumption.
Displacing conventional fuels with green hydrogen in cement kilns	Green hydrogen is universally aligned with the PA because it displaces fossil fuel consumption. Producing hydrogen with renewable electricity maximizes emission reductions.
Electrifying cement manufacturing kilns using renewable electricity	Electrifying energy demand with renewable energy is universally aligned with the PA. Implementing renewable electrification displaces fossil fuel use and related emissions.
Producing renewable electricity for self-consumption	Producing renewable electricity is universally aligned with the PA. Implementing renewable electricity can mitigate 100% of the indirect emissions associated with cement industry electricity consumption.
Cement recycling using zero-emission processes and transportation	Recycling with electricity from renewable energy and electric transport is universally aligned with the PA.

Source: Prepared in-house.

5.5.2 UNALIGNED INVESTMENTS

According to the IDB Group Sustainable Energy Sector Guidelines (GN-2613-1), the IDB Exclusion List of the Environmental and Social Policy Framework (ESPF),[153] and the IDB Invest Environmental and Social Sustainability Policy (ESSP), investments inconsistent with the PA include activities related to the exploration and production of coal, oil, and gas.

For the cement industry this includes consuming energy from fossil fuels and processes that release carbon when treating raw materials. The table below lists measures applicable to the cement industry that are not considered universally aligned with the PA.

[153] The Exclusion List contains activities that are incompatible with the IDB Group's commitments to address climate change in coal, oil, and gas issues.

Table 5. Cement Industry Measures that are not Aligned with the PA

Measures	Conditions and Guidelines
Fossil fuel-based heat generation in kilns	Burning fossil fuels to generate heat in cement kilns is not aligned with the PA. Developing this infrastructure supports continued carbon emissions.
Fossil fuel-based power generation plants	Electricity generation plants based on fossil fuels are not aligned with the PA.

Source: Prepared in-house.

5.5.3 INVESTMENTS REQUIRING REVIEW

This section considers investments that can potentially align with the PA. They must demonstrate tangible changes and benefits in displacing carbon-intensive production processes in line with industry policies and national climate change goals. The table below describes measures that require validation to be universally aligned with the PA.

Table 6. Cement Industry Activities Requiring Validation of Alignment with the PA

Measures	Conditions and Guidelines
Blue hydrogen	Blue hydrogen is extracted from natural gas fields. If it can be produced without also releasing underground CO2 it would be in line with the PA. Producing blue hydrogen under zero-emission conditions raises costs and is therefore not competitive for industry project developers.
Replacing clinker with supplemental cementitious materials (SCMs)	SCMs such as fly ash and slag are waste materials that would be aligned with the PA but may have to be transported long distances for use in cement manufacture. Limestone and pozzolans must be mined and transported, which would likely involve fossil fuel consumption.
Displacing conventional fuels with MSW	Burning MSW in cement kilns may be aligned with the PA if disposing of the MSW by traditional means would have produced GHGs (such as incineration or methane emissions from landfills). Transporting MSW long distances for use in cement kilns may not be aligned with the PA.

Source: Prepared in-house.

6. Policy Roadmap for Individual Countries

The cement industry is central to infrastructure and housing development, but its competitiveness will increasingly depend on its ability to transition toward low-carbon cement production. Decarbonization is especially complex because of both the process emissions from calcination and the high reliance on fossil fuels for heat. Large-scale investment, strong policy frameworks, and funding for research and development are needed to enable the technological transition.

This section presents a roadmap, summarized in the table below, that governments can follow to decarbonize the cement industry. The policy recommendations are based on technological pathways identified in this chapter for cement decarbonization, which include replacing fossil fuels with alternative fuels and electrification, deploying CCUS, reducing the clinker-to-cement ratio by incorporating supplementary cementitious materials (SCMs), increasing concrete recycling, and improving energy efficiency. The recommendations are complementary to the work done by FICEM in the region.

Table 7. Summary of Cement Decarbonization Roadmap for LAC Countries

Period	Goals
2025–2030	Design national cement decarbonization strategies to 2050; review regulations and update codes to enable high-SCM cements and RCA in concrete; establish permitting for co-processing, alternative fuels, and CO_2 storage; expand efficiency improvements and promote no-regrets measures such as high-efficiency motors; design and launch early CCUS and SCM demonstration projects; implement national concrete recycling strategies; begin regional capacity building; and coordinate with and engage the EU on CBAM.
2031–2037	Implement embodied-carbon procurement and staged carbon pricing with revenue for recycling; mandate measurement, reporting, and verification (MRV), including Environmental Product Declarations (EPDs) and clinker-ratio/CO_2 disclosure; enable renewable PPAs, priority interconnection, and time-of-use tariffs; raise thermal substitution and begin electrification; scale SCM use by regional supply; establish municipal recycling hubs and launch full-scale pilots (H_2-ready burners, MSW co-processing, and CCS); and implement a finance toolbox (CfDs/carbon contracts, tax credits/grants/variable grants, blended finance/PPPs/project bonds).
2038–2045	Mandate emissions-intensity standards, minimum clinker substitution, and recycled-aggregate content; align trade/customs with CBAM; deploy CCS at scale and connect to shared CO_2 hubs; expand electrification and deepen industrial symbiosis (slag, bagasse ash, qualified by-products) and cluster logistics; prepare asset transition plans to repower/repurpose/retire least-efficient plants; shift finance to private capital with blended finance for shared infrastructure and promote competitive auctions/long offtake; scale reskilling and advanced control systems; harmonize safety/standards; and coordinate cross-border CO_2 hubs.
2046–2050	Tighten to near-zero standards; mandate high SCM substitution and full end-of-life concrete recovery; ensure all major plants have CCS or equivalent; make sure alternative fuels/electrification dominate heat; complete circular concrete systems embedded in codes and procurement; focus finance on O&M optimization, reinvestment/repowering and maintain just-transition funds and targeted innovation for next-gen binders and process breakthroughs; and use refinancing/securitization and transition bonds to lower long-term costs for assets and shared infrastructure.

6.1 Vision and Baseline

Cement production in Latin America varies widely in plant age, technology, and integration with construction supply chains. For governments drafting effective cement decarbonization strategies, the first step is to establish their national position within the cement value chain, whether as major producers (such as Brazil, Mexico, Colombia, Argentina, and Peru), importers, exporters, recyclers, or end-use consumers, and then determine the role they hope to play in a low-carbon cement future.

A baseline assessment should consider the availability of SCMs in the region, such as blast furnace slag from Brazil and Mexico's steel industries, fly ash from coal plants in Colombia and parts of the Caribbean (although declining with coal phaseout), natural pozzolans available in volcanic regions such as Central America, Mexico, and the Andes, and calcined clays with potential in Brazil and the Caribbean islands.

Producing countries should map clinker ratios, SCM substitution potential, alternative fuel supply chains, and CO_2 storage capacity, while assessing GHG emissions of operations and supply chains. Importing countries should consider the embodied-carbon requirements of their trade partners. A clear baseline analysis will enable governments to design tailored roadmaps that align industrial, energy, and trade policies with decarbonization and competitiveness goals.

6.2 2025–2030: Foundations and Early Demonstration Projects

6.2.1 Policies and Regulations

Governments should first set the direction by publishing national cement decarbonization strategies to 2050 that include modeled technology-adoption pathways, marginal abatement cost curves, and just transition considerations for regions most dependent on cement jobs.

Simultaneously, governments can review their regulations to remove regulatory bottlenecks that slow investment and innovation. For example, building codes and material standards can be updated to enable higher clinker substitution with locally available SCMs (e.g., pozzolans, calcined clays, slag, or fly ash). Standards that allow recycled RCA in structural and non-structural applications can be adopted or upgraded with clear performance criteria and quality control. Waste regulations can be modernized to enable MSW co-processing (including pre-sorting requirements, input specifications, and continuous emissions monitoring) and establish permitting for alternative fuels and hydrogen readiness (especially safety codes and burner certification). Governments can also create a complete CCUS legal framework covering capture, transport, and storage, including site screening and liability. Finally, establishing criteria and mandating disclosure and MRV of emissions intensity, clinker-to-cement ratios, and environmental product declarations (EPDs) will ensure that decarbonization efforts are grounded in fact.

6.2.2 Projects, Technologies and Infrastructure

Early action should focus on identifying champion companies that want to decarbonize, cutting emissions in the short term through existing measures, and de-risking innovation to scale decarbonization efforts in the medium and long term.

Governments should also promote “no-regrets” measures. For fuels and efficiency, this can include increasing alternative fuels in the precalciner and kiln (biomass and RDF), deploying waste-heat recovery, and implementing digital optimization and advanced process control. In grinding and auxiliaries, cement producers can replace ball mills with vertical roller mills, where viable, and install high-efficiency motors.

During this phase, demonstration projects should also be designed and launched to validate technologies that can be later scaled, including CCUS, hydrogen and MSW trials where feasible. For materials, producers can run clinker-substitution demonstrations matched to local SCM availability, supported by quality and durability protocols. In urban areas, pilot concrete-recycling systems can be created to test logistics, contamination control, and RCA upgrading (crushing, cleaning, grading) so that recycling infrastructure is ready when procurement rules tighten.

For next stages, governments and technical assistance can undertake studies to design logistics platforms that connect SCMs to demand centers and channel slag from steel hubs. Further analysis of MSW supply chains could also reduce reliance on distant suppliers and cut transport emissions. For CCUS, site studies and mapping of potential CO_2-hub corridors near industrial clusters would be an important first step.

6.2.3 Funding and Incentives

In Brazil and Mexico, the CIF Industry Decarbonization Program can anchor first movers. Other countries should launch similar blended-finance platforms that support private capital with the support of MDBs and climate funds. Countries should also design a combination of supply-side incentives (accelerated depreciation, tax credit benefits, grants for demonstration projects, and

viability gap support for RCA and MSW) and demand side de-risking such as infrastructure public procurement with CO_2 intensity thresholds. MDBs can also support these efforts through instruments such as loans, guarantees, and results-based financing.

6.2.4 Capacity Building and Regional Cooperation

MDBs, cooperation agencies, and governments should join forces to build capabilities across the cement value chain, including SCM testing and certification, RCA quality management, MSW co-processing operations (pre-sorting, emissions control), hydrogen safety, CCUS operations, and digital energy management. They should also help municipalities, waste operators, and cement companies understand the logistics and economics of pre- and co-processing MSW, including contracting models and quality specifications. Embedded just-transition measures, such as reskilling programs and community engagement, should be launched to manage upgrades, fuel shifts, and any potential asset retirements.

Regionally, governments should harmonize SCM definitions and testing protocols, RCA performance standards, and co-processing emission limits while strengthening local and regional value chains to reduce dependence on distant suppliers, cut transport emissions, and develop regional SCM and RCA markets. Governments can also coordinate planning for cross-border CO_2 hubs where storage basins are shared and engage early with the EU on CBAM alignment.

6.3 2031–2037: Scaling and Infrastructure

6.3.1 Policies and Regulations

Governments should begin adopting embodied-carbon standards in public procurement for cement and concrete to create predictable demand for low-carbon products. They can also introduce carbon pricing for cement and concrete domestic production and imports through a staged pathway:

- **Phase 1 (Transition):** Initial measures include implementing shadow pricing and mandatory reporting; running a demonstration ETS or carbon tax sandbox with a low initial rate and simplified compliance; and offering transitional free allocations/rebates to address leakage and protect trade-exposed firms.
- **Phase 2 (Scale-up):** Later, governments can move to full pricing with a transparent price corridor, broadened coverage, and border measures aligned with international regimes, such as the EU CBAM. Part of the revenues earned in this phase should go towards funding decarbonization and just-transition programs.

Simultaneously, governments can mandate disclosure of clinker ratio and CO_2 intensity using standardized MRV, establish a complete permitting framework for CO_2 hubs and transport/storage infrastructure (site screening, MRV, liability, third-party access), and reflect emerging industrial loads in power-system planning to enable priority grid connections (without competing with residential loads) and tariff designs that reward flexible, off-peak electrified heat.

6.3.2 Projects, Technologies and Infrastructure

In this phase, thermal fuel substitution rates should rise significantly. Process electrification should also begin in the region. SCM adoption should scale across the region, especially slag in Brazil and Mexico, calcined clays in the Caribbean, and natural pozzolans in Central America. Identifying synergies across industries, such as cement and steel, can expand the implementation of mitigation measures and improve their economic performance and access to key resources or infrastructure. Demonstration projects involving hydrogen-ready burners and MSW co-processing should also be scaled.

Recycling hubs should be established in major metropolitan areas. The first full-scale hydrogen and MSW and CCUS demonstration projects should be launched while next-generation demonstration projects continue to be supported.

6.3.3 Funding and Incentives

During this phase, a full toolbox should be implemented that incentivizes demand for low-carbon cement and cuts capital costs. Governments can introduce green public procurement with CO_2-intensity thresholds for cement/concrete and advance market commitments for low-carbon cement and concrete. For revenue certainty, governments can implement contracts for difference (CfDs) or carbon contracts to de-risk early CCUS and hydrogen deployments. On the capital side, they can pair tax benefits with grants or viability-gap support for front-end engineering and development (FEED), MSW pre-processing, and RCA plants, mobilize blended finance with MDBs, and tap green bonds and sustainability-linked loans (with KPI ratchets). For larger infrastructure projects, such as CO_2 pipelines, hubs, and recycling infrastructure, public-private partnerships (PPPs) and project bonds can be considered.

6.3.4 Capacity Building and Regional Cooperation

In this phase, governments should collaborate to enable trade by harmonizing SCM/RCA/co-processing standards, creating mutual recognition across countries, and establishing accredited regional labs and digital registries for quality and carbon data. Lessons from CCUS and hydrogen demonstration projects and recycling hubs should be shared regionally.

Regional low-carbon cement and SCM trade should be enabled, such as exporting pozzolans from Central America to Caribbean islands. Training for companies and governments should include bankable template contracts for MSW supply, RCA offtake, low-carbon product offtake, SCM testing, RCA quality, MSW pre-/co-processing (including emissions control and health, safety, and environmental [HSE] considerations), and just-transition solutions for reskilling displaced workers.

6.4 2038–2045: Transformation and Deployment

6.4.1 Policies and Regulations

Governments should move from enabling frameworks to binding performance by mandating progressively tightened emissions-intensity standards for cement and setting minimum clinker-substitution thresholds, where supply chains allow, complemented by minimum recycled-aggregate content in public works. They should also align customs and trade with global low-carbon rules (including the EU's CBAM), require product-level environmental product declarations, and streamline multi-year permits for CCUS and CO_2 networks. Clear transition packages, such as reskilling and supplier programs, should be implemented at the same time for communities and firms affected by retrofits or retirements.

6.4.2 Projects, Technologies, and Infrastructure

During this phase, the focus should shift from demonstration projects to large-scale deployment while still supporting innovative ideas that promote decarbonization and efficiency efforts. For example, CCUS should be installed at scale on large kilns and plants connected to shared CO_2 hubs with third-party access, where available. Electrification in grinding and auxiliaries should be expanded and energy efficiency measures should continue to be rolled out. Industrial symbiosis can also be deepened (such as using steel slag and other qualified by-products in blended cements) and fuel pre-processing and logistics can be coordinated across clusters. Asset transition plans can also be used to repower, repurpose, or retire the least-efficient lines while safeguarding production security.

6.4.3 Funding and Incentives

As technologies mature, private capital should dominate with public support narrowing down to large infrastructure projects such as networks and hubs, de-risking at scale, and just-transition needs. Governments and MDBs should continue with blended finance for CO_2 systems and recycling hubs (such as providing first-loss financing, guarantees, and political-risk cover) and promote competitive auctions and long-term offtake agreements for green cement and concrete. Carbon-pricing revenues should be recycled into decarbonization efforts, CO_2 networks, and community transition funds. Transition bonds, sustainability-linked loans with KPI ratchets, and project bonds for hub infrastructure should continue to be unlocked.

6.4.4 Capacity Building and Regional Cooperation

During this phase, reskilling for CCUS operations, hydrogen and alternative-fuel handling, advanced quality-control systems for SCM and RCA, and digital plant optimization should be emphasized.

Regionally, harmonization and common SCM/RCA standards with mutual recognition should be updated. Cross-border CO_2 hub coordination can include aligned permits, liability, and access rules.

6.5 2046–2050: Consolidation to Net Zero

6.5.1 Policies and Regulations

During this phase, standards should tighten to near-zero CO_2 emissions for cement. Building codes should mandate high rates of SCM substitution, where technically feasible, and require full end-of-life recovery of concrete (100% collection with high-value recycling targets). Customs and procurement should be aligned with global carbon-border rules and require universal EPDs.

6.5.2 Projects, Technologies and Infrastructure

All major plants should be equipped with CCUS or equivalent abatement where residual process emissions persist. Alternative fuels and electrification should dominate heat supply. SCM-rich cements should be mainstream, drawing on regional pozzolans, calcined clays, slag, and biomass ashes. Complete circular concrete systems including collection, advanced processing, and high-grade RCA use should be integrated into procurement and design codes.

6.5.3 Funding and Incentives

By this stage, clearer revenue signals and mature technologies should let private capital finance most low-carbon and efficiency upgrades across the cement fleet. Investors should focus on O&M optimization and reinvestment/repowering cycles, while governments should maintain just-transition funds and provide targeted innovation support for next-generation binders, such as carbon-cured concretes, and process breakthroughs. Refinancing, securitization, and transition bonds will still be required to lower long-term capital costs for mature assets and shared CO_2 and recycling infrastructure.

6.5.4 Capacity Building and Regional Cooperation

By this phase, regional cooperation should be consolidated with governance of standards, MRV, and certification, and expansion of benchmarking and transparent data sharing. Latin America should be positioned as a global hub for sustainable cement and SCM exports and should be exporting know-how on CCUS operations, circular concrete, and low-carbon procurement.

7. Recommendations

Decarbonizing the LAC cement industry requires support for demonstration programs for emerging technologies, investment in renewable energy capacity, expanded access to climate finance funds, and further studies to inform investment decision-making.

The following key steps would be particularly beneficial to prepare the region for a low-carbon pathway:

1. **Complete and implement the FICEM country-level decarbonization roadmaps.** Once completed, these roadmaps will provide a detailed baseline of current LAC cement industry GHG emissions and identify the potential for the selected technology and policy options to reduce the industry's emissions by mid-century. Developing these country-level roadmaps using a shared approach also allows them to contribute to regional policy coordination.

2. **Construct a regional emissions abatement curve.** This analysis involves compiling and evaluating the costs associated with adopting the identified decarbonization technologies across LAC and estimates their benefits from fuel cost savings and carbon offsets. The economic valuation will help identify the most cost-efficient alternatives for decarbonizing the LAC cement industry and options to improve the economic performance of technically feasible alternatives, including synergies with other sectors. The economic valuation will also identify the impact of the evaluated decarbonization alternatives on cement costs. The assessment will be the primary input for an emissions abatement curve showing each measure's cost and impact on emissions reduction to 2050.

3. **Identify the funding gap.** Estimating the financing needed to implement the decarbonization alternatives is key to understanding financial needs, planning strategically, raising funds, and making informed decisions. It involves assessing the aggregate financing needed to decarbonize the entire LAC cement industry by 2050, the financing that is currently available, and the resulting gap. Assessing the possible causes of these gaps and defining the routes to overcome them is essential.

PULP AND PAPER

1. Introduction

Decarbonizing the pulp and paper industry represents a major challenge for the Latin American and Caribbean (LAC) region. Decarbonization strategies include energy efficiency measures, such as more efficient mill technologies; process optimization and heat recovery; non-conventional low-carbon energy sources, such as hydrogen (H2), landfill gas, and geothermal energy; and substituting virgin raw materials with recycled fibers.

This chapter is organized into seven sections. After the introduction, it describes the processes used to produce pulp and paper. It next details the global and regional markets for pulp and paper. Next, it analyzes the industry's environmental impact and estimates the direct and indirect carbon emission factors linked to pulp and paper production. The following section describes pulp and paper industry decarbonization measures, highlighting their contributions, limitations, and implementation costs. It then presents decarbonization scenarios to achieve zero-carbon emissions by 2050. Next, it examines the proposed decarbonization measures' alignment with the Paris Agreement (PA). Finally, it provides policy recommendations to promote decarbonization in the LAC pulp and paper industry.

2. Production Processes

The pulp and paper industry is based on cellulose fiber[154], which is primarily extracted from wood and, to a lesser degree, from other plants, such as bagasse, bamboo, and cotton. Cellulose can also be obtained from secondary fibers from recycled paper and textile waste (CEPI, 2021).

The industry is composed of two interconnected subsectors – pulp manufacturing and paper production – which can be vertically integrated into one industry or separated into two (CEPI, 2021).

This chapter analyzes the pulp and paper industry as non-integrated units to identify decarbonization measures applicable to each phase. The production processes for each industry are described below.

2.1 Pulp Production

2.1.1 Primary Production

Primary pulp is produced by separating out cellulose and hemicellulose fibers (typically between 70% and 75% for wood) from the lignin (between 20% and 27%)[155] and other materials (Rullifank et al., 2020).

Logs are first debarked, chipped, and screened to ensure that the chips are the right size for further processing. Chip quality is crucial to pulp making, energy efficiency, and efficient use of raw materials. The removed bark is used either as fuel for the production process or sold. The primary consumers of energy are the conveyor belt motors, the operational debarking motors, and the wood chipping motors. The energy required for debarking and wood chipping is influenced by the wood's moisture and hardness, the technology and equipment used, and the production speed.

The wood chips are then converted into pulp by removing the lignin from the cellulosic fibers through a mechanical or chemical method.

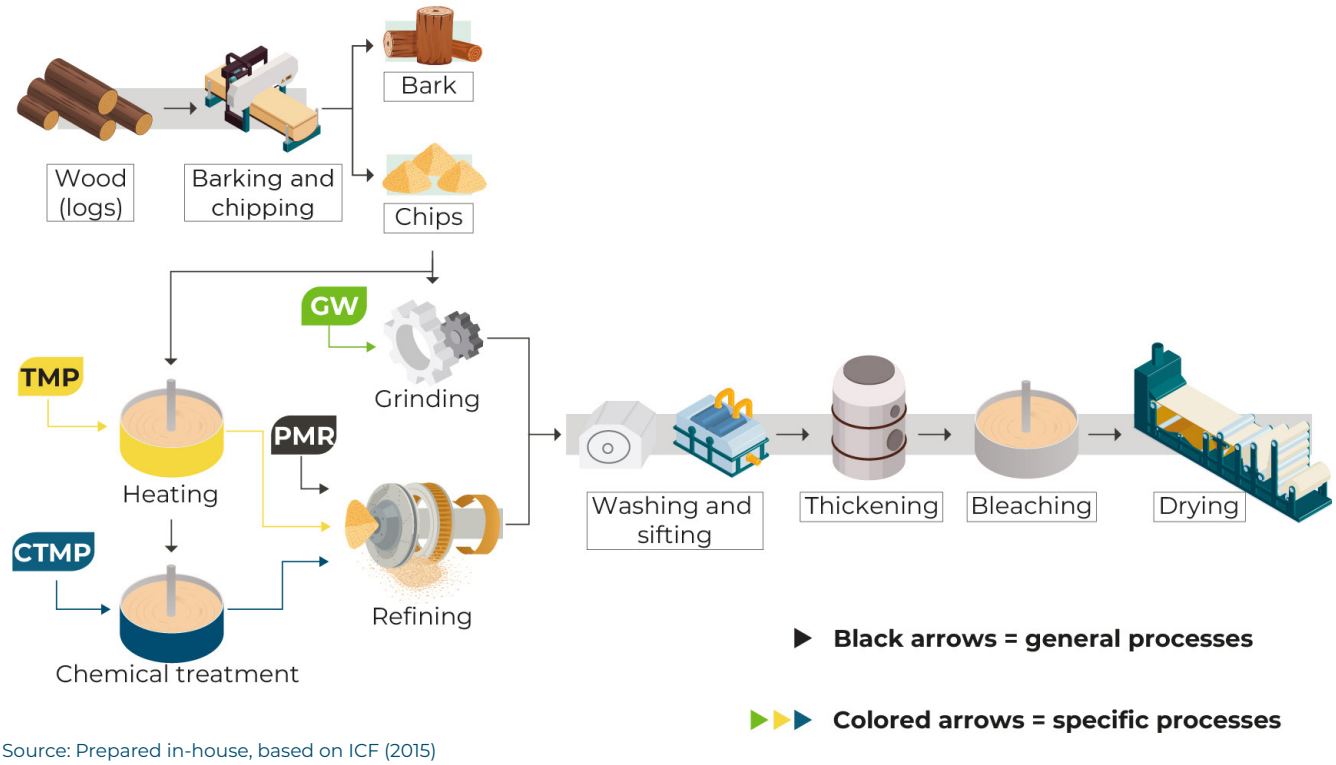
[154] Cellulose is a polysaccharide that forms the tough fibers that provide support and protection to plant cells, and is also responsible for tissue stiffness and strength.
[155] Phenolic polymer contained in the cell wall of plant vascular tissue, provides structural rigidity.

2.1.1.1 Mechanical Pulping

Mechanical pulping accounts for 20% of global pulp production (Scott et al., 2002; Bajpai, 2018), separating the fibers by mechanical means and retaining some of the lignin in the paper. The main mechanical manufacturing routes are: ground wood (GW), refined mechanical pulp (RMP), thermo-mechanical pulp (TMP), and chemi-thermomechanical pulp (CTMP). In general, mechanical production processes have higher yields, with the produced pulp mass ranging between 85-90% of the original fiber mass (Rahnama et al., 2021). However, the retained lignin generates fibers with lower strength compared to chemical pulps. Each mechanical pulp production process is described in greater detail below.

- **GW:** This process uses agglomerated stones made of silicon carbide or aluminum oxide grains to crush the wood chips. Water is added during crushing to reduce the generated heat. The heat and water soften the lignin bond within the wood material and release the fibers. The ground fibers are then screened and cleaned to remove unwanted fragments. The resulting fibers are then thickened and stored in tanks until used in paper production. Optionally, the pulp can be bleached and dried, as required.
- **RMP:** This process refines the wood chips by grinding them between two slotted discs. This refining process produces longer and stronger fibers than the crushing used in GW, improving fiber quality. The fibers are then screened and cleaned, thickened and, optionally, bleached and dried.
- **TMP:** This process is similar to RMP except that the chips are first steamed in pressurized tanks at temperatures between 120° C - 130° C to soften them before being refined, screened, cleaned, thickened, bleached, and dried.
- **CTMP:** This process adds a chemical variant to the TMP process. Wood chips are first chemically pre-treated with sodium sulfite and chelating agents at moderate temperatures (120° C - 130° C) prior to refining. Chemical pretreatment allows the wood fibers to be separated with less damage, resulting in a higher share of long fibers. The figure below summarizes the mechanical pulping processes.

Figure 1. Mechanical Pulp Manufacturing Process, by Type of Pulp



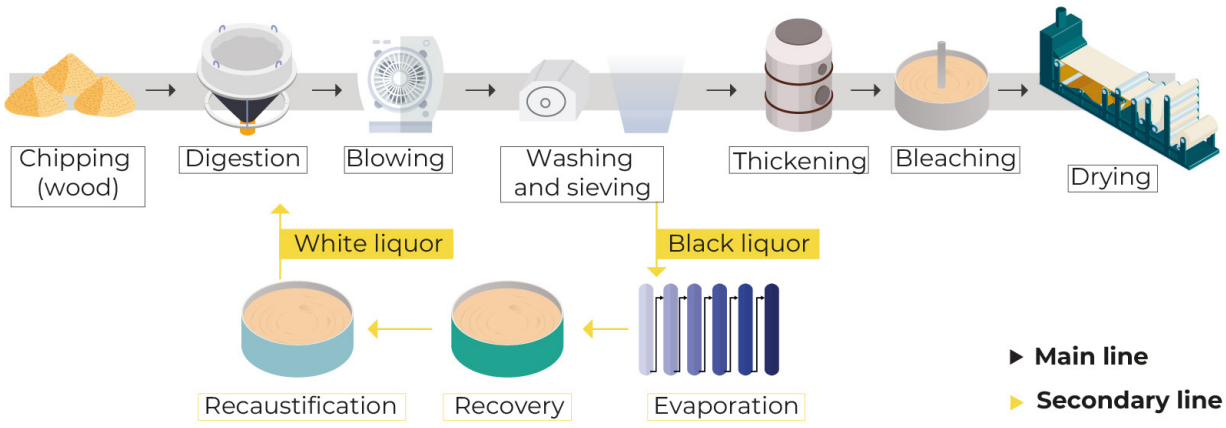
Source: Prepared in-house, based on ICF (2015)

2.1.1.2 Chemical Pulping

Chemical pulping is divided into two main types: kraft (sulfate) pulp and sulfite pulp. In both types, a digester processes the raw material with aqueous chemical solutions, at temperatures between 145° C - 170° C and pressures of 660 kPa to 925 kPa to extract the fibers from the raw material (Fernandez *et al.*, 2019).

The kraft method accounts for about 80% of chemical pulp production (Rahnama *et al.*, 2021). This process combines sodium hydroxide and sodium sulfide at a temperature of 160° C - 180° C and pH > 12 (known as white liquor), to generate a fibrous material by destroying the raw material's lignin chemical bonds (Rullifank *et al.*, 2020). After cooking in the digester, the softened wood chips are transferred to a blowing tank where they are broken down into fibers. The pulp and the cooking liquor, known as black liquor (consisting of organic and inorganic substances), are then separated through filtering and washing. The separated liquid is then sent to the cooking chemical and energy recovery system. Here, the water in the black liquor is evaporated to generate high pressure steam, and the remaining liquid is re-causticized with lime to produce white liquor that is returned to the digester. The figure below summarizes the kraft pulp production process.

Figure 2. Kraft Pulp Manufacturing Process

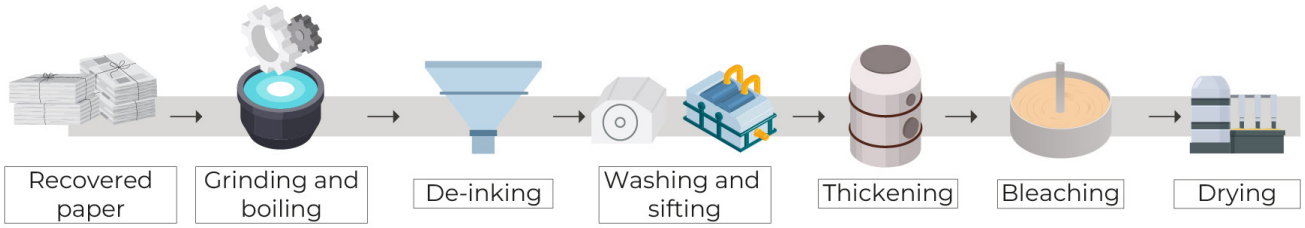


Source: Elaboration based on ICF (2015)

2.1.2 Recycled Pulp Production

Recycled pulp is obtained from a light pulping process using recycled paper as the primary raw material. The process consists of mechanically shredding the paper and dissolving it in hot water to separate the fibers without destroying them. The pulp is then washed and screened to remove impurities, and if necessary, an additional de-inking step is performed (for paper types that require white pulp). The pulp is then thickened via a process to increase the fibers' concentration and dispersion. Finally, it is bleached and dried, depending on the pulp's final use. The figure below summarizes the recycled pulp manufacturing process.

Figure 3. Manufacturing Process of Recycled Pulp

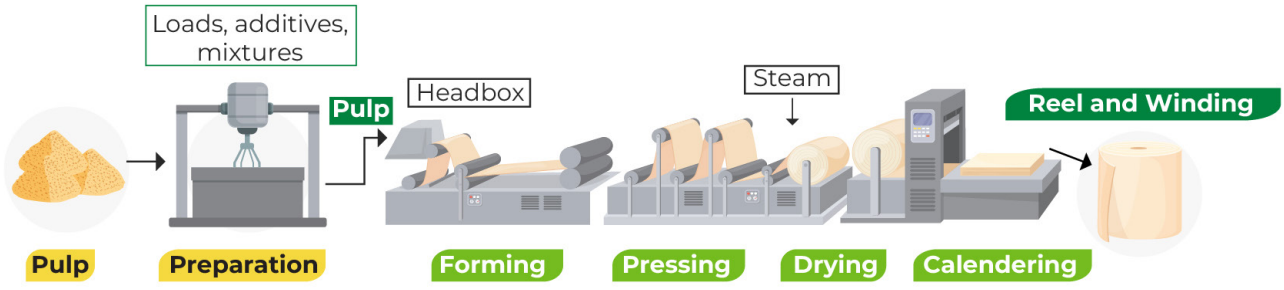


Source: Elaboration based on Furszyfer Del Rio, *et al.* (2022)

2.2 Paper Production

Paper is made by processing fiber pulp into paper and paperboard. In the first pre-treatment step, the pulp is mixed and refined to ensure that it has optimal dissolution conditions, and then mineral fillers or chemicals are added to increase the pulp yield and change the properties of the paper produced, such as paper strength, texture, and brightness (Rahnama *et al.*, 2021). After pre-treatment, the mixture goes through four consecutive sub-processes: forming, pressing, dewatering or drying, and calendering. The forming process distributes the fibers homogeneously and removes part of the moisture from the mixture. The formed paper is then pressed using rolls that remove the moisture content and increase the fiber density, followed by drying with steam-heated cylinders to remove the remaining moisture and further increase fiber content density. Calendering and winding consist of pressing the paper again with a roller that controls the paper's final smoothness and thickness, and then winding using a rotating reel to obtain transportable paper rolls (ICF, 2015). The figure below shows the paper production process.

Figure 4. Paper Production Process



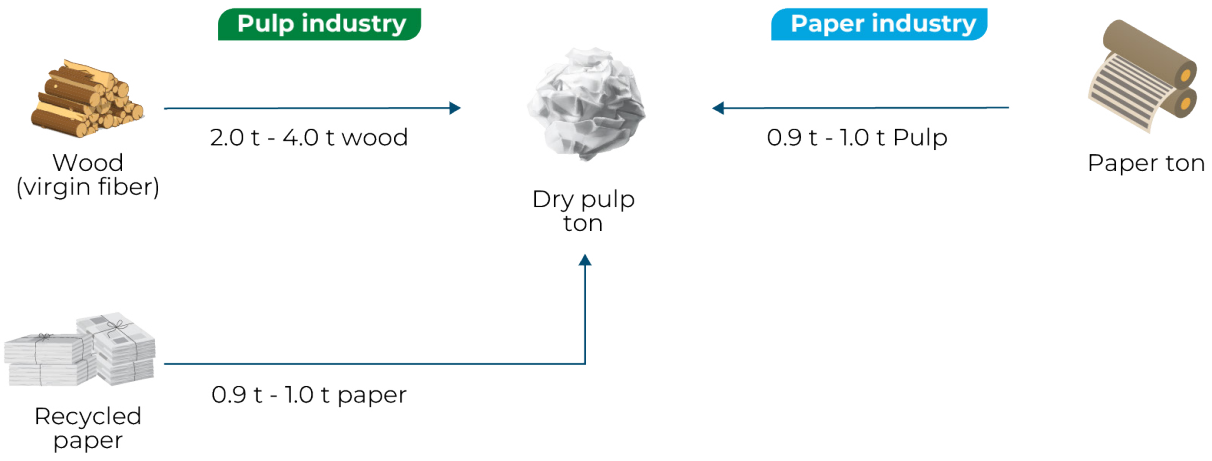
Source: Elaboration based on ICF (2015)

2.3 Inputs

2.3.1 Raw Materials

Pulp production accounts for 14% of global wood consumption and between 33% and 40% world's industrial wood market (Furszyfer Del Rio, *et al.*, 2022). The amount of wood required to produce one ton of pulp depends on wood density, the type of fiber used (long or short), and production efficiency, among other factors. On average, two to four tons of wood are consumed for each ton of pulp produced (Martin & Haggith, 2018). Pulp can also be manufactured from recycled paper, requiring 1.4 tons of paper per ton of pulp on average. The paper industry in turn requires between 0.9 and 1 ton of dry pulp to produce one ton of paper. The figure below shows the raw material inputs required to produce pulp and paper.

Figure 5. Inputs for Pulp and Paper Production

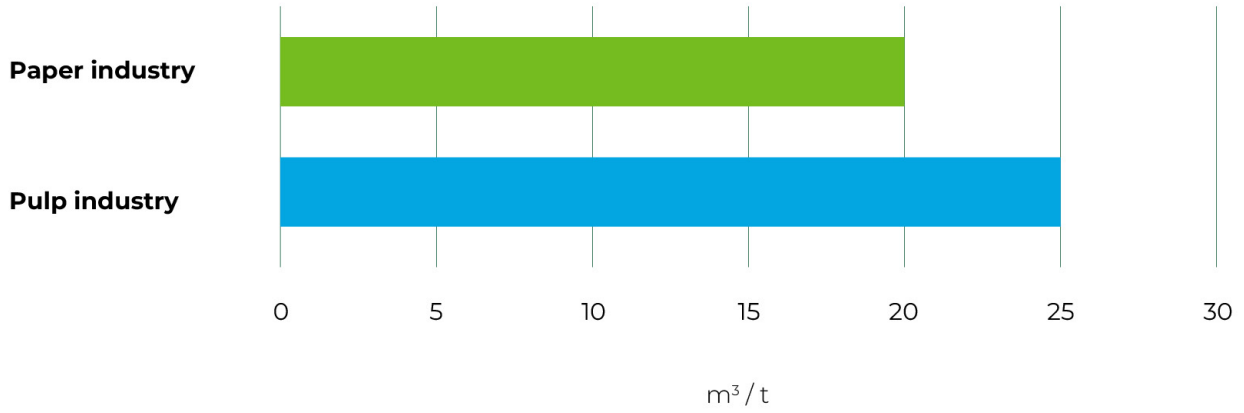


Source: Elaboration based on Martin & Haggith (2018)

2.3.2 Water

Water is mainly used to dissolve raw materials, wash materials, and as a heat exchange and steam production fluid. The pulp industry consumes an estimated 18 m^3 to 30 m^3 of water per ton of product (Olejnik, 2011), and the paper industry between 5 m /t^3paper and 35 m /t^3paper (Boguniewicz-Zabłocka & Kłosok-Bazan, 2019). The figure below shows the average water consumption for these industries.

Figure 6. Average Water Consumption in the Pulp and Paper Industry



Source: Elaboration based on Olejnik (2011) and Boguniewicz-Zabłocka & Kłosok-Bazan (2019)

Printing paper production consumes the most water, followed by newsprint and packaging paper, as detailed in the table below.

Table 1. Water Consumption by Type of Paper

Paper Type	Range m /t³	Average
Domestic	5 - 15	10
Print	11 - 60	35
Press	18 - 25	21
Packaging	6 - 35	20

Source: Elaboration based on Boguniewicz-Zabłocka & Kłosok-Bazan (2019)

2.3.3 Energy

The pulp and paper industry is the fourth-largest energy-consuming industrial sector, accounting for roughly 6% of global industry energy demand (Kong et al., 2020). Energy use varies by product type and pulp and paper manufacturing integration. Each sector's energy consumption is described below.

2.3.3.1 Pulp Industry Energy Consumption

Mechanical and chemical pulp production processes have distinct energy requirements. Approximately 77% of mechanical pulp production energy consumption is electrical. CTMP is the most energy intensive, averaging 2,677 kWh/t, followed by TMP (2,371 kWh/t), RWP (2,242 kWh/t), and GW (1,920 kWh/t). The refining and milling stage consumes the most energy, as shown in the table below.

Table 2. Average Energy Consumption in Mechanical Pulp Manufacturing

Processes	Method	Electricity (kWh/t)	Heat (GJ/t)
Wood Chipping	All	30	
Wood Milling	GW	1,590	0
Refining	RWP, TMP, CTMP	1,912	0
Heating	TMP	129	0.9
Chemical Treatment	CTMP	306	0
Washing and Screening	All	50	0
Thickening	All	60	0
Bleaching	All	100	0
Drying	All	90	2

Source: Elaboration based on ICF (2015), Bajpai (2018), and Rahnama *et al.* (2021)

Chemical (kraft) pulp production consumes half as much electricity as mechanical processes but has a significant thermal energy demand, using 9.87 GJ/t, which accounts for 85% of its total energy demand. Some LAC companies co-generate electricity when producing the required thermal energy. This co-generated electricity can exceed the electricity consumed in the production process, so that surplus electricity is dispatched to the electrical grid. Pulp digestion, bleaching, and drying processes consume 87% of the electricity and 59% of the heat required, with the remainder used in the auxiliary black liquor recovery line, as shown in the table below.

Table 3. Energy Consumption in the Chemical Pulp Manufacturing Process (Kraft)

Processes	Electricity (kWh/t)	Heat (GJ/t)
Main line		
Wood Chipping	30	0
Digestion	481	2.4
Blowing	75	0.5
Washing and Screening	30	0
Thickening	60	0
Bleaching	120	0.4
Drying	125	2.5
Auxiliary Line		
Liquor Evaporation	25	2.2
Recovery	58	1.1
Recaustification	50	0.77
Total	1,054	9.87

Source: Elaboration based on ICF (2015), Bajpai (2018), and Rahnama *et al.* (2021)

The kraft pulp manufacturing process can produce a significant portion of its energy from burning organic residues, such as lignin and black liquors, generated during wood cooking in recovery boilers (Jafri, 2019). Self-produced energy can vary depending on the plant's specific configuration, but in many cases can generate enough thermal energy to supply their own operations and even generate surpluses.

Recycled pulp production requires much less energy: 34% of mechanical pulp production and 73% of chemical production, on average. The table below breaks down recycled pulp energy consumption by step.

Table 4. Energy Consumption in the Recycled Pulp Manufacturing Process

Processes	Electricity (kWh/t)	Heat (GJ/t)
Paper Shredding and Fiber Separation	392	0
Sieving	50	0
Deinking	80	0
Thickening	40	0
Bleaching	30	0
Drying	90	2

Source: Elaboration based on ICF (2015), Bajpai (2018) and Rahnama *et al.* (2021)

2.3.3.2 Paper Industry Energy Consumption

Paper production uses energy to form, press, and dry the paper. It consumes an average 503 kWh/t of electricity and 4.7 GJ/t of heat energy. The table show the electricity and heat energy required to produce different types of paper.

Table 5. Average Energy Consumption in Paper Production

	Electricity (kWh/t)		Heat (GJ/t)	
Paper Type	Forming and Pressing	Drying	Forming and Pressing	Drying
Newsprint	422.0	29.3	0.0	4.3
Printing Paper	527.5	29.3	0.0	5.5
Writing Paper	527.5	29.3	0.0	5.3
Tissue Paper	533.4	131.9	0.0	4.2
Wrapping Paper	269.6	14.7	0.0	4.2
Average	456.0	46.9	0.0	4.7

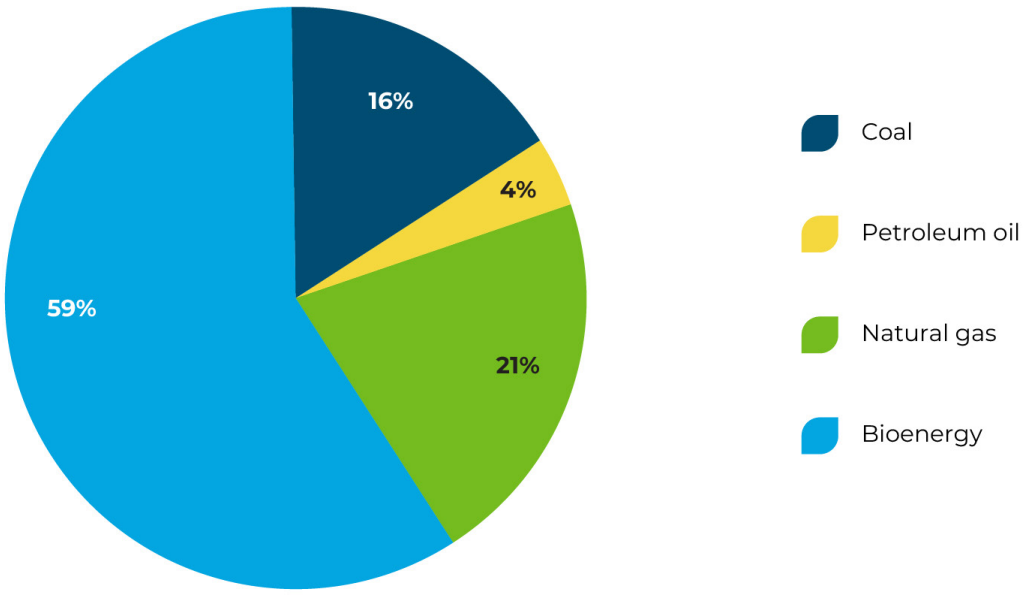
Source: Elaboration based on Rahnama *et al.* (2021)

Machinery operation consumes between 79% and 82% of the total energy, while 7% to 9% is used for general services and 9% for boilers and cooling systems. Steam generation accounts for between 60% and 70% of thermal energy use, followed by heat processes (20% to 30%), machines (3% to 4%), and other uses (2%) (MIEM, 2016).

2.3.3.3 Pulp and Paper Industry Energy Matrix

Globally, the pulp and paper industry uses a high share of biofuels (59%), mainly pulp manufacturing process byproducts, such as black liquor and wood residues. These fuels are used as a source of heat and electricity production from cogeneration plants (Kari Vakkilainen, 2017 and Furszyfer Del Rio, *et al.*, 2022). However, the industry still relies on fossil fuels to supply its total demand. The figure below shows the global pulp and paper industry's primary energy matrix.

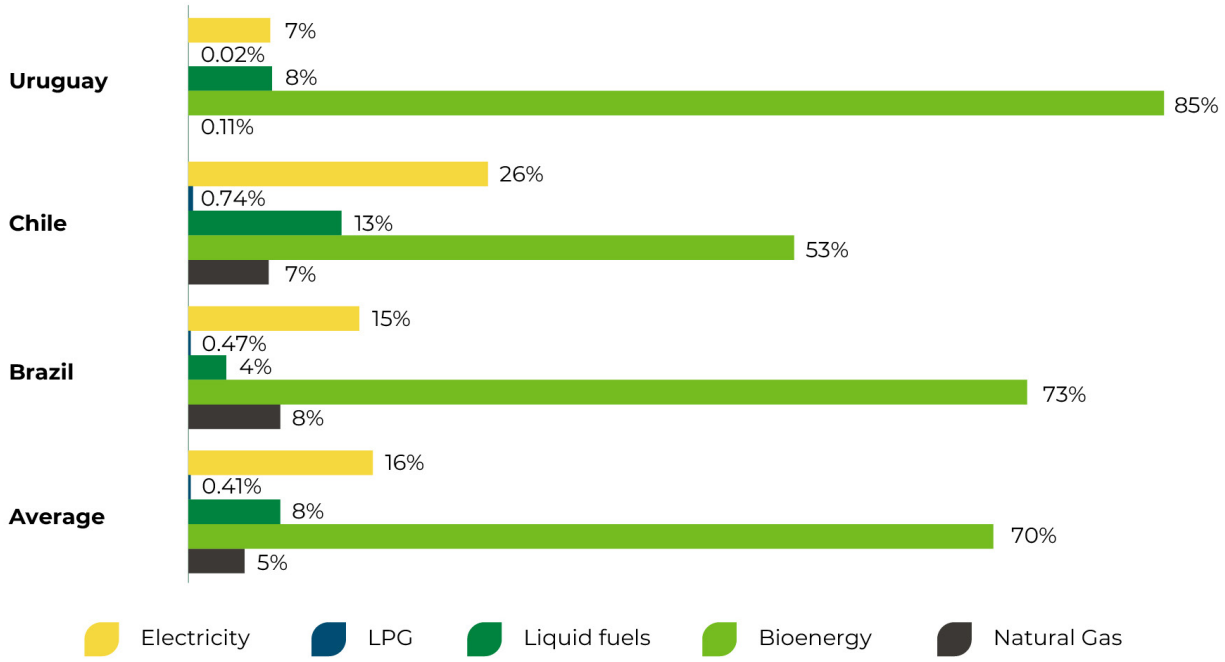
Figure 7. Global Pulp and Paper Primary Energy Matrix



Source: Elaboration based on IEA database (2022)

In LAC, bioenergy supplies 70% of the pulp and paper industry's energy on average – well above the global average. Uruguay has the highest share of biomass use (85%), as shown in the figure below.

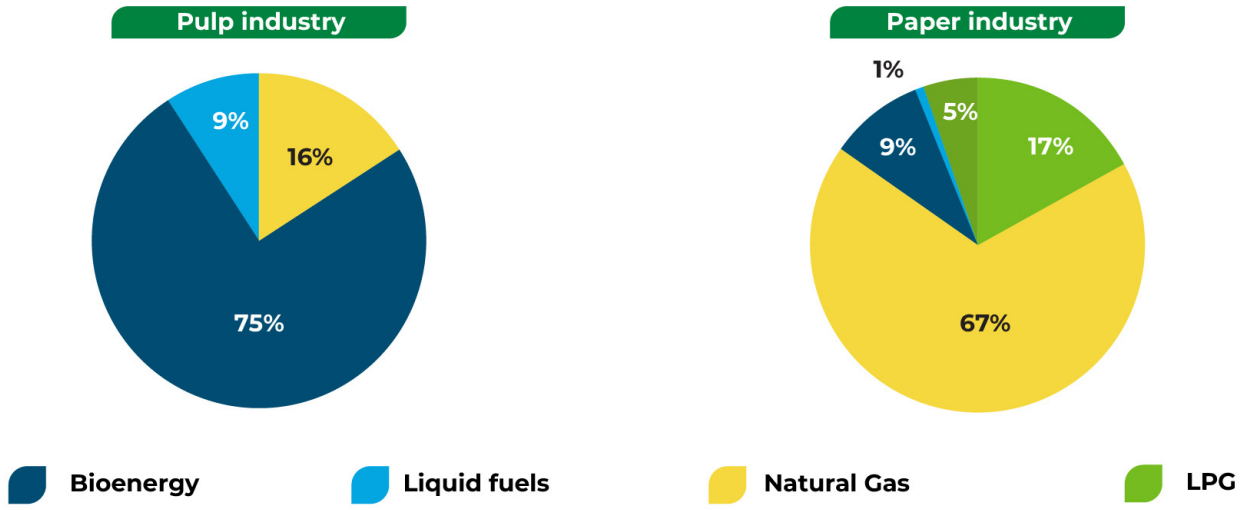
Figure 8. LAC Pulp and Paper Industry Energy Matrix



Source: Elaboration based on energy balances BNE Chile 2021[156] , BEN Brazil 2021[157] and BEN Uruguay 2021[158]

The pulp industry's energy matrix is 75% bioenergy, 16% electricity, and 9% liquid fuels. The paper industry's matrix is 67% natural gas, 17% electricity, 9% bioenergy, and 6% other sources. The figure 9 details the energy matrix for both industries.

Figure 9. LAC Energy Matrix, by Industry



Source: Elaboration based on BNEU industrial Uruguay (2016)[159]

[156] http://energiaabierta.cl/categorias-estadistica/balance-energetico/
[157] https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2022
[158] https://ben.miem.gub.uy/balance.php
[159] https://www.gub.uy/ministerio-industria-energia-mineria/datos-y-estadisticas/estadisticas/balance-nacional-energia-util-del-sector-industrial-datos-2016

2.4 Pulp and paper production costs

Production costs include raw materials, energy, labor, and other necessary inputs. For LAC, pulp and paper production costs were estimated from regional import and export values (USD/t) as of 2022[160](FAOSTAT[161]). The results indicate that the current cost of pulp production averages USD $341/t, and the cost of paper production averages USD $648/t. The table below details the range of costs for each product.

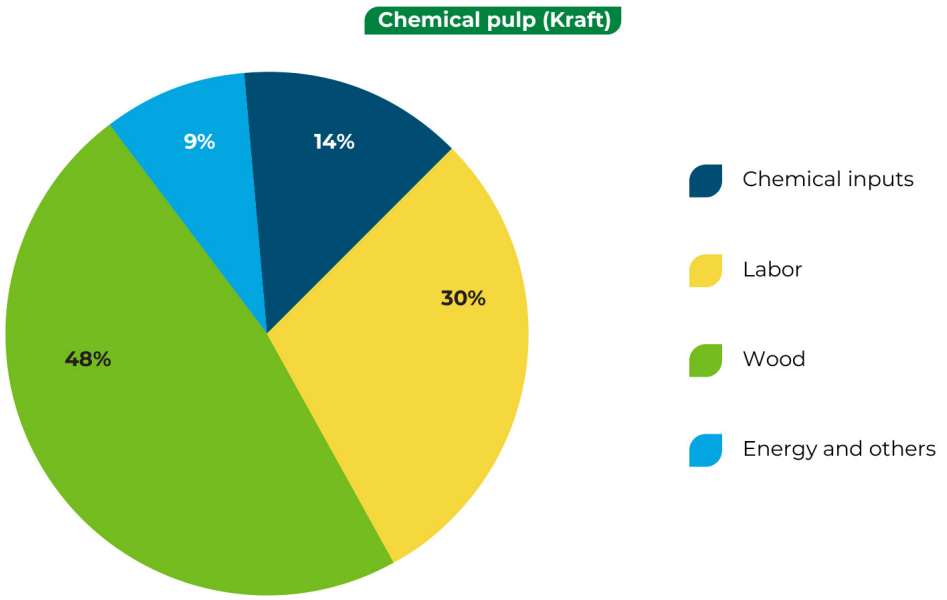
Table 6. LAC Estimated Pulp and Paper Production Costs (2022)

Product	Minimum (USD/t)	Average (USD/t)	Maximum (USD/t)
Pulp (1 ton)	277	341	426
Paper (1 ton)	607	648	689

Source: Elaboration based on FAO´s statistics (FAOSTAT)

For kraft pulp, chemical inputs make up about three-quarters of the total production cost, while for mechanical pulp the cost associated with labor comprises the largest component. The figure below breaks down chemical pulp production costs.

Figure 10. Pulp Production Costs in LAC

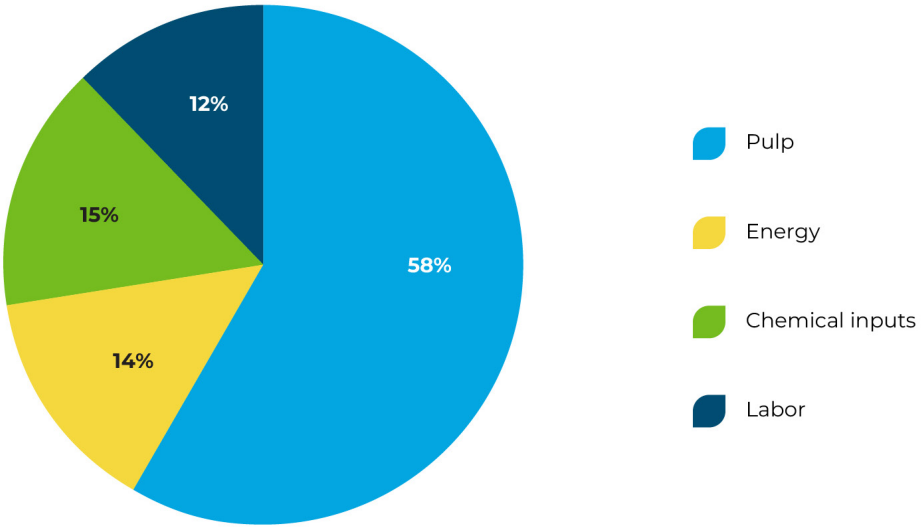


Source: Elaboration based on data from Hawkins Wright (2023), Jaakko Pöyry (1996), Mues, *et al.* (2018)

[160] Discounting an average gross profit margin of 43%.https://csimarket.com/Industry/industry_Profitability_Ratios.php?ind=111
[161] https://www.fao.org/faostat/en/#search/pulp%20and%20paper

The cost of pulp is the largest component of paper production costs, averaging 58% of the total in LAC, followed by chemical inputs, energy, and labor, as shown in the figure below.

Figure 11. Composition of LAC Paper Production Costs

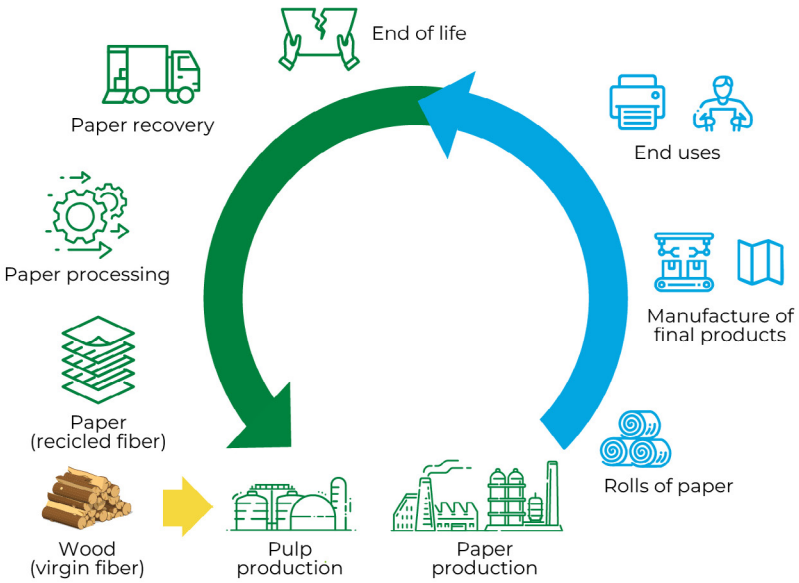


Source: Elaboration based on Jaakko Pöyry (1996), CEPI (2017)

2.5 Lifecycle and End Uses

Paper can be recycled between three and eight times. A percentage of virgin pulp is added each time to maintain the recycled fiber's strength and quality[162]. This allows recovered paper and forest products to complement each other, generating a circular economy. Paper packaging's short lifecycle also facilitates paper use circularity. Globally, packaging accounts for more than half of paper use (55%), and printing and writing a further 26% (Martin & Haggith, 2018). The figure below illustrates the paper lifecycle.

Figure 12. Paper Lifecycle

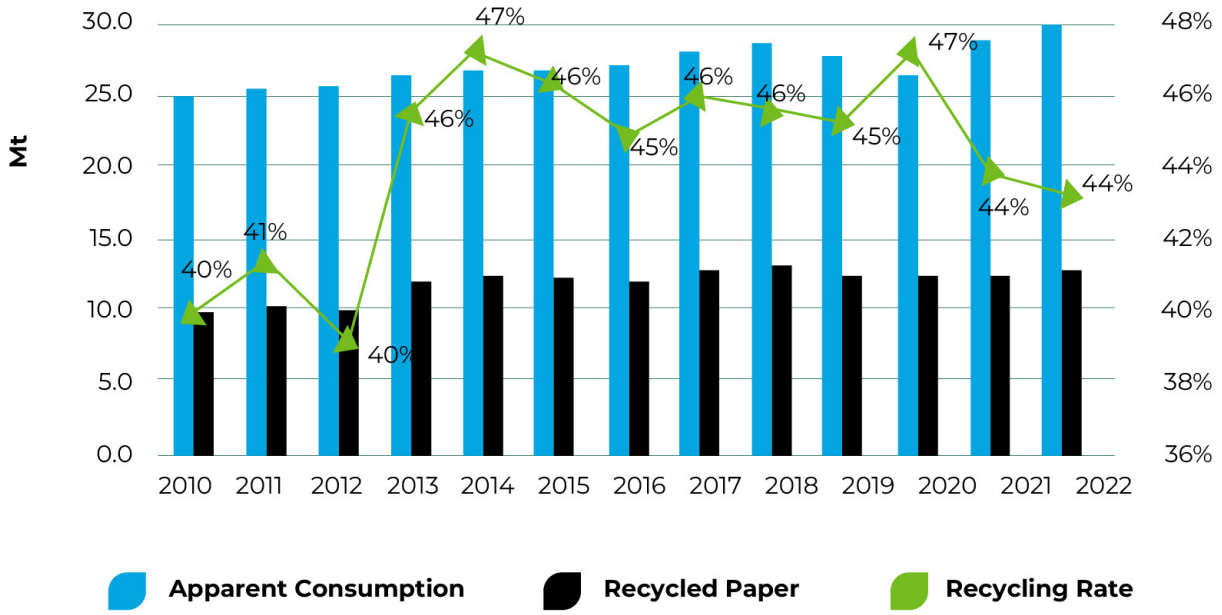


Source: Prepared in-house

[162] Paper and Board Recycling Report. Bureau of International Recycling (BIR), 2019. https://www.bir.org/the-federation

In 2019, LAC recycled pulp production consisted of 80% packaging paper, followed by tissue paper (7%), printing and writing paper (3%), newsprint (2%) and other papers (1%) (BIR, 2021). Between 2010-2022, LAC's annual paper recovery averaged 44% of total apparent consumption[163]. This suggests the potential for additional recovery to displace primary pulp consumption[164] . The figure below shows the paper recovery rate evolution in LAC.

Figure 13. Apparent Consumption and Paper Recovery in LAC (2010-2022)

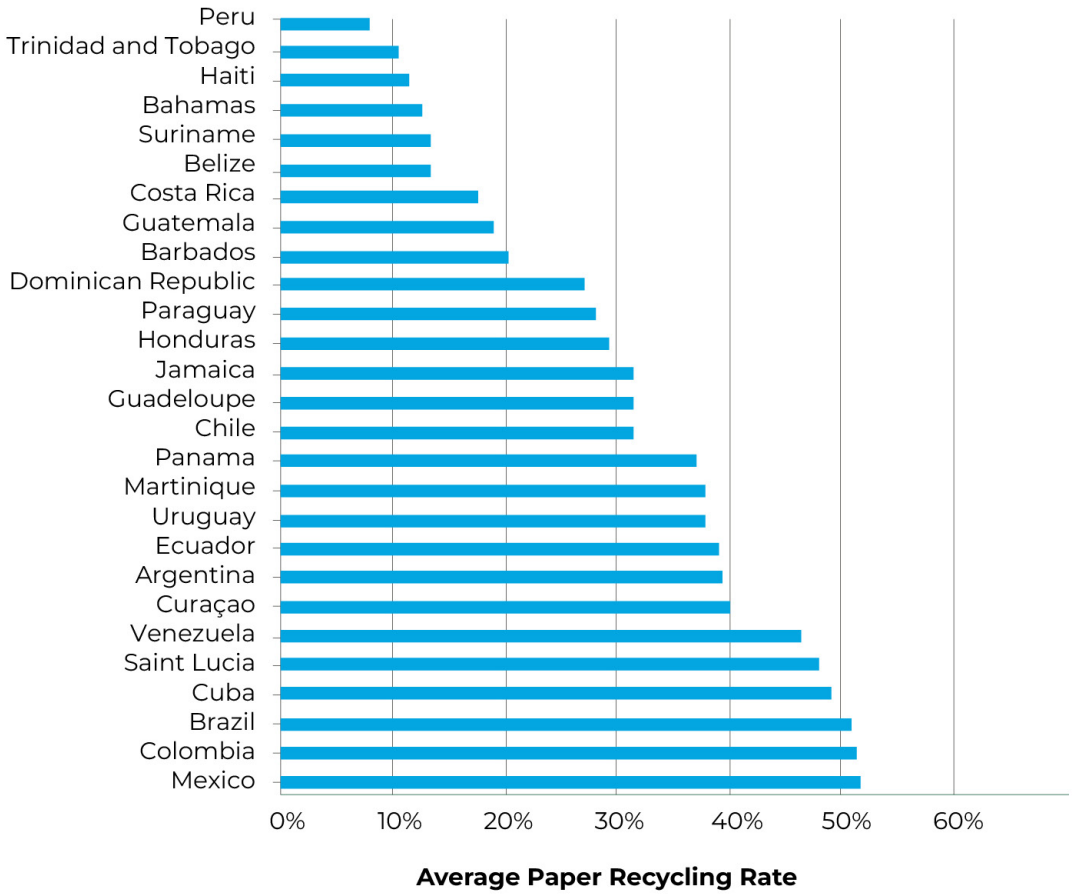


Source: Elaboration based on FAO´s statistics (FAOSTAT)

Mexico, Colombia, Brazil, and Cuba have the highest average rate, recovering 50% or more of the paper they consume. Other high-recycling countries include Saint Lucia (49%) and Venezuela (47%). Peru and Trinidad and Tobago reported the lowest recovery rates, as shown in the figure below.

[163] Availability of paper for consumption = production + imports - exports.
[164] According to BIR - Papel, between 15% and 20% of paper collected is not recoverable.

Figure 14. Average Paper Recovery Rates in LAC (2010-2022)



Source: Elaboration based on FAO statistics (FAOSTAT)

Developing paper recycling policies and value chains dedicated to collecting and treating recovered paper (both formal and informal) can increase recycling rates. For example, in 2018 Colombia enacted Resolution 1407[165] to regulate waste management for paper, cardboard, glass, and metal packaging. This resolution, which went into effect in 2020, sets a target for companies to recover 10% (by weight) of the products placed on the market, with an annual increase of 2% until 2030.

Mexico's paper recycling policy dates from the mid-2010s and urges federal government agencies and entities to acquire paper containing recycled material or natural fibers not derived from wood[166]. In 2022, the Mexican Congress approved reforms to the Organizational Law of the Federal Public Administration to recycle paper consumed in the public sector[167]. Recently, the Congress of Mexico City approved the Circular Economy Law of Mexico City to promote sustainable production actions by reusing, recycling and recovering materials.[168]

Likewise, since 2010 Brazil's National Solid Waste Policy establishes the principles, objectives, and instruments related to the comprehensive management and treatment of solid waste[169].

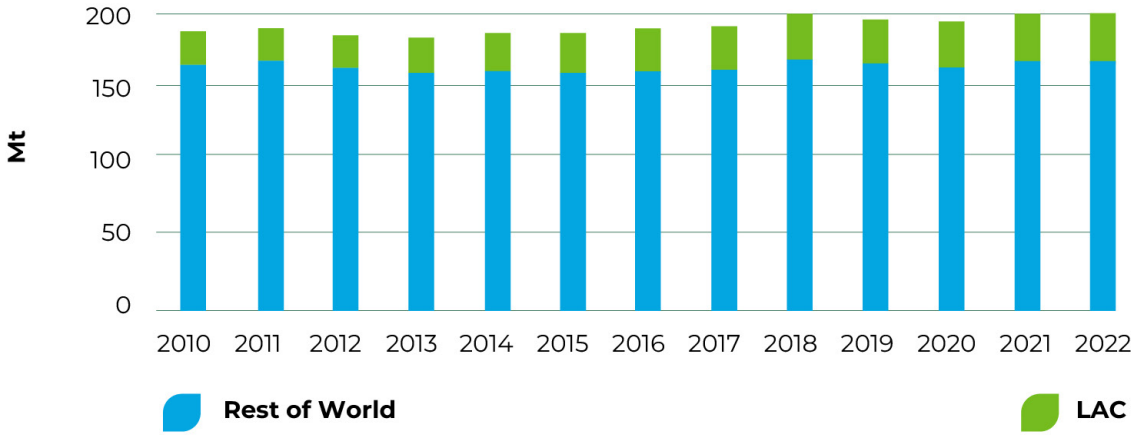
[165] https://www.andi.com.co/Uploads/RES%201407%20DE%202018.pdf
[166] https://dof.gob.mx/nota_detalle.php?codigo=4999881&fecha=05/09/2007#gsc.tab=0
[167] https://congresodurango.gob.mx/obligatorio-el-reciclaje-de-papel-en-administracion-publica/
[168] https://www.sedema.cdmx.gob.mx/storage/app/uploads/public/640/775/796/640775796545e564034573.pdf
[169] https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm

3. Global and Regional Market

3.1 Paper Pulp Production

Between 2010 and 2022, global primary pulp[170] consumption grew 2.2%, reaching a total of 199 million tons (Mt) by 2022. In 2022, LAC accounted for 17% (33.8 Mt) of world production, representing an increase of 50% compared to the 11.3% share recorded in 2010. Both world pulp production and LAC's share is shown in the figure below.

Figure 15. World Production of Primary Pulp for Paper (2010 - 2022)



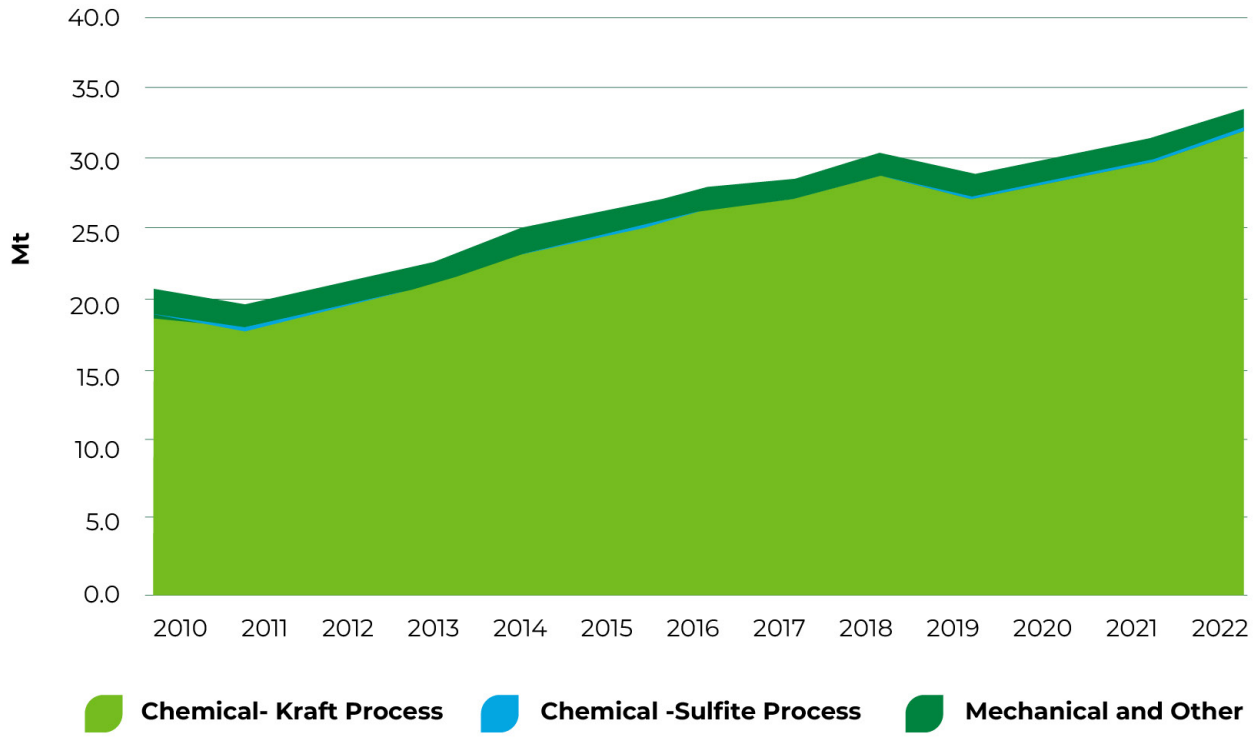
Source: Elaboration based on FAO´s statistics (FAOSTAT)[171]

[170] Includes only the use of fiber prepared from wood.
[171] https://www.fao.org/faostat/en/#search/pulp%20and%20paper

The region's production growth is supported by its vast forest resources. The LAC governments and private investors that focus on establishing large forest plantations with fast-growing species have significantly increased the availability of raw material and intensified the industry's regional development. It is estimated that Brazil currently has more than 5 million hectares (ha) of forest plantations for pulp production; Chile has approximately 2 million ha; and Uruguay has close to 1 million ha.

Between 2010 and 2022, LAC annual pulp production averaged 27 Mt. 93.8% (25.4 Mt) was produced by chemical methods and the remaining 6.2% (1.6 Mt) by mechanical processes. Within the chemical method, kraft pulp dominates production with a 99.7% share (25.3 Mt), the remaining 0.3% being sulfite pulp[172]. The figure shows LAC pulp production by method during the period.

Figure 16. Primary Production of Pulp for Paper in LAC (2010 - 2022)



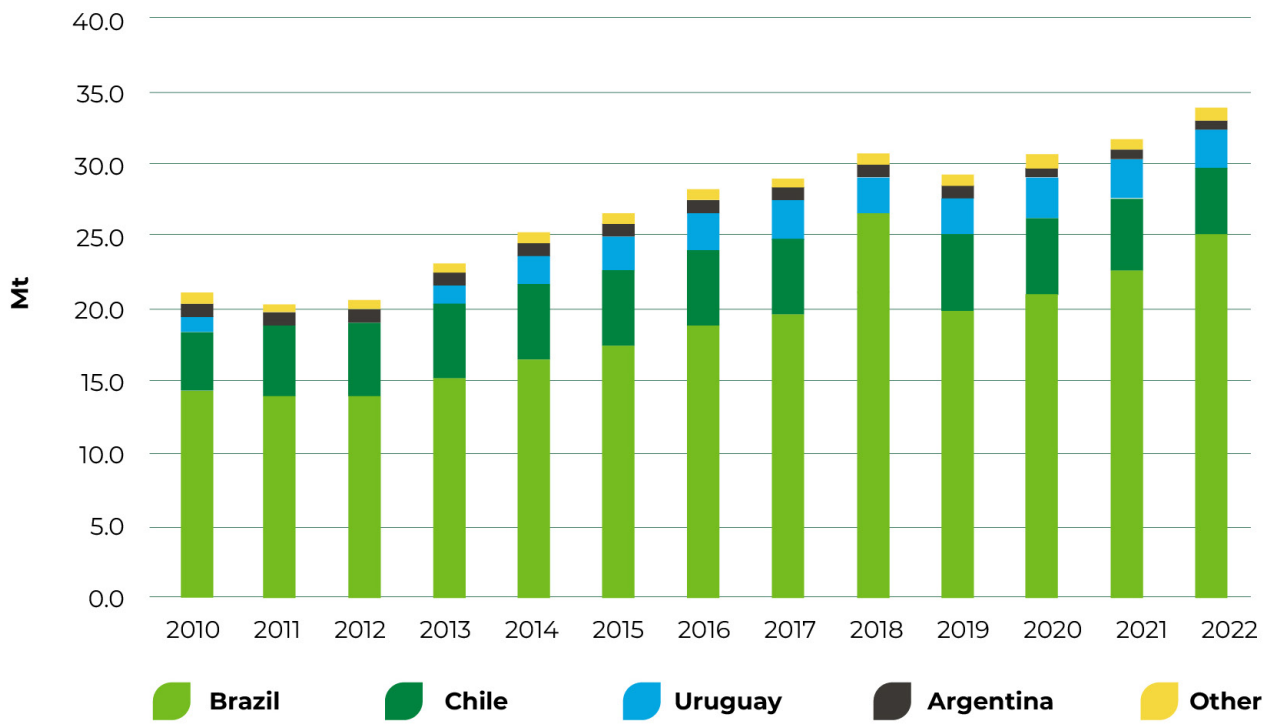
Source: Elaboration based on FAO statistics

Between 2010 and 2022, mechanical pulp production decreased 6.4% while chemical pulp production increased by 67%, owing to the chemical pulp industry's better performance and profitability compared to the mechanical production industry[173].

Brazil accounted for 74.1% of LAC pulp production in 2022, followed by Chile (13.8%), Uruguay (8%) and Argentina (2.1%). The remaining 2.1% is produced in Colombia (1.2%), Costa Rica (0.5%), Mexico (0.3%), Venezuela (0.05%), and Ecuador (0.05%). The figure below shows LAC's main producing countries.

[172] The kraft process delivers a better quality pulp at a lower cost, as compared to the sulfite process. In addition, sulfite pulping can only process a few types of wood, while kraft pulping is more flexible and can be applied to most wood species. In the region, 3.4 m3 with a density of 0.7 t/m3 are required to produce short-fiber pulp, thus 2.38 tons of wood per ton of pulp. In the case of long-fiber pulp, 5.2 m3 of wood is required; this has a density of 0.45 t/m3 , giving 2.34 t wood/t pulp.
https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/sulfite-process
[173] https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/mechanical-pulp

Figure 17. Main Pulp-Producing Countries in LAC (2010 - 2022)



Source: Elaboration based on FAO statistics.[174]

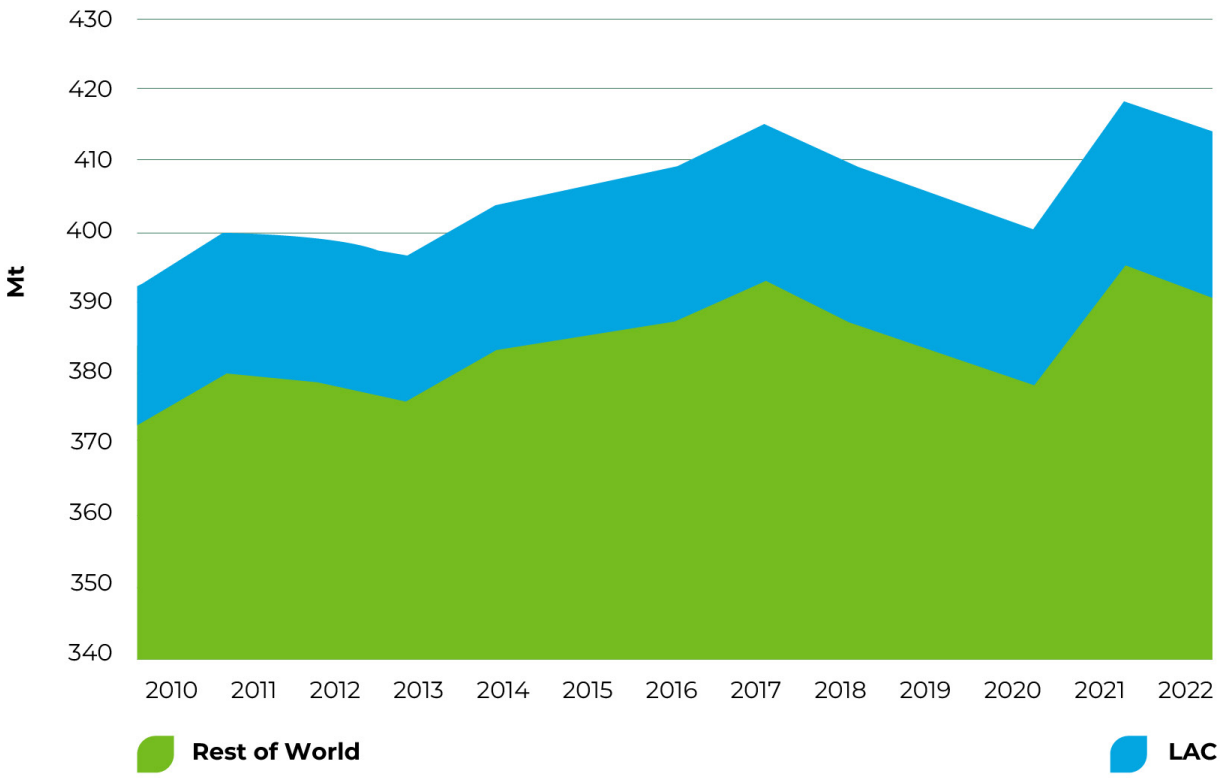
Statistics exclude secondary or recycled pulp production information[175] in LAC. According to the Bureau of International Recycling, LAC produced 13.42 Mt of pulp from paper recovery in 2019 (BIR, 2021), the latest year of available data.

3.2 Paper and Paperboard Production

World paper and cardboard production grew 5.6% from 2010 to 2022, reaching 414 million tons in 2022. In 2022, LAC supplied 5.7% (23.7 Mt) of world production, as shown in the figure below.

[174] https://www.fao.org/faostat/en/#search/pulp%20and%20paper
[175] Produced from recovered paper and cardboard fibers.

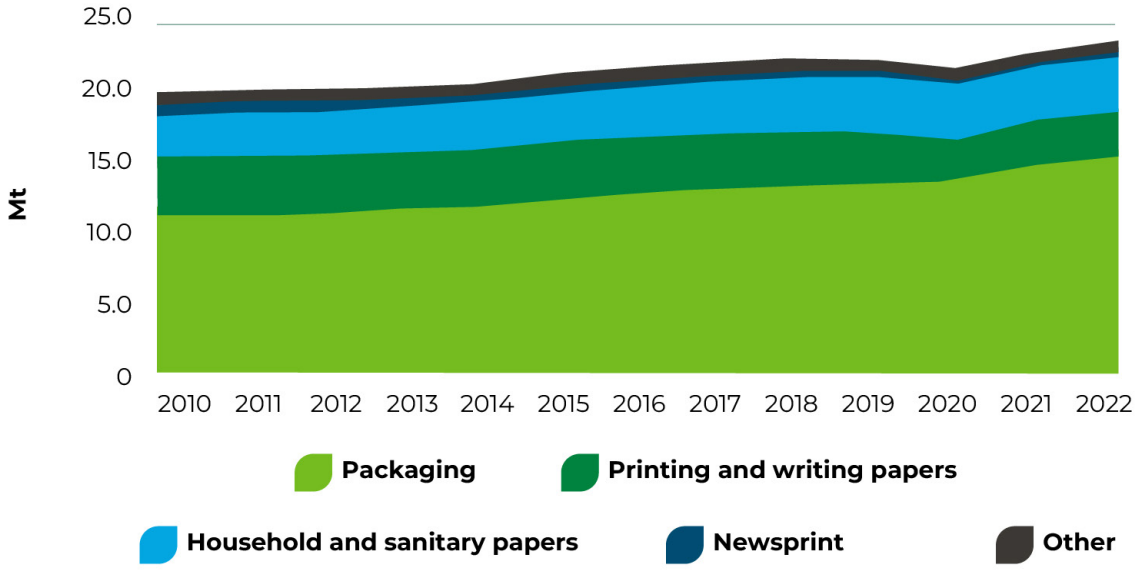
Figure 18. World Paper and Board Production 2010-2022



Source: Elaboration based on FAO statistics.[174]

Packaging paper dominates production in LAC, reaching a 65% share (15.4 Mt) in 2022, followed by household and sanitary paper (17%), printing and writing paper (14%), newsprint (1%), and other papers with the remaining 3%. The figure below shows LAC paper and cardboard production from 2010 to 2022.

Figure 19. Paper and Cardboard Production in LAC (2010 - 2022)



Source: Elaboration based on FAO statistics

Household and sanitary paper and packaging paper production both grew 38% from 2010 to 2022, while printing and writing paper production declined 24% and newsprint production decreased by 70%. Document and information digitization contributed to reducing printing and writing paper and newsprint consumption (Latta et al., 2015; McKinsey, 2019).

LAC paper production in 2022 was concentrated in seven countries: Brazil (46.7%), followed by Mexico (27.6%), Argentina (7.3%), Chile, (5.5%), Colombia (5.3%), Peru (2.2%), and Venezuela (1.4%). Together, these countries account for 22.6 Mt of LAC's total production. The remaining 3.9% (0.9 Mt) is distributed among Costa Rica, Ecuador, Dominican Republic, El Salvador, Paraguay, Uruguay, Honduras, Guatemala, Cuba, Trinidad and Tobago, and Barbados. The figure below shows paper and paperboard production for LAC's main producing countries.

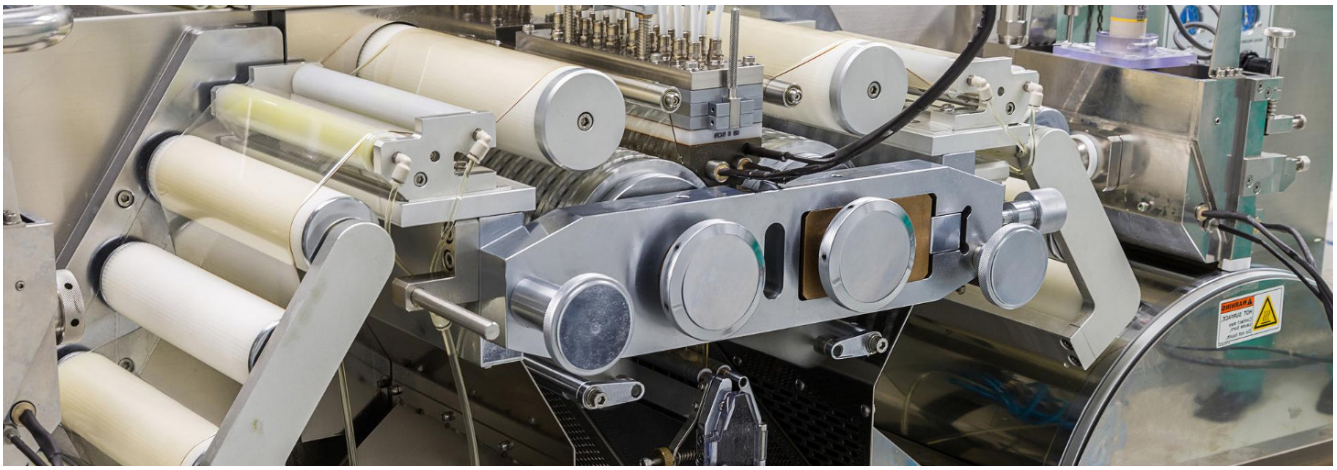
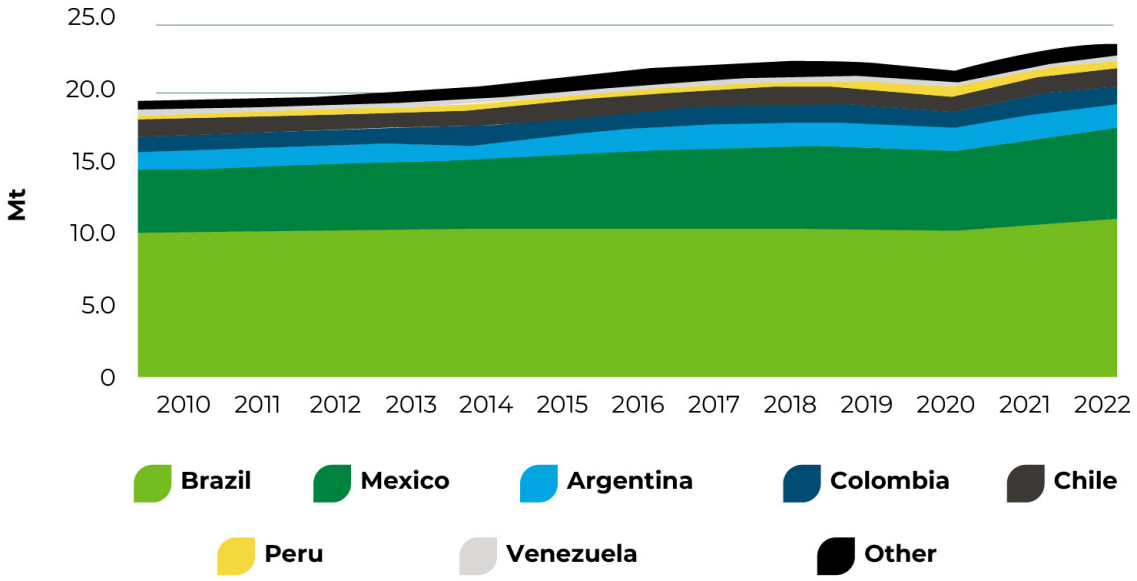


Figure 20. Main Paper- and Board-Producing LAC Countries (2010-2022)



Source: Elaboration based on FAO statistics

3.3 Imports, Exports, and Consumption in LAC

3.3.1 Pulp for Papermaking

3.3.1.1 Exports

In 2022, LAC exported 25.8 million tons of pulp, equivalent to 76% of regional production. Brazil is the primary exporter, accounting for 74% of the total in 2022, followed by Chile (15%) and Uruguay (10%). The table below lists LAC pulp exports and participation by country in 2022.

Table 7. LAC Countries' Export Volume of Primary Pulp for Paper (2022)

Country	Tons	Participation
Brazil	19,150,764	74%
Chile	3,807,872	15%
Uruguay	2,697,199	10%
Argentina	150,197	1%
Peru	1,614	0.01%
Mexico	1,255	0.005%
Guyana	829	0.003%
Ecuador	676	0.003%
Colombia	638	0.002%
Other	1,215	0.005%

Source: Elaboration based on FAO statistics

3.3.1.2 Imports

Pulp imports are less significant than the export market. Pulp imports in LAC reached 2.05 million tons in 2022, equivalent to 6.1% of total production. The main purchasing countries were Mexico (49%), Argentina (13%), Colombia (11%), Brazil (8%), and Peru (7%). The table below shows import volumes in 2022 by country.

Table 8. Import Volume of Primary Pulp for Paper in LAC Countries (2022)

Country	Tons	Participation
Mexico	1,014,231	49%
Argentina	256,976	13%
Colombia	225,898	11%
Brazil	154,575	8%
Peru	134,411	7%
El Salvador	56,003	3%
Bolivia	39,440	2%
Chile	31,020	2%
Trinidad and Tobago	25,227	1%
Guatemala	24,835	1%
Ecuador	24,085	1%
Venezuela	15,983	1%
Costa Rica	15,567	1%
Dominican Republic	14,222	1%
Cuba	5,471	0%
Uruguay	4,374	0%
Belize	2,402	0%
Paraguay	2,394	0%
Honduras	1,026	0%
Other	1,337	0%
Total	2,049,478	100%

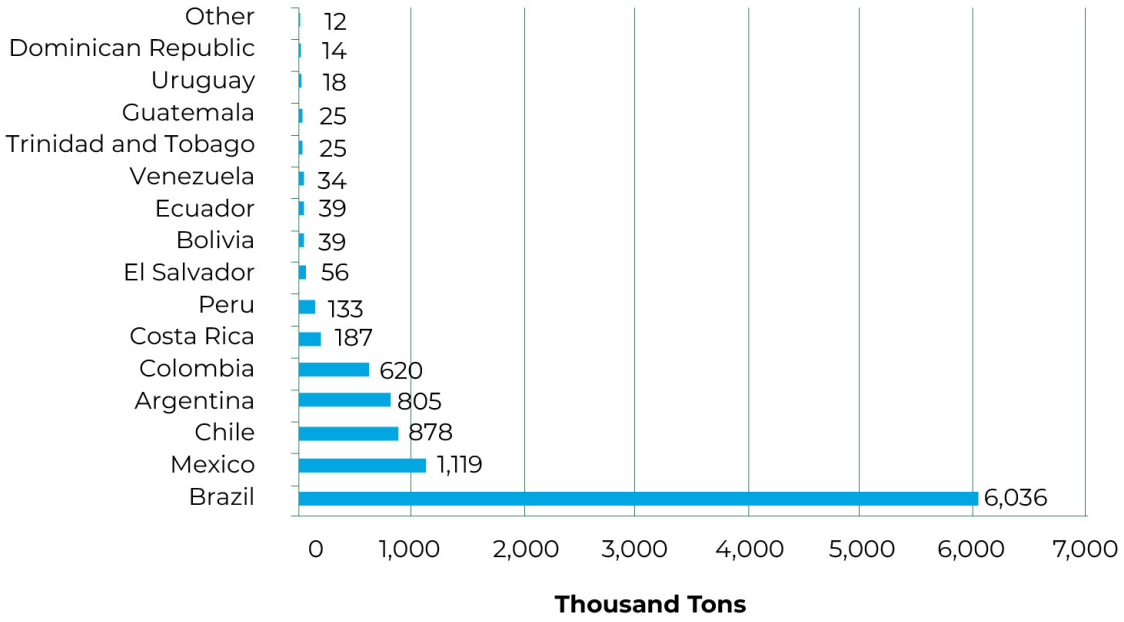
Source: Elaboration based on FAO statistics

3.3.1.3 Apparent Consumption

The balance between pulp production, imports, and exports determines a country's apparent consumption. Brazil has the region's highest primary pulp apparent consumption[176] at 6.04 Mt in 2022, followed by Mexico (1.12 Mt), Chile (0.88 Mt), Argentina (0.81 Mt), and Colombia (0.62 Mt). The figure below shows the countries with apparent consumption over 10,000 tons.

[176] Availability of pulp for consumption = pulp production + pulp import - pulp export.

Figure 21. Apparent Consumption of Primary Pulp in LAC Countries (2022)



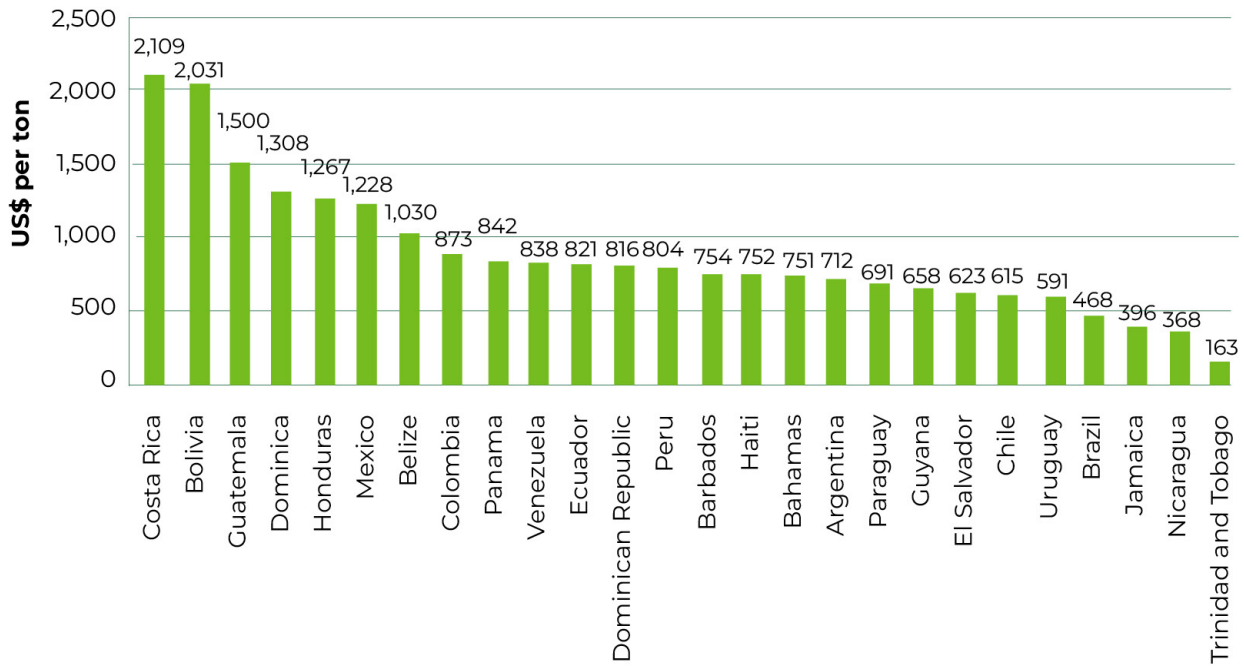
Source: Elaboration based on FAO´s statistics

Primary pulp consumption is expected to rise along with demand for paper and cardboard, as paper is not completely recyclable and its production requires a minimum share of new pulp fibers. In LAC, primary pulp consumption is influenced by economic and demographic growth, fluctuations in international trade, and changes in the use of raw materials, including increased recycled paper fiber use.

3.3.1.4 Commercialization Values

Between 2010 and 2022, primary pulp exports' commercial value averaged USD $513/t. During this period, the value fell by 19% from USD $598/t in 2010 to USD $486/t in 2022. Trinidad and Tobago recorded the lowest average commercial value at USD $163/t. The highest prices were recorded in Costa Rica (USD $2,109/t) and Bolivia (USD $2,031/t), as shown in the figure below.

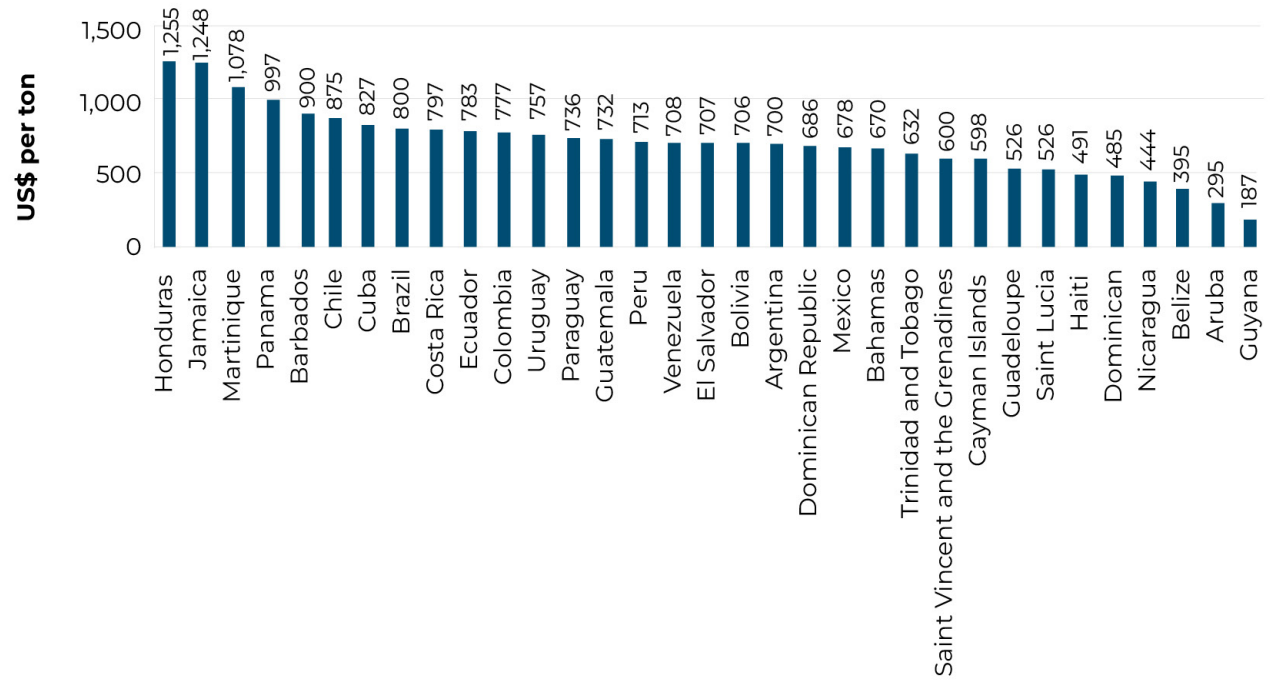
Figure 22. Average Export Values of Primary Pulp in LAC (2010-2022)



Source: Elaboration based on FAO´s statistics

The value of LAC pulp imports averaged US$712/ton between 2010 and 2022, declining 7.3% from US$805 per ton in 2010 to USD $747 per ton in 2022. The figure below shows LAC countries' average primary pulp import value from 2010 to 2022.

Figure 23. Pulp Import Values in LAC (2010-2022)



Source: Elaboration based on FAO´s statistics

3.3.2 Paper and Cardboard

3.3.2.1 Exports

Paper exports represent a small share of LAC's total paper production. Exports reached 3.45 Mt in 2022, equivalent to 14.7% of LAC production. Brazil led with a 65.6% share, followed by Chile (14.1%), Mexico (7.0%), Colombia (2.3%), Paraguay (2.0%), and Argentina (1.9%), as shown in the table below.

Table 9. Paper and Paperboard Export Volume in LAC (2022)

Country	Tons	Participation
Brazil	2,263,834	66%
Chile	485,355	14%
Mexico	242,264	7%
Colombia	79,295	2%
Paraguay	67,940	2%
Argentina	66,290	2%
Peru	53,590	2%
Ecuador	38,468	1.1%
Guatemala	31,180	0.9%
Costa Rica	29,185	0.8%
Panama	20,141	0.6%
Dominican Republic	18,995	0.6%
El Salvador	16,931	0.5%
Trinidad and Tobago	13,279	0.4%
Bolivia (Plurinational State of)	10,079	0.3%
Venezuela (Bolivarian Republic of)	4,146	0.1%
Other	5,477	0.2%
Total	3,446,450	100%

Source: Elaboration based on FAO statistics

3.3.2.2 Imports

In 2022, LAC paper and cardboard imports equaled nearly half of domestic production. The main paper buyers were Mexico, Chile, Guatemala, Chile, Colombia, Argentina, Peru, the Dominican Republic, Costa Rica, and Brazil. These countries accounted for 87% of total imports, as shown in the table below.

Table 10. LAC Countries Paper and Paperboard Import Volume (2022)

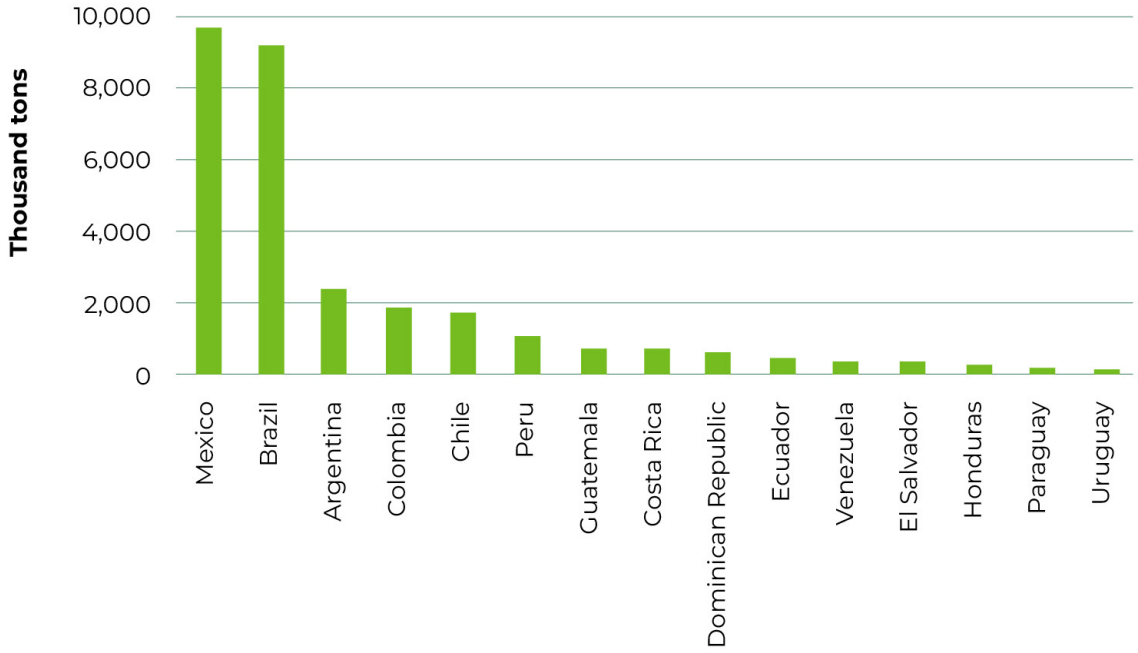
Country	Tons	Percentage
Mexico	3,527,265	36%
Chile	944,907	10%
Guatemala	731,110	7.5%
Colombia	668,228	6.8%
Argentina	656,037	6.7%
Peru	552,294	5.6%
Dominican Republic	484,940	5.0%
Costa Rica	474,596	4.9%
Brazil	469,757	4.8%
Ecuador	244,615	2.5%
El Salvador	229,870	2.4%
Honduras	209,227	2.1%
Paraguay	129,356	1.3%
Bolivia (Plurinational State of)	84,420	0.9%
Uruguay	70,380	0.7%
Panama	57,606	0.6%
Nicaragua	51,704	0.5%
Trinidad and Tobago	49,503	0.51%
Jamaica	36,573	0.37%
Venezuela (Bolivian Republic of)	32,614	0.33%
Cuba	20,248	0.21%
Haiti	8,559	0.09%
Guadeloupe	6,385	0.07%
Martinique	5,400	0.06%
Other	33,112	0.34%
Total	9,778,679	100%

Source: Elaboration based on FAO´s statistics

3.3.2.3 Apparent Consumption

In 2022, Mexico and Brazil had the highest paper and cardboard apparent consumption (over 9 Mt), followed by Argentina, Colombia, Chile, and Peru, with consumption between 1.0 Mt and 2.5 Mt. The remaining countries recorded consumption below 1 Mt. The figure below shows LAC countries with the highest apparent consumption of paper and cardboard.

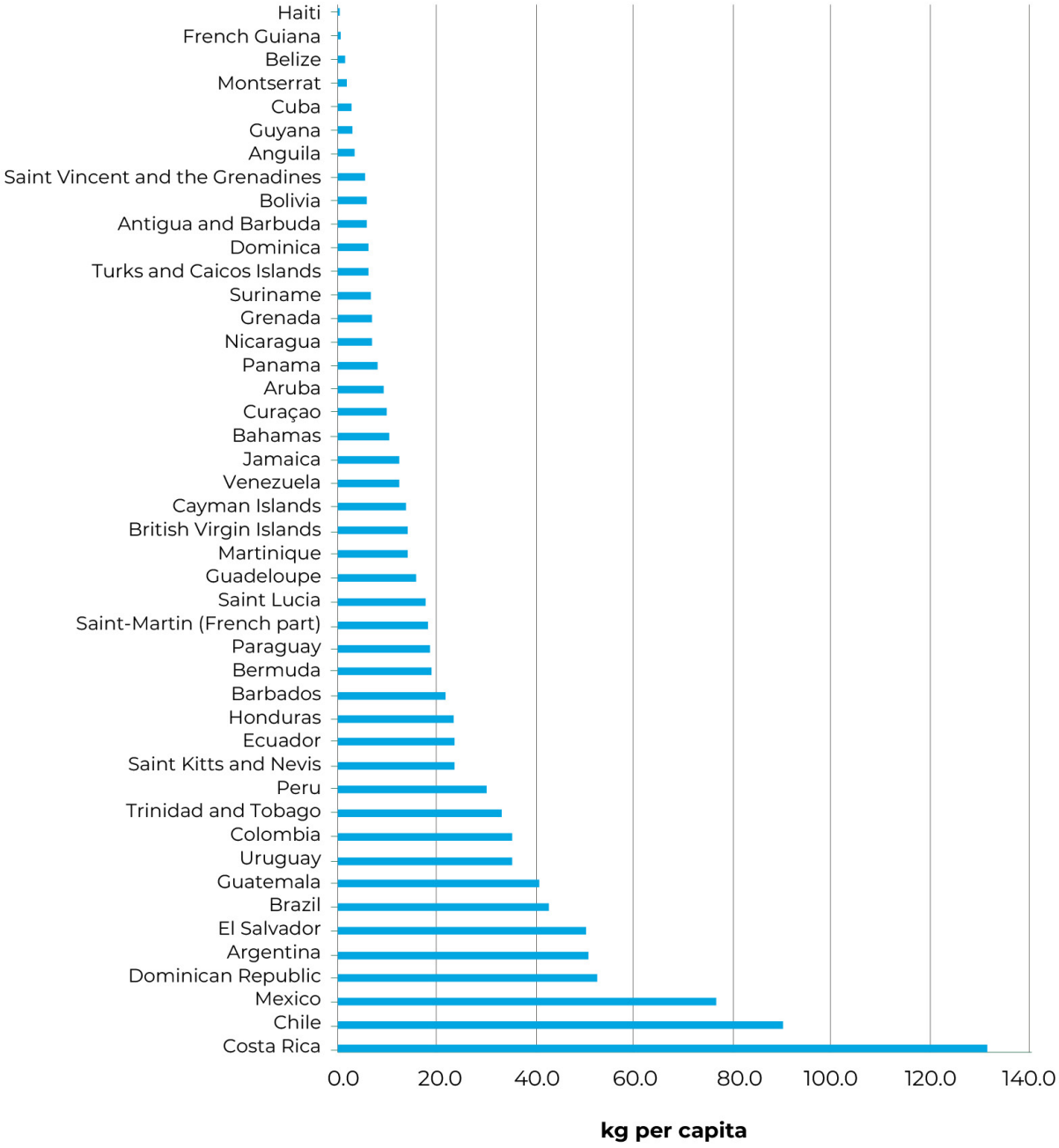
Figure 24. LAC Countries with the Highest Apparent Consumption of Paper and Cardboard by 2022



Source: Elaboration based on FAO´s statistics

In 2022, LAC consumed an average of 45.5 kg per inhabitant per year (kg/inhab/yr), while industrialized countries such as the United States, Japan, and Germany consumed between 150 and 200 kg/inhab/yr. Individually, Costa Rica and Chile had the highest consumption per capita in 2022, with 131 kg/inhab/yr and 90 kg/inhab/yr, respectively. Mexico, Dominican Republic, Argentina, El Salvador, Brazil, and Guatemala recorded consumption above 40 kg/inhabitant. Haiti, French Guiana, and Belize had the lowest consumption per capita in the region, as shown in the figure below.

Figure 25. Per Capita Consumption of Paper and Cardboard in LAC (2022)

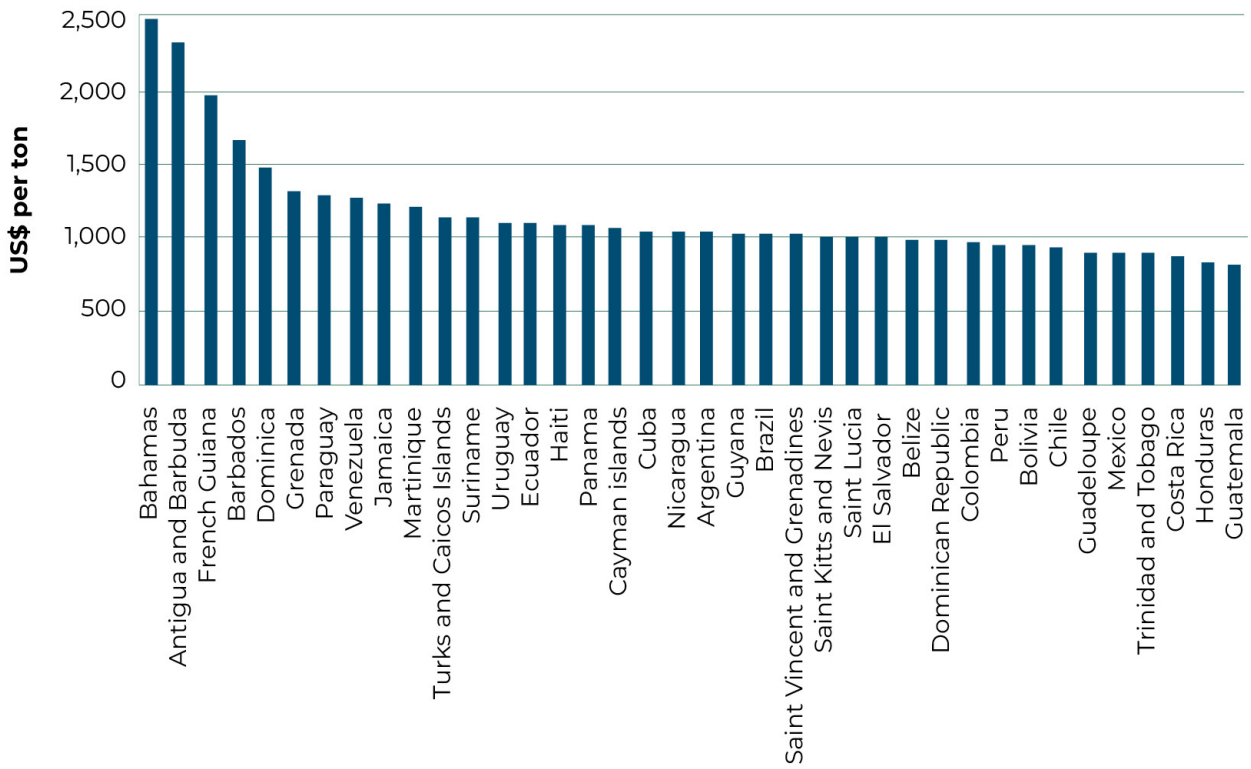


Source: Elaboration based on FAO´s and World Bank´s statistics as of 2020

3.3.2.4 Commercialization Values

Between 2010 and 2022, paper and cardboard commercial import values averaged USD $949/t. The region's lowest average import values were Guatemala (USD $814/t) and Honduras (USD $821/t). The Bahamas and Antigua and Barbuda had the highest average import values, at USD $2,480/t and USD $2,320/t, respectively, as shown in the figure below.

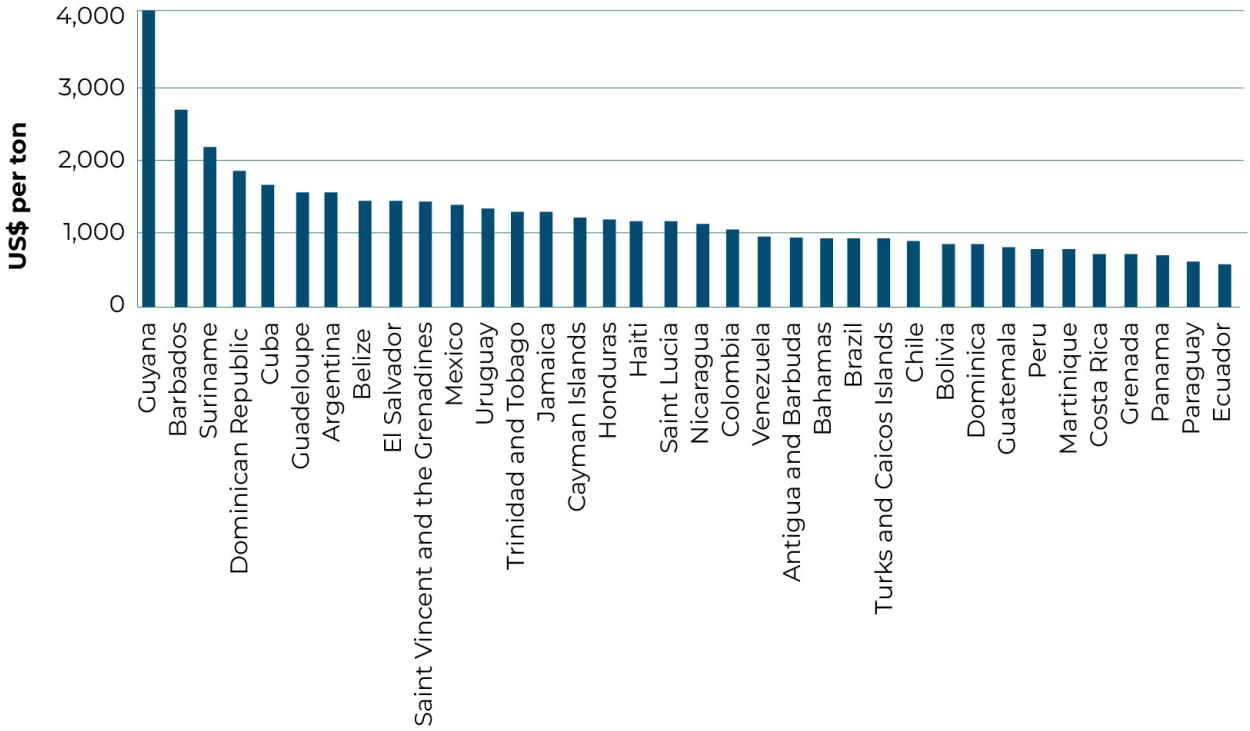
Figure 26. Average Import Values of Paper and Cardboard in LAC (2010-2022)



Source: Elaboration based on FAO´s statistics.

Paper export values also show a large variation across countries. The highest average export values were recorded in Guyana (USD $3,946/t) and Barbados (USD $2,607 /t), while the lowest were USD $583/t in Ecuador and USD $610/t in Paraguay. The figure below shows LAC's paper and cardboard average export value from 2010 to 2022 by country.

Figure 27. Average Export Values of Paper and Paperboard in LAC (2010-2022)



Source: Elaboration based on FAO statistics

4. Environmental Impact of the Industry

Pulp and paper industries emit pollutant gases that affect air quality and global climate change, including nitrogen dioxide, sulfur dioxide, chlorine dioxide, carbon dioxide (CO_2), and hydrogen sulfides (Jiang *et al.*, 2021). In addition, these industries generate other solid and liquid wastes[177], which may damage the local environment if not properly managed. This section focuses on pulp and paper industry CO^2 emissions.

In 2021, pulp and paper industries emitted a combined 190 Mt CO_2, equivalent to 2% of global industrial emissions (IEA, 2022). On average, producing a ton of paper generates between 0.6 t and 0.95 t CO_2e (Furszyfer Del Rio, *et al.*, 2022), while producing a ton of pulp generates between 0.4 t CO_2e (recycled pulp) and 0.51 tCO_2e (kraft pulp) (Sun *et al.*, 2018).

LAC emission factors are estimated from the average energy consumption recorded in the primary pulp and paper-producing countries (Brazil, Chile, and Uruguay). Data on direct emissions[178] and indirect emissions[179] is not available and is estimated based on averages of industrialized countries in Northern Europe (Yang, 2021). Individual emission factors for pulp and paper production fuels are considered for liquefied petroleum gas (LPG), natural gas (NG), liquid fuels (gasoline), wood, and black liquor in the table below.

[177] Per ton of product, pulp production generates 391 kg of solid waste, 78% of which is wood waste, 12.3% screenings, 2.5% sodium salts, and 7.2% causticizing residues (Gavrilescu et al., 2012). In addition, it produces ash and sludge at the outlet of drying processes. Chemical pulp production originates liquid effluents at the rate of 20 m3 - 50 m3 per ton of pulp, which may contain up to 15 kg/t of suspended solids (Gavrilescu et al., 2012). The paper industry generates paper sludge at a rate of 200 kg per ton, originating from additives used in preparing and conditioning fibers, which may also contain inks and soaps from recycled fibers (CPI, 2021).
[178] CO_2 emissions generated within the industry, resulting from the consumption of fuels for the generation of electric and thermal energy.
[179] CO_2 emissions from purchased electricity.

Table 11. Fuel Emission Factors

Fossils	2006 IPCC Factor (tCO_2 /GJ)	Fossil Matrix Participation in the Pulp Industry
LPG	0.063100	5%
Liquid Fuels (Gasoline)	0.069300	1%
Natural Gas	0.056100	67%
Weighted Average (pulp industry fossil emission factor)	0.056760	73%

Biofuels	2006 IPCC Factor (tCO_2 /GJ)
Black Liquor Products	0
Wood	0
Average	0

Source: Elaboration based on IPCC (2006)

Assumptions regarding pulp industry emissions calculations include that: i) biofuels cover 80% of the thermal energy demand, and liquid fossil fuels the remaining 20%; ii) 70% of industry electricity purchases are from hydroelectric plants, and the remaining 30% from thermal sources; iii) cogeneration covers 50% of kraft process electricity demand, and the remaining 50% is purchased electricity; and iv) bleaching and drying processes are included.

For the paper industry, it is assumed that 90% of thermal energy is generated from fossil fuels and 10% from biomass.

4.1 Emission Factors of Pulp and Paper Processes in LAC

Results indicate that LAC mechanical pulp production emits between 0.4367 tCO_2 /t and 0.6112 tCO_2 /t of dry pulp[180], depending on the process used. The CTPM processes had the highest emissions, driven by refining (67% of the total emission factor). The table below shows direct and indirect emissions by mechanical pulp production process.

[180] If the mechanical pulp drying process were not included, the emission factor would be reduced by an average of 20%.

Table 12. Emission Factors for Mechanical Pulp Production (tCO_2 /t of Dry Pulp)

Processes	Direct Emissions	Indirect Emissions	Total
Wood Chipping (all)	0	0.006	0.006
Wood Milling (GW)	0	0.339	0.339
Refining (PMR, TMP, CTMP)	0	0.408	0.408
Heating (TMP, CTMP)	0.0125	0.028	0.0405
Chemical Treatment (CTMP)	0	0.065	0.065
Washing and Screening (all)	0	0.011	0.011
Thickening (all)	0	0.013	0.013
Whitewashing (all)	0	0.021	0.021
Drying (all)	0.0207	0.019	0.0467
Total by Type of Pulp			
GW	0.0207	0.409	0.4367
PMR	0.0207	0.478	0.5057
TMP	0.0402	0.506	0.5462
CTMP	0.0402	0.571	0.6112

Source: Elaboration based on energy consumption presented by Rahnama *et al.* (2021) and CO_2 emission factors from IPCC (2006)

Kraft chemical pulp has the highest emissions intensity per ton of pulp produced, as compared to mechanical pulp manufacturing, reaching 0.617 tCO_2 /t of dry pulp181 in LAC. Of this total, 54% corresponds to direct emissions and the remaining 46% to indirect emissions. Within the production processes, digestion accounts for 42% of the total emission factor, followed by drying (14%). The auxiliary processes (liquor evaporation, recovery, and recaustification) account for 18% of emissions, as shown in the table below.

Table 13. Kraft Chemical Pulp Production Emission Factors ($tCO/t)_2$

Processes	Direct Emissions	Indirect Emissions	Total
Wood Chipping	0.000	0.014	0.014
Digestion	0.142	0.115	0.257
Blowing	0.024	0.018	0.042
Washing and Screening	0.000	0.014	0.014
Thickening	0.000	0.029	0.029
Bleaching	0.034	0.029	0.063
Drying	0.058	0.030	0.088
Black Liquor Evaporation	0.031	0.006	0.037
Black Liquor Recovery	0.026	0.014	0.040
Recaustification	0.021	0.012	0.033
Total	0.336	0.281	0.617

Source: Elaboration based ondata from Rahnama et al. (2021) and CO_2 emission factors from IPCC (2006)

It is important to note that the source of electricity used in the kraft process plays a significant role in determining the emissions factor. The analysis above assumes that 50% of electricity is self-generated with biomass (pulp waste) and 50% is from the grid. If instead, 100% of required electricity were supplied by self-generation with biomass, the total emissions factor would be reduced to 0.112 tCO_2/t of dry pulp. Many pulp producers in Latin America report co-generation in excess of their own needs, and so help to reduce CO_2 emissions from grid-supplied electricity, in addition to their own processes.

Substituting virgin pulp with recycled paper reduces emissions intensity by 50% to 70%. Pulp from recycled fibers emits 0.334 tCO_2/t of dry pulp, largely from the drying process, which represents 100% of direct emissions and 62% of total emissions, followed by paper shredding and fiber separation, with 25%. The table below breaks down direct and indirect emissions from recycled pulp production.

Table 14. Emission Factors of Recycled Pulp Production (tCO_2 /t of Dry Pulp)

Processes	Direct Emissions	Indirect Emissions	Total
Paper Shredding and Fiber Separation	0.000	0.084	0.084
Sieving	0.000	0.011	0.011
Deinking	0.000	0.017	0.017
Thickening	0.000	0.009	0.009
Bleaching	0.000	0.006	0.006
Drying	0.023	0.019	0.208
Total	0.023	0.146	0.169

Source: Elaboration based on energy consumption presented by Rahnama *et al.* (2021) and CO2 emission factors from IPCC (2006)

LAC paper production emission factors average 0.396 tCO_2 /t of product. Producing printing and writing paper generates the highest emissions while packaging and newsprint generate the lowest. Direct emissions account for 73% of total emissions, all of which are from thermal energy for paper drying. Paper forming and pressing generates 91% of indirect emissions, the rest is from drying. The table below breaks down paper production emission factors by type and process.

Table 15. Emission Factors for Paper Production (tCO_2 /t)

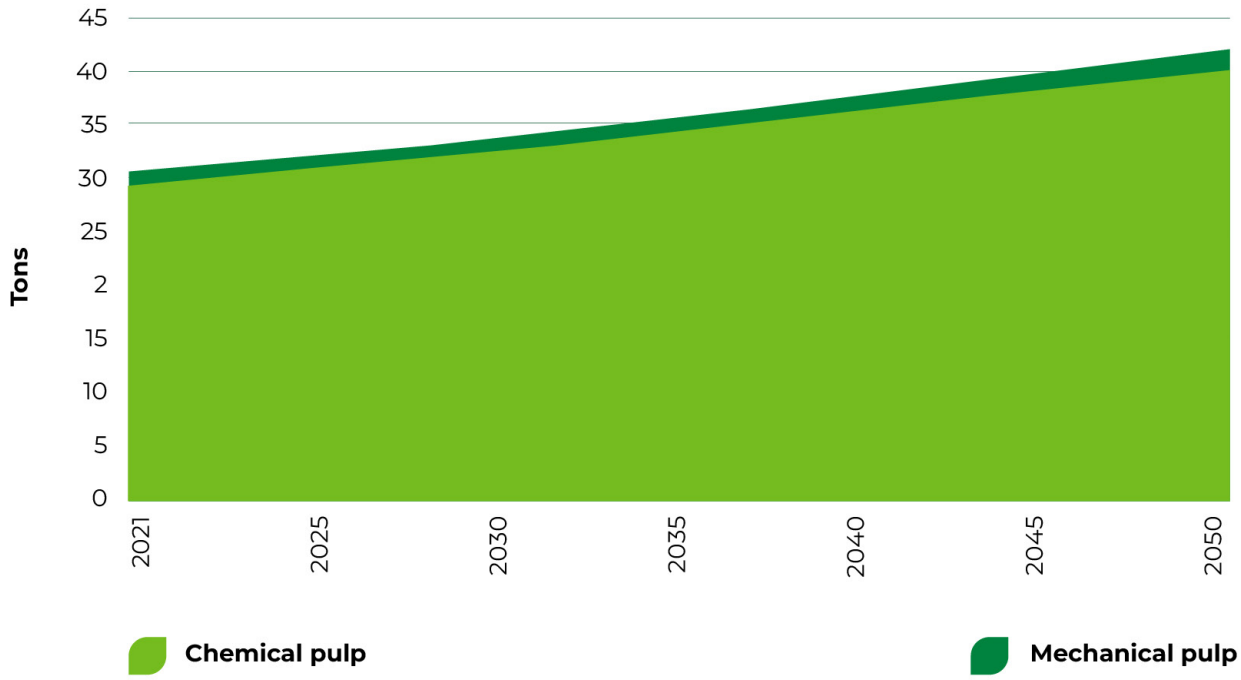
	Direct Emissions		Indirect Emissions		
Paper Type	Forming and Pressing	Drying	Forming and Pressing	Drying	Total
Newsprint	0.0	0.264	0.090	0.006	0.360
Printing Paper	0.0	0.338	0.113	0.006	0.457
Writing Paper	0.0	0.326	0.113	0.006	0.444
Tissue Paper	0.0	0.258	0.114	0.028	0.400
Wrapping Paper	0.0	0.258	0.058	0.003	0.319
Average	0.0	0.289	0.097	0.010	0.396

Source: Elaboration based on energy consumption presented by Rahnama et al. (2021) and CO2 emission factors from IPCC (2006)

4.2 Projected Pulp and Paper Production in LAC

FAO estimates (2022) indicate that LAC primary pulp production will grow 36.6% by 2050, equivalent to 1.22% average annual growth. Mechanical pulp is projected to reach 1.45 Mt and chemical pulp 40.71 Mt, for a total of 42.16 Mt[182]. The figure below projects pulp production to 2050.

Figure 28. Projected Growth of Primary Pulp Production in LAC

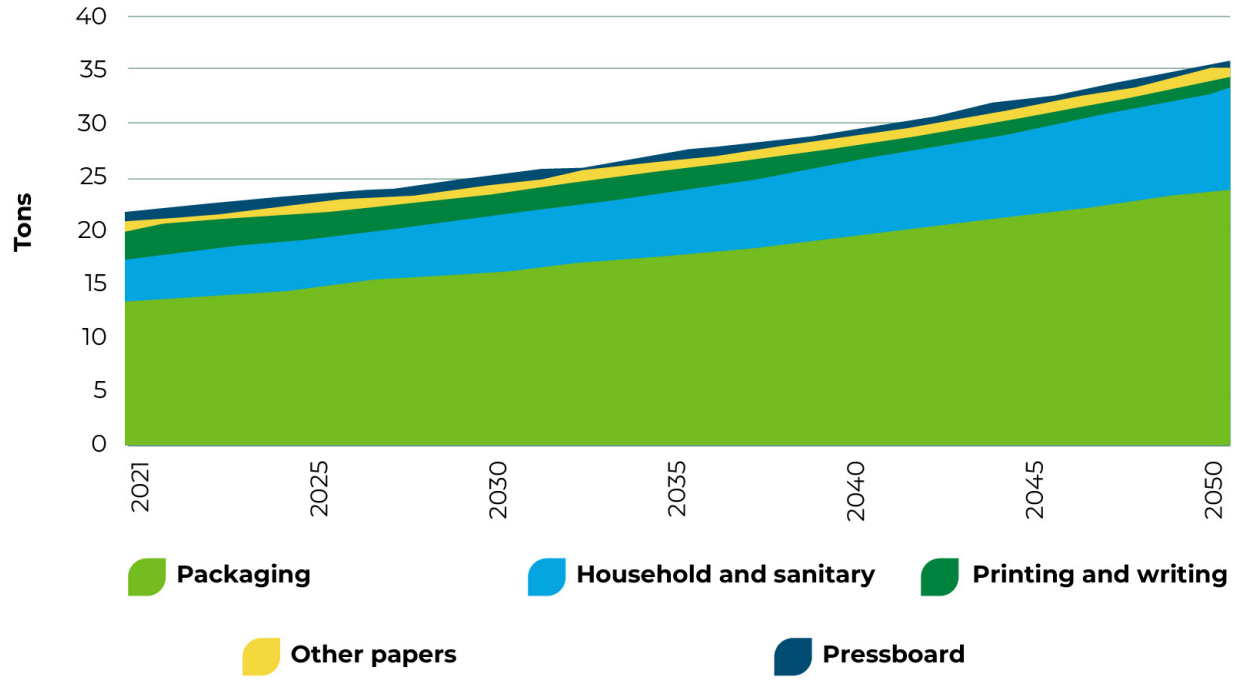


Source: Elaboration based on FAO´s statistics

Paper production is forecast to grow 1.7% per year on average, reaching a volume of 36 Mt in 2050. Packaging paper production grows 1.96% per year to contribute 67.63% to this total, followed by household and sanitary papers growing 3.0% per year to contribute 26.54%, as shown in the figure below.

[182] Based on production trends observed for the period 2010-2020, it was assumed that mechanical pulp production in the region will decrease 0.08% per year and chemical pulp production will increase 1.14% per year until 2050.

Figure 29. Projected Growth of LAC Paper Production

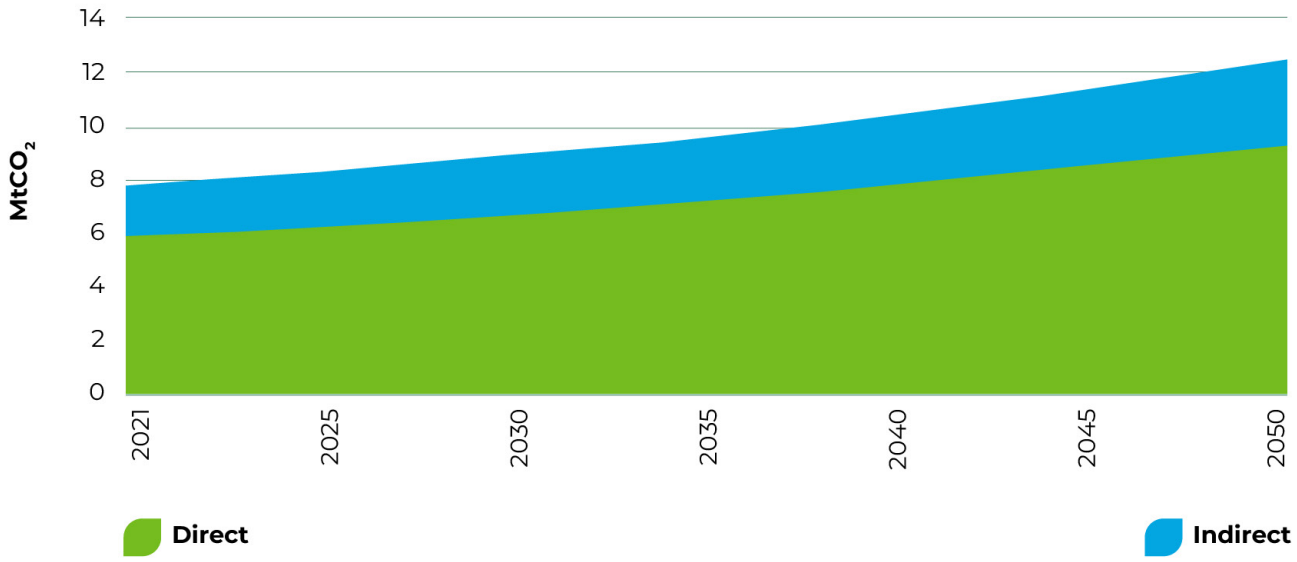


Source: Elaboration based on FAO´s statistics

4.3 LAC Projected Emissions for the Pulp and Paper Industry

By 2050, primary pulp production CO_2 emissions will increase 38%, from 41.4 Mt in 2021 to 56.9 Mt[183]. Of this total, 79% corresponds to direct emissions, as shown in the figure below.

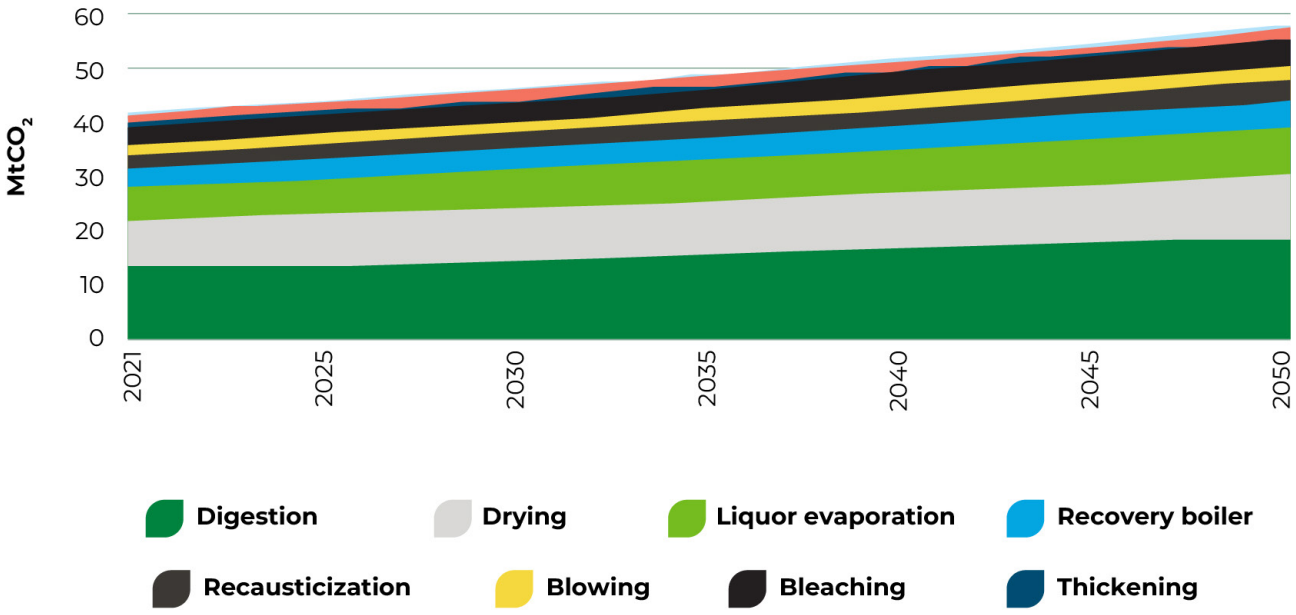
Figure 30. CO_2 Emissions of LAC Primary Pulp Production by 2050



Source: Produced in-house
[183] Based on aggregate production of CTMP and kraft pulp.

The kraft method will contribute 97.8% (55.6 $MtCO_2$) of total emissions and CTMP the remaining 2.2% (1.26 $MtCO_2$). In addition, kraft pulp contributes 99% of direct emissions (44.3 $MtCO_2$) and 93.2% of indirect emissions (11.4 $MtCO_2$). Within the main kraft pulp production line, digestion and pulp drying account for 52% of emissions (29.2 $MtCO_2$ in 2050). In the auxiliary production line, liquor evaporation, recovery, and recaustification add 31% of emissions (17.1 $MtCO_2$ in 2050). The figure below shows kraft pulp production emissions by process stage.

Figure 31. CO_2 Emissions Kraft Pulp Production in LAC to 2050

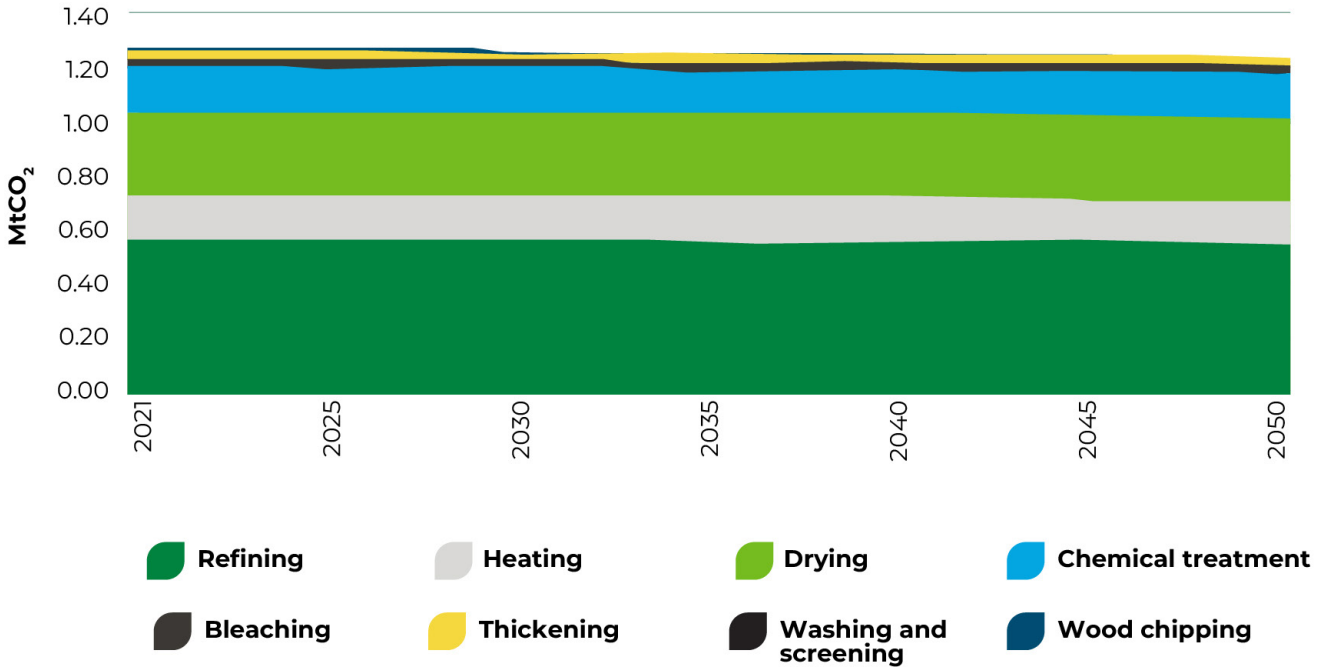


Source: Produced in-house[184]

In the CTMP process, refining, heating, and drying contribute 86.6% of emissions (1.1 $MtCO_2$ in 2050). The figure below details CTMP pulp production emissions.

[184] For certain companies in the region, the highest emissions are concentrated in Scope 3 companies.

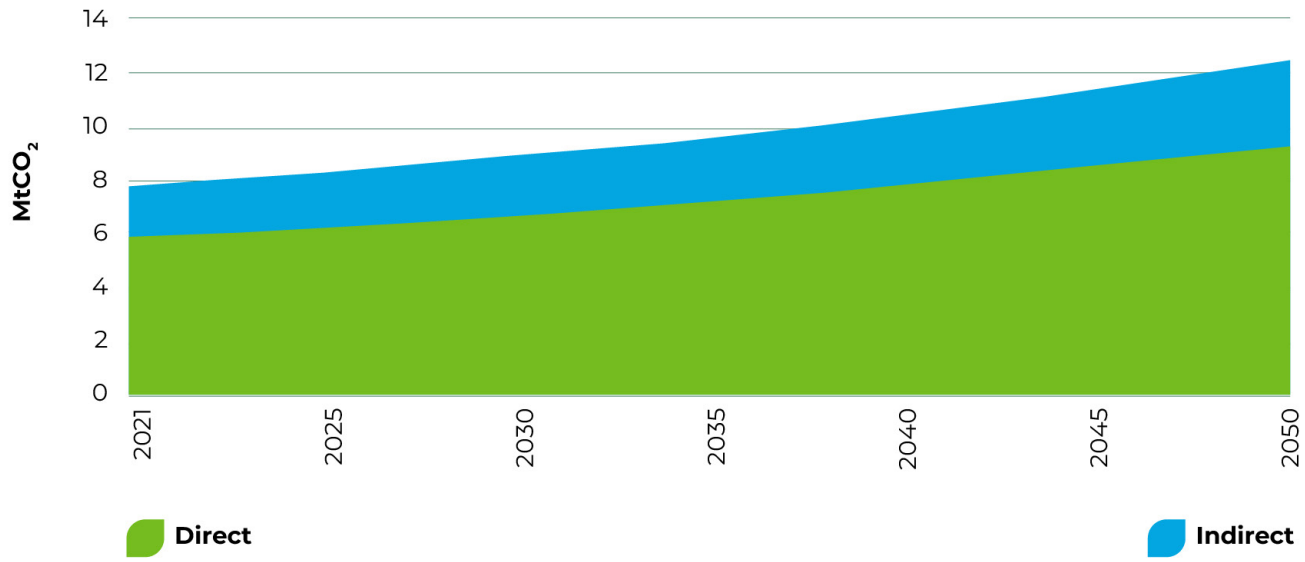
Figure 32. CO_2 Emissions LAC CTMP Production by 2050



Source: Produced in-house

Paper production CO_2 emissions are projected to increase by 60% from 2021 to 2050, reaching 12.5 $MtCO_2$. Of the total, direct emissions account for 75%, as shown in the figure below.

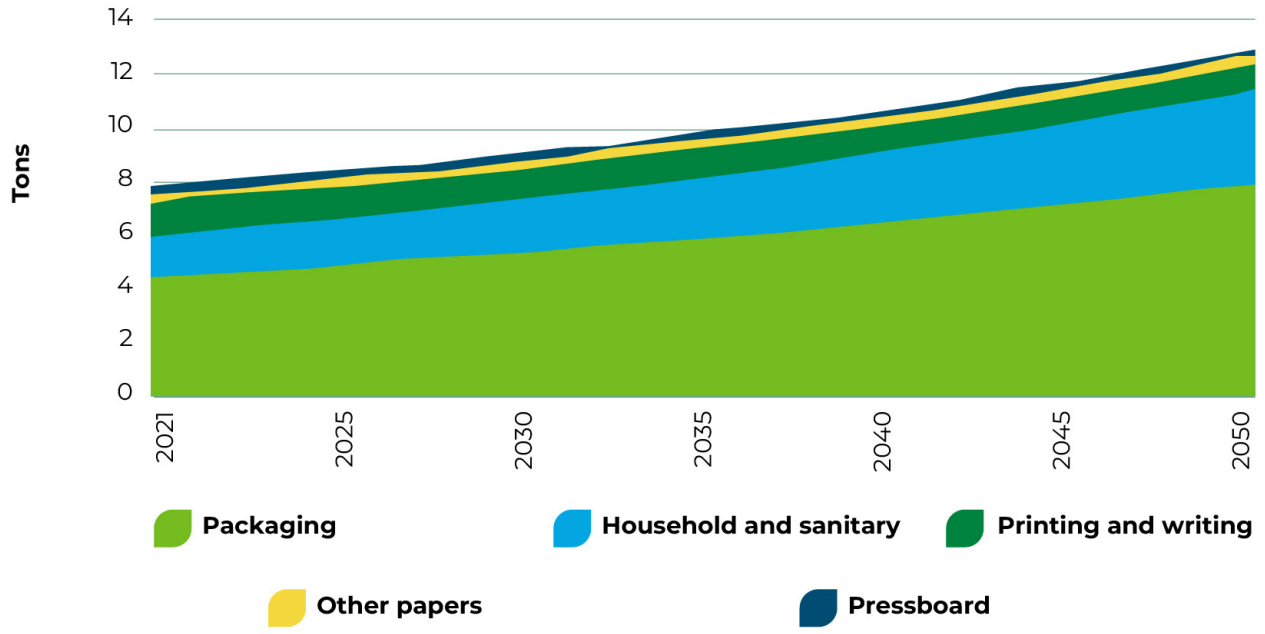
Figure 33. CO_2 Emissions for LAC Paper Production by 2050



Source: Produced in-house

Packaging paper and household and sanitary paper account for the largest share of CO_2 emissions, contributing 62.1% and 30.6%, respectively. Printing and writing paper contributes 4.9%, other papers (2.4%), and newsprint (0.04%), as detailed in the figure below.

Figure 34. LAC CO_2 Emissions by Type of Paper by 2050



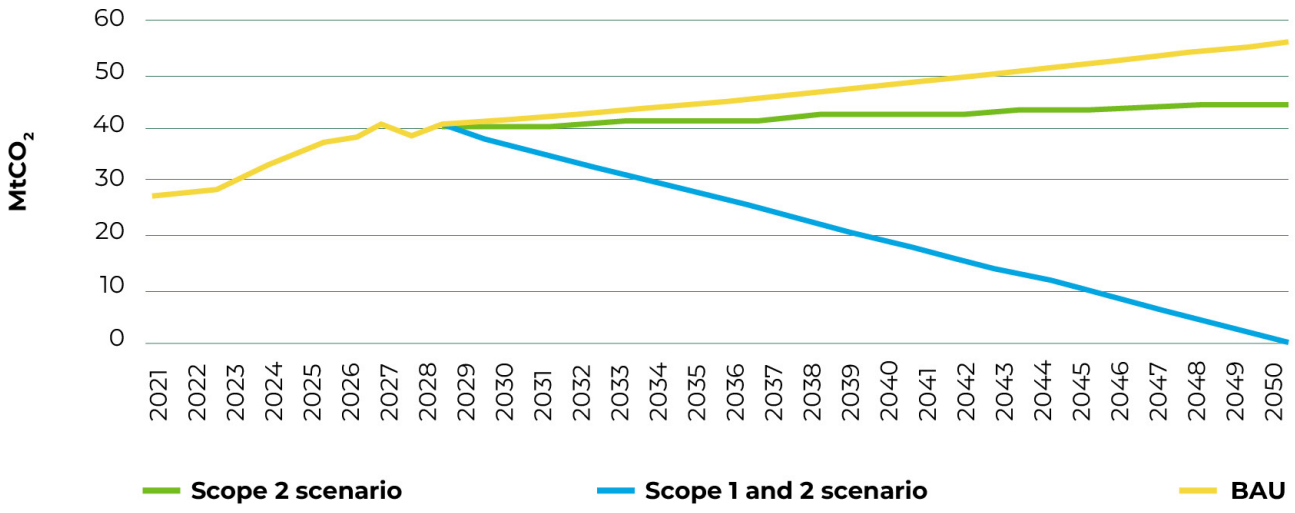
Source: Produced in-house

5. Pulp and Paper Decarbonization in LAC

5.1 Decarbonization Scenario for LAC

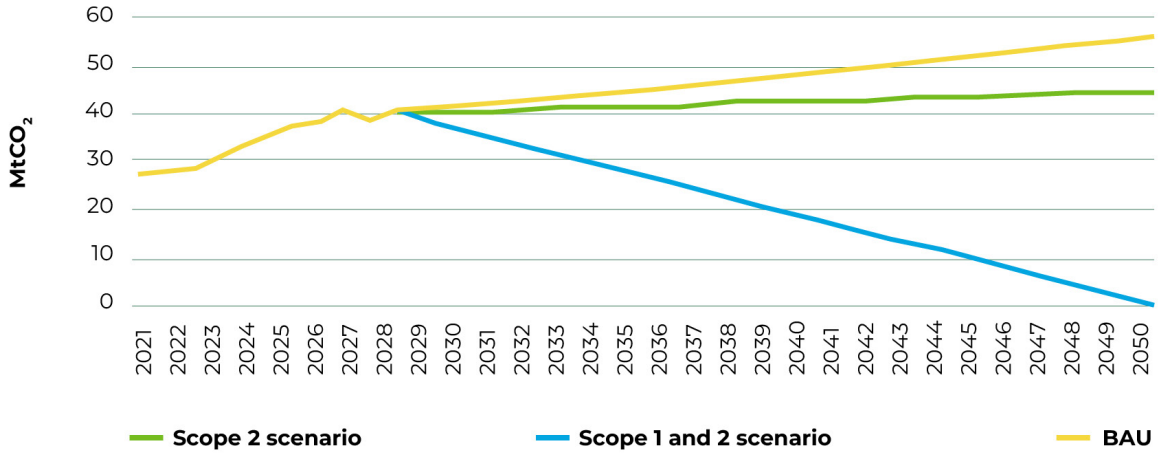
This section considers a scenario to achieve a 100% reduction in pulp and paper industry direct (Scope 1) and indirect (Scope 2) emissions by 2050. The figures below show the decarbonization scenarios for the pulp and paper industry, respectively. The figures compare a business as usual (BAU) case against 100% reduction of Scope 1 emissions and 100% reduction of both Scope 1 and Scope 2 emissions.

Figure 35. Decarbonization Scenario for Primary Pulp Production in LAC



Source: Produced in-house

Figure 36. Decarbonization Scenario for Paper Production in LAC



Source: Produced in-house

For both industries, the analyzed scenarios exclude Scope 3 emissions, i.e., extraction and primary processing of wood and emissions from the use of auxiliary materials and transport of by-products in different processes. The table below identifies Scope 1 and 2 emissions, according to the processes considered in this analysis.

Table 16. Scope 1 and 2 Emissions from the Pulp and Paper industry

Pulp Industry	Scope
Mechanical Pulping	
Wood Chipping	1
Wood Milling	1
Refining	1
Heating	1 & 2
Chemical Treatment	1
Washing and Screening	1
Thickening	1
Bleaching	1
Drying	1 & 2
Chemical Pulp (Kraft)	
Wood Chipping	1
Digestion	1 & 2
Blowing	1 & 2
Washing and Screening	1
Thickening	1
Bleaching	1
Drying	1 & 2
Liquor Evaporators	1 & 2
Recovery Boiler	1 & 2
Recaustification	1 & 2
Paper Industry	**Scope**
Forming	1
Pressing	1
Drying	1 & 2

Source: Produced in-house

5.2 Mitigation Trends

Several technologies and approaches are available to mitigate CO_2 emissions in the pulp and paper industry. This section first reviews alternatives to reduce carbon emissions related to generating the heat used in pulp and paper manufacturing. Next, it examines ways to reduce carbon emissions in other components of pulp and paper manufacturing.

5.2.1 Energy Alternatives

One path to pulp and paper decarbonization involves adopting cleaner, lower-carbon energy alternatives, such as hydrogen, biogas, geothermal, biomass, and electrification. These alternatives are described below.

5.2.1.1 Clean Hydrogen

Clean hydrogen's economic viability in the pulp and paper industry is currently limited[185] due to its low level of development and competitiveness, as compared to other decarbonization technologies, although business synergies related to its adoption may improve the conditions for its adoption.

Clean hydrogen would replace natural gas for heat generation, mainly in paper drying processes. Pilot projects to validate its use include Essity, a German hygiene and health company, which is using clean hydrogen to operate the paper drying hood at its Mainz-Kostheim production facilities[186]. As the technology matures, there is significant potential for regional implementation. LAC is expected to be one of the most competitive regions for hydrogen production by 2030.

Chile, Colombia, Brazil, and Costa Rica are currently deploying clean hydrogen projects for industrial use (Diazgranados *et al.*, 2022). The current high cost of production (USD $4 to $6/kg) (IRENA, 2022) is the main obstacle to widespread use. In addition, the cost to convert pulp and paper drying equipment to use clean hydrogen is estimated to be between USD $50/kW - USD $200/kW. The adaptation of steam boilers is expected to cost between USD $90/kW and USD $200/kW (Durusut *et al.*, 2019).

5.2.1.2 Biogas from Wastewater

Producing biomethane through the anaerobic digestion (AD) of pulp and paper wastewater would help diversify access to renewable energy sources and mitigate both fossil fuel consumption and CO_2 emissions. Wastewater AD is estimated to reduce CO_2 emissions by 500 g/m3 of treated water, and an average of 7 $kgCO_2$ /kg of pulp (Berger *et al.*, 2021). AD has been applied to renewable gas production in mechanical and chemical (sulfite) pulp mills, as well as in recycled paper production plants. However, in kraft pulp mills, its application has been little studied (Ekstrand, 2019). The main technical limitation to pulp and paper industry biomethane production is the presence of chemical compounds in the wastewater and that inhibit AD, such as chlorine from bleaching processes. This measure's economic feasibility and energy savings depends on the pulp production process and the size of the plant.

5.2.1.3 Gas Recovered from Municipal Solid Waste (MSW) Landfills

Captured landfill gas has been successfully used in industrial boilers, dryers, furnaces, and heaters. Its direct use offsets fossil fuel consumption in thermal processes[187]. In LAC, the main cities in Brazil, Chile, Mexico, and Uruguay have the required infrastructure to capture and use landfill gas to

[185] The adoption of this technology is mainly evaluated in transportation logistics systems that could achieve competitive values, with respect to substitute fuels.
[186] https://www.essity.com/media/press-release/essity-launches-green-hydrogen-pilot-for-co-2-free-tissue-production/9259da573b0f34bf/
[187] https://www.epa.gov/lmop/basic-information-about-landfill-gas#landfill

produce energy. Landfills in cities with more than 500,000 inhabitants have an estimated 810 MW gas production potential (ESMAP, 2006). LAC produces about 541,000 tons/day of municipal waste, which is estimated to increase by at least 25% by 2050. Of this total, about 27% end up in improperly managed landfills, reducing the capture potential (Savino, *et al.*, 2018). In addition, relatively high capital, operational, and maintenance costs may pose a barrier to investment for some LAC countries. MSW landfill gas recovery systems have an estimated current capital cost between USD $0.9/GJ and USD $8.2 /GJ, while operation and maintenance costs are between USD $2/GJ and USD $17.3/GJ (IEA, 2020).

5.2.1.4 Geothermal

Geothermal has applications for pulp and paper industry heat-using processes, such as digestion, pulp thermal treatment, black liquor evaporation, and drying, among others (Moya and Pavel, 2018). LAC's 11 GW to 55 GW geothermal potential remains mostly untapped (Gischler, *et al.*, 2020). Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Bolivia, Chile, and Guadeloupe have installed geothermal capacity and proven experience in geothermal energy use. However, the high cost (on average, USD $4 million per MW) of geological exploration and the investment risk involved limit its development (Gischler, et al., 2020). Steam generation from geothermal energy is estimated to cost USD $3,125/kWt on average, with a USD $940/kWt deviation. Fixed operating costs are roughly USD $134/kWt/year (Rademaker & Marsidi, 2019).

5.2.1.5 Biomass Gasification

Gasifying biomass reduces dependence on fossil fuels and contributes to generating zero-carbon energy. In the pulp and paper industry, both black liquor and wood and paper residues (lignocellulosic biomass) could be gasified, as detailed below.

5.2.1.5.1 Black Liquor Gasification

Black liquor gasification (BLG) replaces the conventional liquor recovery cycle, generating energy more efficiently. The gas can be used directly to generate thermal energy in the digestion, liquor evaporation and pulp drying processes, or can produce electricity when integrated with combined cycle technology (BLGCC), doubling the energy efficiency (based on the calorific value of the black liquor). This is equivalent to an additional 900 kWh per ton of pulp produced, as compared to a conventional recovery boiler system (Naqvi *et al.*, 2010; Moya and Pavel, 2018). However, BLG capital costs are estimated to be USD $260 - USD $650 million, or two to three times a conventional recovery boiler. In turn, annual non-fuel operation and maintenance costs are estimated at USD $10 - USD $30 million (Bajpai, 2016).

5.2.1.5.2 Gasification from Industrial Wastes (Wood and Paper)

Gasification projects from paper industry residues show 30% fossil fuel consumption reductions (IEA Bioenergy, 2020). Using the gas in combined cycle technologies that replace old steam turbines improves energy efficiency a further 20-30% (Rey et al., 2021). Capital costs to gasify wood and paper waste vary between USD $9/GJ and USD $18/GJ (Larson *et al.*, 2006).

5.2.1.6 Electrification for Heat Generation

Electricity can replace fossil fuels to generate high-temperature heat through the use of heating elements, infrared, induction, microwave, and plasma (Madedu *et al.*, 2020). It is easier to regulate heat temperature with electric systems and they have lower maintenance costs compared to other heating technologies. Electrification is also simple to implement because the primary process does not have to be completely redesigned. This technology has low investment costs of between USD $190 /kW and USD $240 /kW (Rademaker & Marsidi, 2019).

5.2.2 Other Alternatives

Cleaner, lower-carbon energy alternatives that can be applied to other components of the pulp and paper manufacturing processes include electricity from renewable energy sources, carbon capture and storage, energy efficiency measures, and increasing the use of recycled materials in pulp production. These alternatives are described below.

5.2.2.1 Electricity from Renewable Energy Sources

The electricity required for pulp and paper manufacturing can be generated from renewable resources rather than traditional fossil fuels. As noted in Section 5.1.1, much of the electricity used in kraft process pulp manufacturing in Latin America is already provided by biomass, and many plants sell excess zero-carbon electricity to the grid. Vertically integrated pulp and paper companies with land and forests can also partner with electricity project developers to install wind farms or solar photovoltaic farms, among others.

Hydropower has the best potential, as it allows for a reliable and continuous supply to electricity-intensive processes, such as pulp and paper drying. Hydro systems, combined with solar and wind energy, also have potential. The cost of capital (CAPEX) and levelized cost of energy (LCOE) for hydroelectric, solar, and wind generation are highly competitive. The table below shows the CAPEX and LCOE for the primary renewable electricity generation technologies.

Table 17. CAPEX and LCOE of Electricity Generation Technologies (2023)

	Capital cost (USD / kW)			LCOE (USD / kWh)		
	Min.	Max.	Weighted average*	Min.	Max.	Weighted average*
Solar Photovoltaic	526	1663	758	0.031	0.110	0.044
Onshore Wind	777	2115	1160	0.019	0.072	0.033
Hydropower	1245	8504	2806	0.027	0.320	0.057
Bioenergy	877	4596	2730	0.056	0.135	0.072
Offshore Wind	1605	5601	2800	0.053	0.171	0.075
Geothermal	3413	6595	4589	0.053	0.094	0.071
Concentrated Solar Power	5968	7940	6589	0.107	0.139	0.117

* According to generation

Source: Elaboration based on IRENA

5.2.2.2 Carbon Capture and Storage

The pulp and paper industry can contribute to negative emissions by applying carbon capture, use, and storage (CCUS) to the steam-generating boilers and kilns used in kraft pulp mills (Svensson et al., 2021). If biomass used for boilers is managed sustainably, its CO_2 emissions from power generated may be considered neutral. In this neutrality scenario, capturing and storing biomass-fired power generation emissions would provide a carbon sink and be classified as negative (Moya and Pavel, 2018). At present, the absence of a market for negative CO_2 emissions discourages the pulp and paper industry from implementing CCUS technologies. CCUS studies in pulp and paper mills indicate that CCUS project developers require negative CO_2 emission credits valued at between USD \$70/tCO_2 and USD \$100/tCO_2 to reach cost parity (Onarheim *et al.*, 2017a, 2017b). Retrofitting a pulp mill for post-combustion CCUS costs between USD \$120/tCO_2 and USD \$140 /tCO_2 (Nwaoha & Tontiwachwuthikul, 2019).

5.2.2.3 Energy Efficiency

Low-cost, high-impact energy efficiency measures include incorporating technologies in wood chip digestion and black liquor evaporation (kraft pulp); wood chip refining (mechanical pulping); and paper dewatering and drying (paper production). The EE technologies applicable to each of these processes are described below.

5.2.2.3.1 Kraft Pulp Production

- **Use cold blowing to improve batch digestion.** This technology consists of recovering the heat from cooling the pulp discharged from the batch digester, for use in the next cooking process. Once the pulp reaches the target cooking temperature in the digester (160°C and 170°C), the digester is filled from the bottom with liquor to reduce the temperature below 100°C and perform the blowing process at a lower temperature (cold). The cold liquor vertically displaces the hot liquor, which is then filtered and stored to be used in the subsequent cooking process. By reusing the recovered hot liquor, the cooking heating time is reduced by 50%, and the digestion steam consumption between 2.4 GJ/t and 4.1 GJ/t (on average a 41% reduction) (Bajpai, 2016). The cold blowing method requires additional pumps to transfer liquor between various tanks and pressure accumulators. The digesters must also be able to inject cold liquor and extract hot liquor during the process. Implementing this technology requires an estimated investment of USD $6 to USD $8/t of product (Berger *et al.*, 2021).

- **Improve black liquor evaporation efficiency.** Minimizing the water that must be evaporated can significantly improve the boiler's thermal performance. The black liquor's dry solids content can be increased by installing a solids concentrator between the evaporator and the recovery boiler. Increasing the dry solids content by, for example, 15%, would save an estimated 59 kWh/t black liquor. Based on Suhr *et al.* (2015), a kraft pulp production plant with 1,500 t/d capacity would require between USD $2.4 - USD $2.8 million to increase the black liquor solids content by 7%,; between USD $4.9 - USD $5.6 million to increase it by 12%, and between USD $11.2 - USD $12.6 million to increase it by 17%.

- **Oxygen-enriched combustion.** Oxygen enrichment improves combustion efficiency in processes requiring high temperatures such as kraft pulp manufacturing black liquor recovery and recausticizing process (Mittal *et al.*, 2020). Oxygen enrichment of the recovery and recausticizing furnaces can reduce fuel requirements by 7% to 12%. The required capital investments are low (approximately USD $100,000[188]) and are limited to feed pipes, an oxygen injection lance, and controls (Berger *et al.*, 2021). Payback periods for these investments are estimated to range from one to three years. However, this method's operations may be expensive and require additional space for oxygen storage.

5.2.2.3.2 Mechanical Pulp Production

- **Refining process optimization.** Refining efficiency can be improved by replacing oversized mills or mills that have reached the end of their useful life. Retrofitting a high-efficiency refiner in new or existing plants depends on the raw material used, as well as the pulp's required properties. Replacing machinery, including feed pumps, refining, and storage boxes, has high investment costs. Installing an efficient 300 dry ton per day refiner can reduce energy consumption by 7% to 20% and cost roughly USD $840,000 (Suhr *et al.*, 2015), equivalent to USD $7.6/t pulp. Based on data from Martin et al. (2000), improving refining efficiency would cost an estimated USD $15.4/t of pulp.

[188] Equivalent to 0.9 USD/t pulp, for a pulp mill with installed capacity of 200,000 t/year and a black liquor recovery factor of 1.7 t/t pulp (Piedralba et al., 2013).

It is challenging to improve energy efficiency for the mechanical wood disintegration stages, as they are directly linked to the raw material's physical and chemical properties, such as wood moisture content, density, strength properties, bark content, chemical composition, chip dimensions, and species used. Wood moisture content has the greatest impact on processing energy consumption and a pulp mill's economical operation. (Eisenlauer & Teipel, 2020; Nuengwang *et al.*, 2020).

Consequently, using variations in moisture content to optimize pulp mill operations in real-time could improve wood pretreatment energy efficiency. To do so, models and control systems to improve the wood pre-drying processes are needed, as are mill air flow speed and control adjustments. Monitoring moisture content in real time during the milling process is key to ensuring it remains within established parameters.

- **Biopulping.** This consists of treating wood chips with biological agents (fungi) to degrade the lignin. After chipping, the chips are heated to 100o C to eliminate any pathogens that may affect the fungus. They are then air cooled and the fungus and nutrients are added. The treated chips are placed in a pile for one to four weeks to give the fungus time to degrade the lignin. This process reduces electricity consumption 25-40%, as compared to mechanical refining (Martin *et al.*, 2000). However, biopulping consumes an additional 0.5 GJ/t of steam and requires space to store the treated chips. Based on data provided by Scott and Swaney (1998), biopulping is estimated to cost between USD $27/t and USD $36/t of pulp.

5.2.2.3.3 Paper Production

- **Waste heat recovery.** Heat recovery systems can reduce a paper mill's primary energy consumption in an economically cost-effective way for both new and existing plants. Installing radial blowers in the vacuum system can save between 20 kWh/t of paper and 30 kWh/t of paper. Using thermocompressors in the dryer section can reduce steam demand and energy consumption by 25 kWh/t of paper. Recovering heat from the paper machine hood also has the potential to save 200 kWh per ton of product (Berger *et al.*, 2021). Heat recovery measures' capital investment is estimated to be between USD $3.2/t, and USD $4.8 per ton of paper.

- **Increase paper dehydration in the press section.** Paper is normally 50-55% water when it exits the press machine, leaving approximately one kilogram of water per kilogram of raw material. Increasing dewatering in the press would reduce energy consumption in the dryer section. Shoe press technology can reduce dryer steam consumption by 20% to 30% (Berger *et al.*, 2021). Although the shoe press may require more electricity than standard presses, the resulting reduction in steam consumption is greater than the increase in electricity consumption. Installing a shoe press in an existing system also increases production capacity by 10-20%. The investment cost of a 5-meter wide shoe press is estimated to be USD $14 million.

- **Energy-efficient frequency converter.** This measure consists of using pumps, fans, and compressors with frequency variation or variable speed systems. Speed variations allow the equipment to adapt and optimize energy consumption to match the process demands. Using frequency converters can save 10.5 kWh per ton of product and can be applied to both new and existing installations (Berger *et al.*, 2021). Motors that could be optimized with variable speed drives include paper machine pumps, dryer fans and any pump or compressor with variable flow. Installing variable speed drives is estimated to cost between USD $0.6/ton and USD $1.1/ton.

- **Condensing boilers.** Condensing boilers use a heat exchanger to recover and convert heat from the exhaust steam into useful energy (Ghosh, 2011). They can operate at lower temperatures than conventional boilers, which reduces the risk of corrosion and increases the equipment lifespan. Using condensing boilers in the paper and cardboard drying can reduce energy demand between

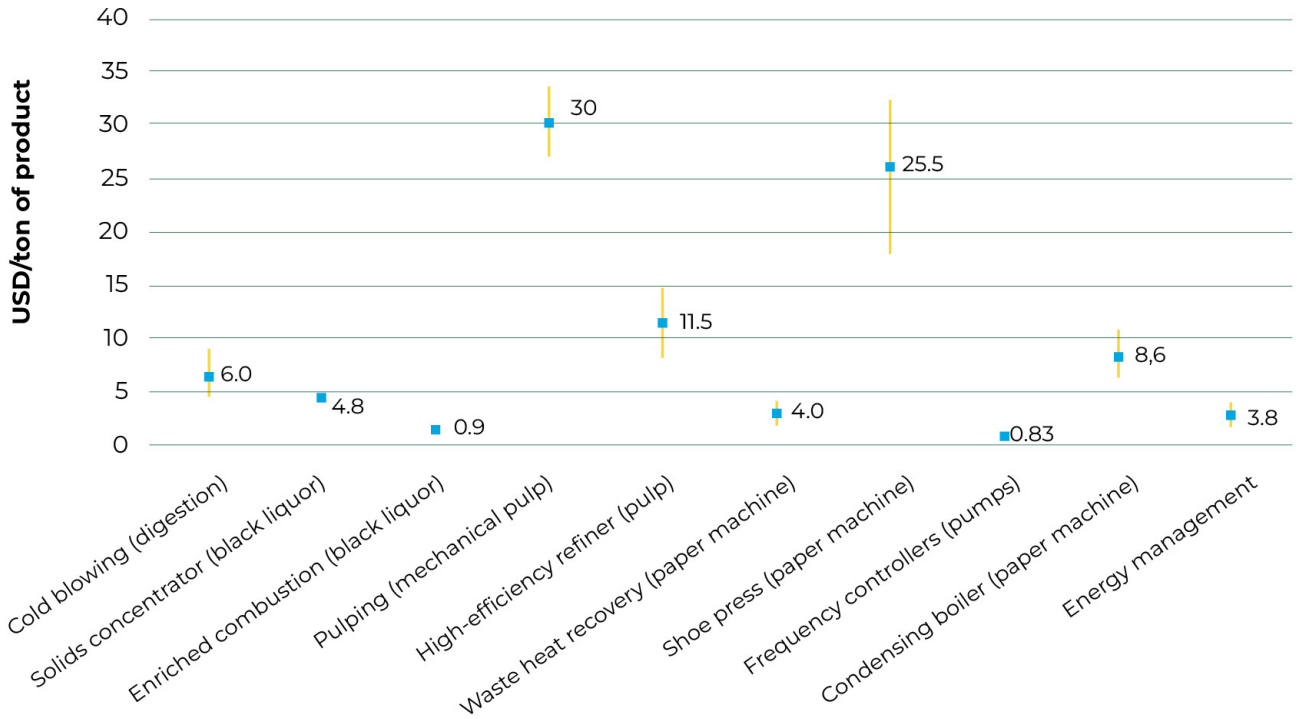
20%[189] and 25%[190]. For the pulp and paper industry, condensed steam recovery costs are estimated between USD $3.85 and USD $4.51/t steam (Alí *et al.*, 2018), equivalent to USD $6.40/t paper and USD $10.8/t paper[191].

5.2.2.3.4 All Processes

Real-time energy management system. An energy management system continuously monitors and optimizes interactions between processes in a system to minimize energy use. Implementing an energy management system could save an estimated 111 kWh/t product, at an average cost of USD $3.8/t (Berger *et al.*, 2021).

The figure below summarizes the cost of pulp and paper energy efficiency measures.

Figure 38. Cost of Energy Efficiency Measures



Source: Elaboration based on Berger et al. (2021); Alí *et al.*, 2018; Suhr et al. (2015); Martin *et al.* (2000)

[189] https://www.spiraxsarco.com/customer-stories/flash-steam-recovery-help-smurfit-kappa-cut-boiler-fuel-costs
[190] https://www.spiraxsarco.com/customer-stories/heat-recovery-system-to-reduce-emissions
[191] Assuming steam consumption per ton of paper ranges from 1.8 to 2.4 tons (Bhutani *et al.*, 2013).

5.2.2.4 Manufacturing Pulp from Recycled Fibers

Producing recycled pulp reduce energy consumption between 30% and 70%, depending on the pulp quality and final yield, the machinery installed, and the virgin pulp production processes it replaces (Rahnama *et al*., 2021; Moya and Pavel, 2018; Kramer *et al.*, 2009). Within kraft production, recycled pulp would displace chipping, digestion, blowing, and the auxiliary black liquor recovery line. In CTMP production, it would avoid chipping, heating, chemical treatment, and refining. On average, replacing virgin pulp with recycled fibers would reduce CO_2 emissions by 37% (Roth *et al.*, 2016). Recycling also reduces water consumption by 32,000 liters and saves 17 trees192 per ton of recycled paper. The equipment to produce pulp from recycled fibers is estimated to cost between USD $250/ton to USD $300/ton.

Recycled pulp production depends on a minimum virgin fiber input. Successive recycling processes deteriorate the cellulose fiber, resulting in a loss of 10% to 20% of the recovered paper. Assuming that the same fiber can be recycled an average of five times, producing one ton of recycled pulp is estimated to require 150 kg of virgin fiber (15% of the total volume) to produce good quality paper.

5.3 Summary of Decarbonization Measures

The table below summarizes the analyzed measures, highlighting where they would be applied within the pulp and paper industry, and their impact on reducing emissions, technical feasibility, and possible implementation limitations.

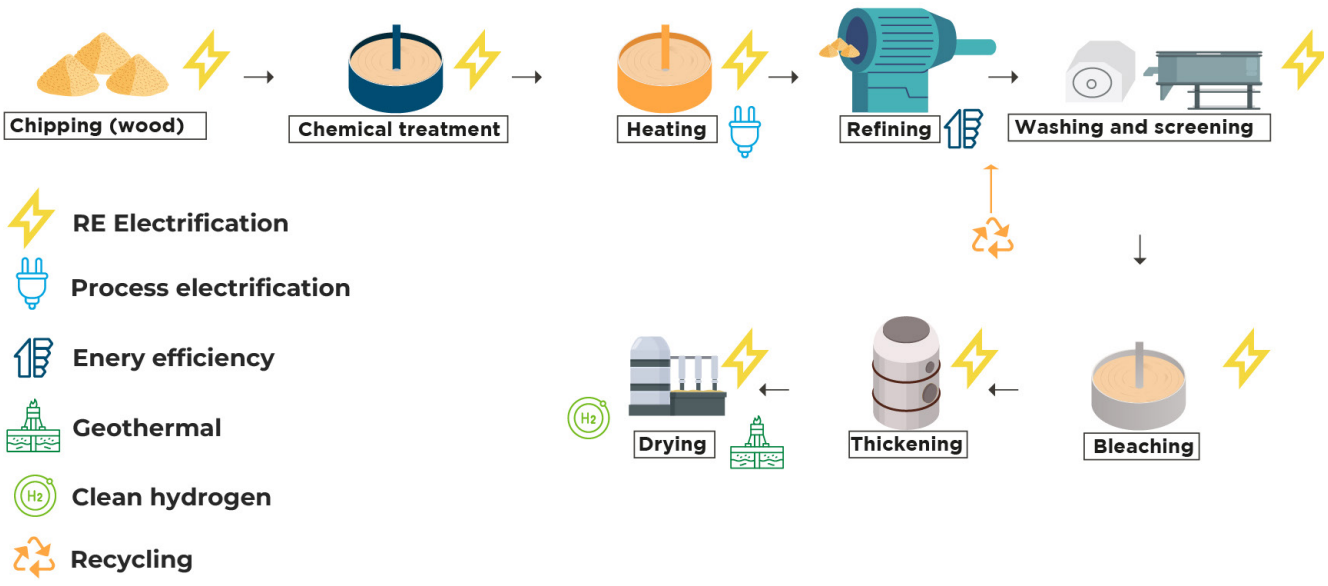
Table 18. Summary of LAC Pulp and Paper Decarbonization Measures

Measure	Industry	Applicability (processes)	Emission Reduction Impact	Technical Feasibility	Possible Limitations
Clean H_2	Pulp	Heating, digestion, blowing, drying, black liquor evaporation, recaustification	High	Moderate	Low technological development for the industry, high capital cost
	Paper	Drying			
Wastewater biogas, Landfill gas and Biomass gasification	Pulp	Heating, digestion, drying, black liquor evaporation, recaustification	Moderate	Moderate	High capital and O&M costs
	Paper	Drying			
Geothermal	Pulp	Heating, digestion, drying, black liquor evaporation, recaustification	High	High	High cost of capital
	Paper	Drying			
Process electrification	Pulp	Heating, digestion, blowing, drying, black liquor evaporation, recaustification	High	High	Adequacy of processes for electrification
	Paper	Drying			
Electrification with RE	Pulp	All	High	High	Access to RE sources
	Paper	All			
CCS	Pulp	Recovery of black liquor	High	High to moderate	High cost of capital
	Paper	-			
Energy efficiency	Pulp	Digestion, black liquor recovery, refining	Under	High to moderate	Adequacy of processes. High cost of capital
	Paper	Pressing and drying			
Manufacture of pulp from recycled fibers	Pulp	Avoids the processes of chipping, heating, refining, digestion and liquor recovery	High	High	Availability of raw materials

Source: Produced in-house

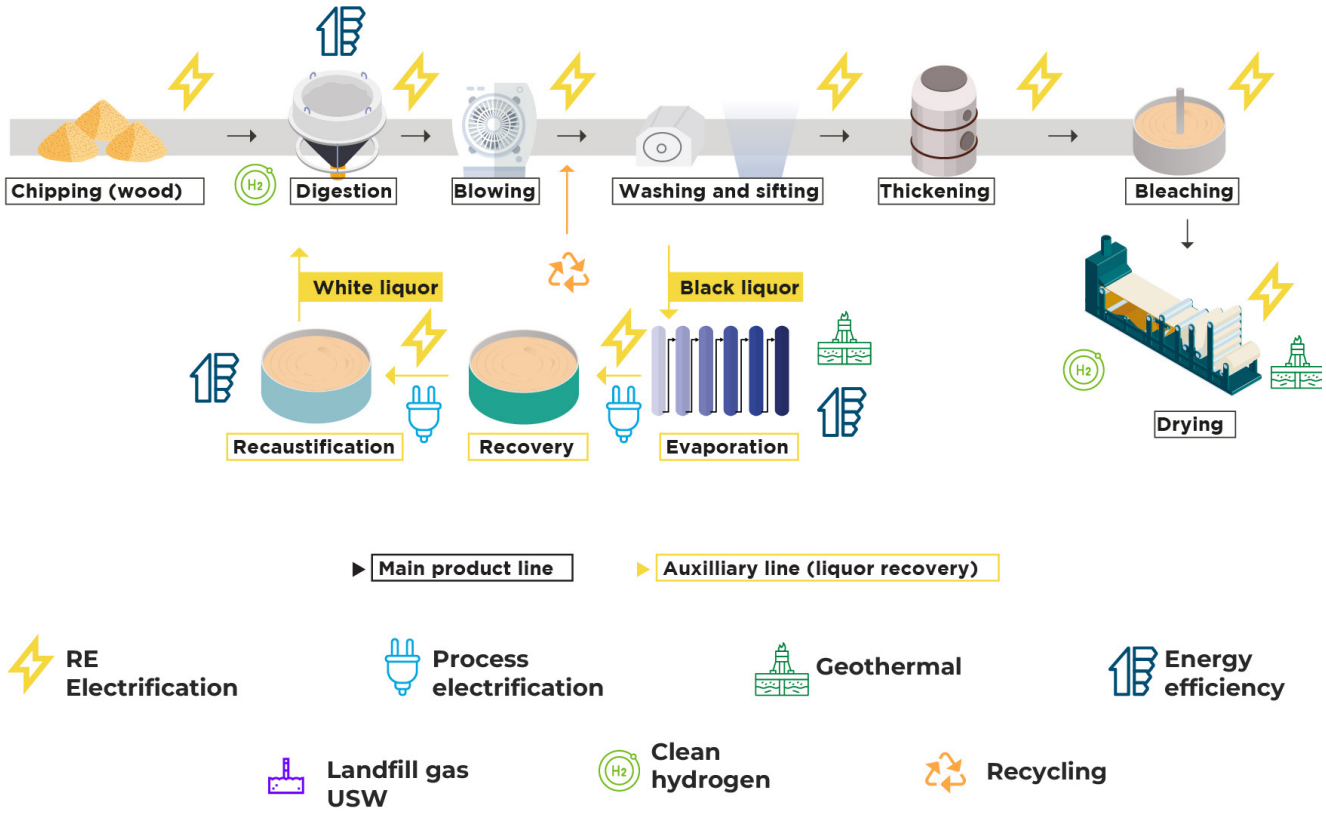
Among the decarbonization measures described, process electrification would be the most practical and fastest way to decarbonize both industries. However, technical and economic feasibility limitations suggest that additional decarbonization options should be combined with partial process electrification to maximize CO_2 emissions mitigation. This includes electrification with directly used renewable energy sources (hydro, biomass, geothermal for steam generation, among others), capturing and using landfill gas, and implementing energy efficiency measures. The three figures below illustrate that these measures could be implemented in CTMP pulp production, kraft pulp production, and paper production processes, respectively.

Figure 39. CTMP Production Decarbonization Measures



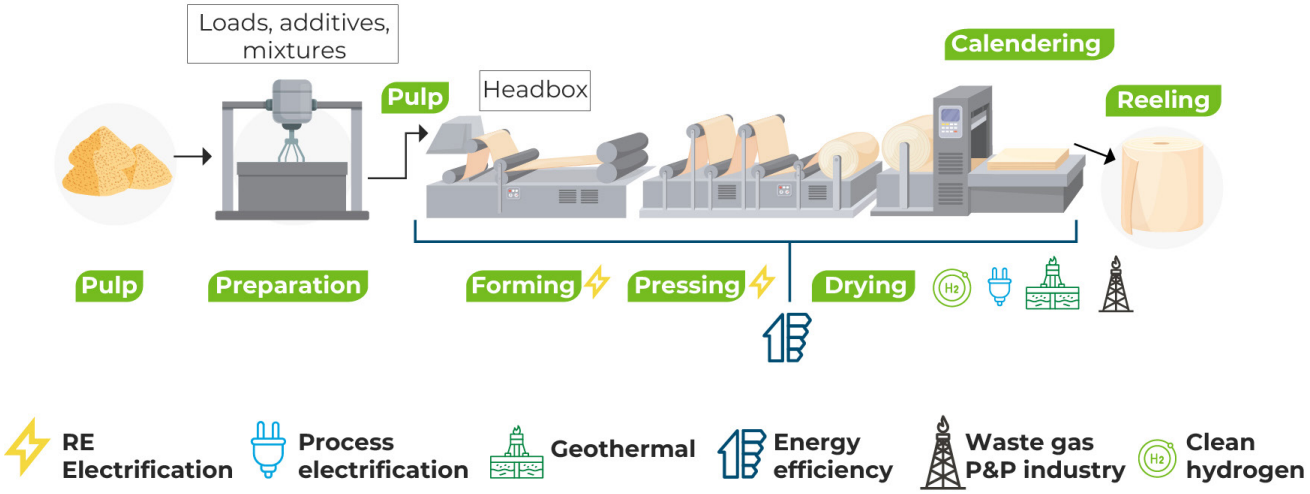
Source: Produced in-house

Figure 40. Kraft Pulp Production Decarbonization Measures



Source: Produced in-house

Figure 41. Paper Production Decarbonization Measures



Source: Produced in-house

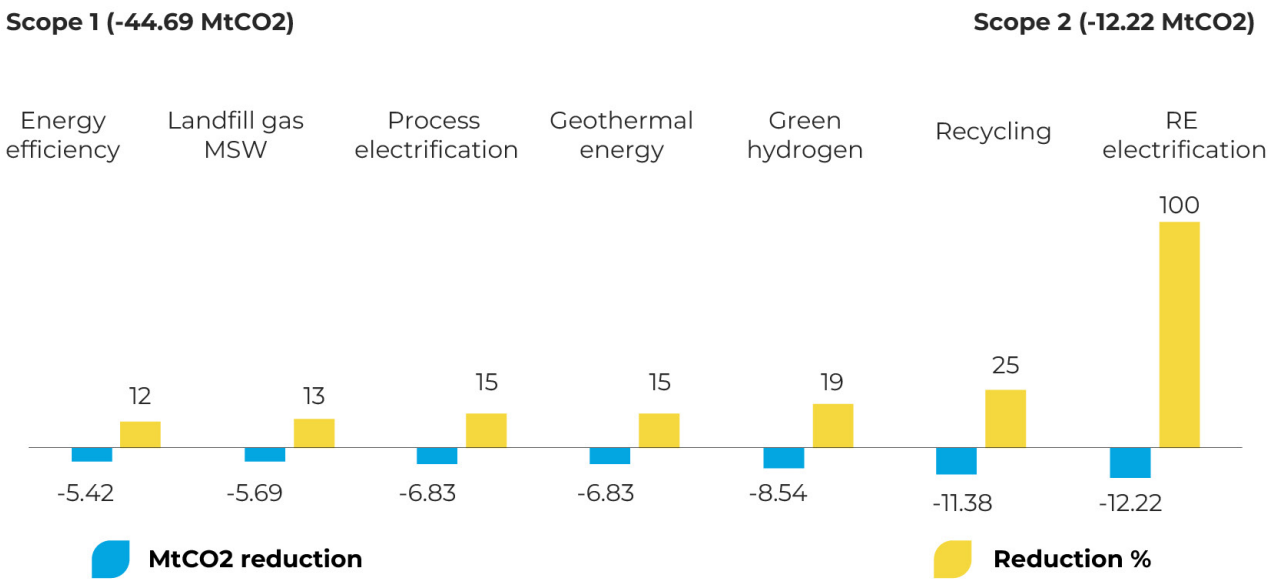
5.4 CO_2 Reduction Scenario Results

This section assesses the economic costs and benefits from implementing the proposed carbon emissions mitigation measures. The analysis considers capital and operating costs at constant prices, and revenue flow from fuel cost savings and carbon offsets, discounted to present value using a discount rate of 12%. Each measure is assumed to have a 25-year economic life. The results for each industry are described below.

5.4.1 Pulp Industry

Decarbonization measures would reduce pulp industry emissions by 56.91 $MtCO_2$ by 2050. Within the Scope 1 scenario, pulp production from recovered paper and cardboard fibers (recycling) can reduce direct emissions by 25% (11.38 $MtCO_2$). This is followed by clean hydrogen (19%), geothermal energy and process electrification (15% each), MSW landfill gas (13%), and energy efficiency (12%). Scope 1 measures account for 78.5% of the region's total primary industry emissions reductions, while Scope 2 accounts for the remaining 21.5%. The figure below shows each measure's emission reduction potential and percentage by 2050.

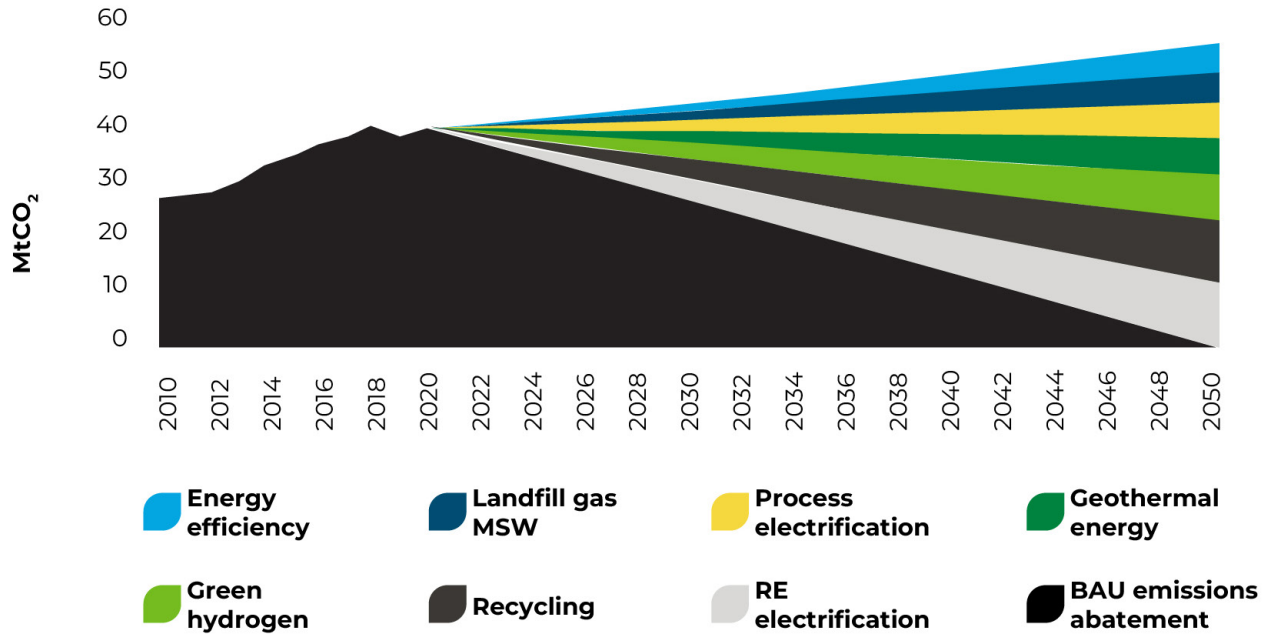
Figure 42. Emission Reductions from Primary Pulp Production



Source: Produced in-house

On an aggregate basis (Scopes 1 and 2), electrification with renewable energies (RE) reduces 21.5% of total emissions. Recycling contributes 20%, followed by clean hydrogen (15%), geothermal and process electrification (12% each), landfill gas use (10%), and energy efficiency (9.5%), as shown in the figure below.

Figure 43. Zero-Emission Primary Pulp Production by 2050



Source: Produced in-house

5.4.1.1 Primary Pulp Industry CO_2 Reduction Costs

Among the measures evaluated, clean hydrogen has the highest investment cost with a present value of USD $1,408 /t, equivalent to USD $1.044 billion to implement the new technologies in LAC. With a hydrogen cost of USD $4 per kilogram, the measure achieves a negative cost-benefit differential due to the increase in energy costs. To achieve a positive differential, hydrogen costs must be reduced to approximately USD $3.3 /kg.

Measures related to electrification from renewable sources and process electrification reach current investment values of USD $959/t and USD $600/t, or a total cost of USD $24.682 billion and USD $1.024 billion, respectively. Both measures bring total benefits associated with fuel savings and an emissions reduction of USD $25/t and USD $44/t, with positive cost-benefit differentials.

Geothermal energy requires an investment cost similar to electrification with renewables (USD $925/t), totaling roughly USD $24 billion to extract and use geothermal heat. This is followed by recycling[193] with USD $439/t (USD $9.948 billion), landfill gas utilization with USD $153/t (USD $695 million), and energy efficiency measures with a total of USD $61/t (USD $620 million). Of this set of measures, process electrification, recycling, energy efficiency, and renewable electrification bring the highest cost-benefit differentials (between USD $25/t and USD $32/t). Within the efficiency measures, cold blowing to improve the chip digestion process would generate the greatest benefit relative to the investment per ton of pulp produced. The table below shows each pulp industry measures' economic valuation.

[193] Pulp production from recycled (paper and cardboard) fibers

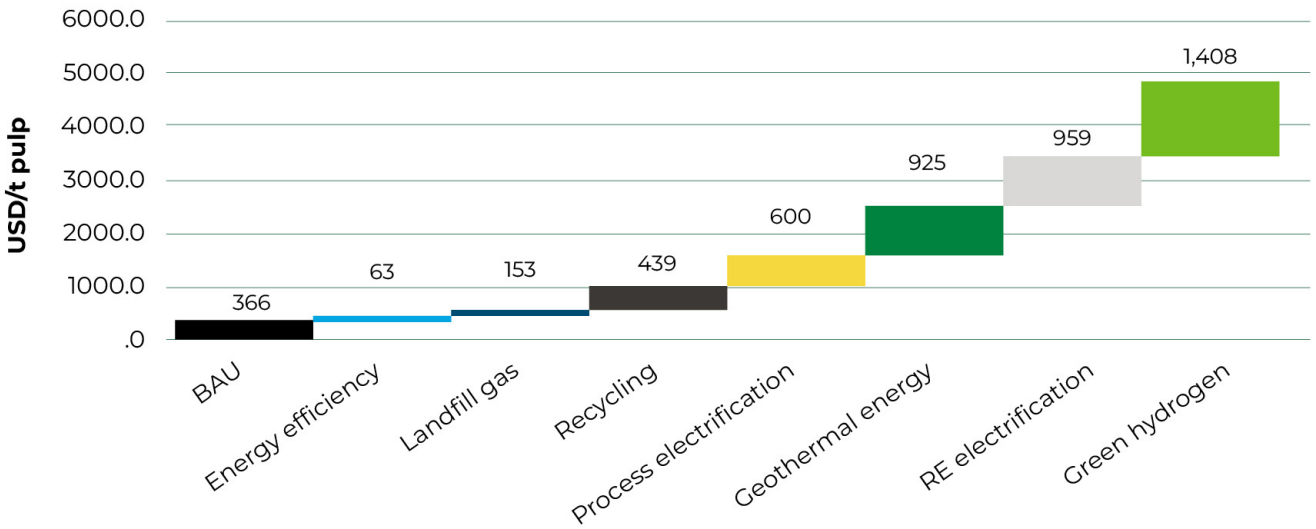
Table 19. Levelized Costs of Investment, Operation, and Benefits, According to Pulp Industry Measure

Measure	Present Value of the Investment	Operating Costs	Benefits			Benefit-Cost Differential
			Energy Savings	Emissions Avoided	Total	
Clean Hydrogen	1,408	176	-29	8	-21	-197
Renewable Electrification	959	35	17	8	25	25
Geothermal	925	28	23	7	30	2
Process Electrification	600	73	39	5	44	44
Recycling	439	21	36	13	49	28
Landfill Gas	153	16	16	4	20	3
Energy Efficiency	63		26.6	5.7	32.3	32.3
Biopulping	*30*		*1.5*	*1.5*	*3.0*	*3.0*
Efficient Refiners	*15*		*0.8*	*0.1*	*0.8*	*0.8*
Solids Concentrator (black liquor)	9		5.7	0.7	6.4	6.4
Cold Blowing (digestion)	7		14.9	2.9	17.8	17.8
Enriched Combustion (black liquor)	1		3.8	0.5	4.3	4.3

Source: Produced in-house

The cost to produce pulp without emitting GHGs in 2050 is estimated to be USD $4,546/t, compared to USD $366/t under the BAU scenario. This dramatic increase in cost is driven by the cost of clean hydrogen (31% of the total), followed by renewable electrification (21%), geothermal (20%), process electrification (13%), recycling (10%), landfill gas use (3%), and energy efficiency (1%). The figure below shows the incremental cost for each pulp industry decarbonization measure.

Figure 44. Cost of LAC Primary Production of Zero-Emission Pulp by 2050

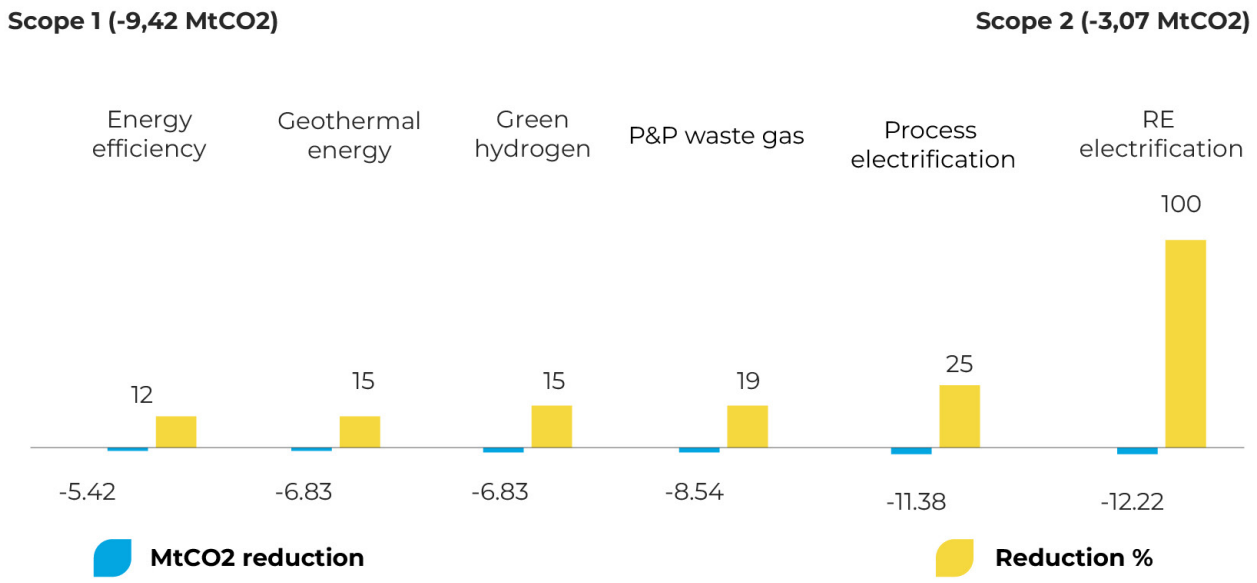


Source: Produced in-house

5.4.2 Paper Industry

The proposed paper industry decarbonization measures would reduce CO_2 emissions by 12.5 Mt by 2050. Process electrification would reduce Scope 1 emissions 30%, equivalent to 2.83 $MtCO_2$. Using gas produced from both industrial waste (pulp and paper) and clean hydrogen would contribute 20% (1.88 $MtCO_2$) each, and geothermal energy and energy efficiency 15% (1.41 $MtCO_2$) each. The figure below shows each measure's emission reduction potential and share within each scope, by 2050.

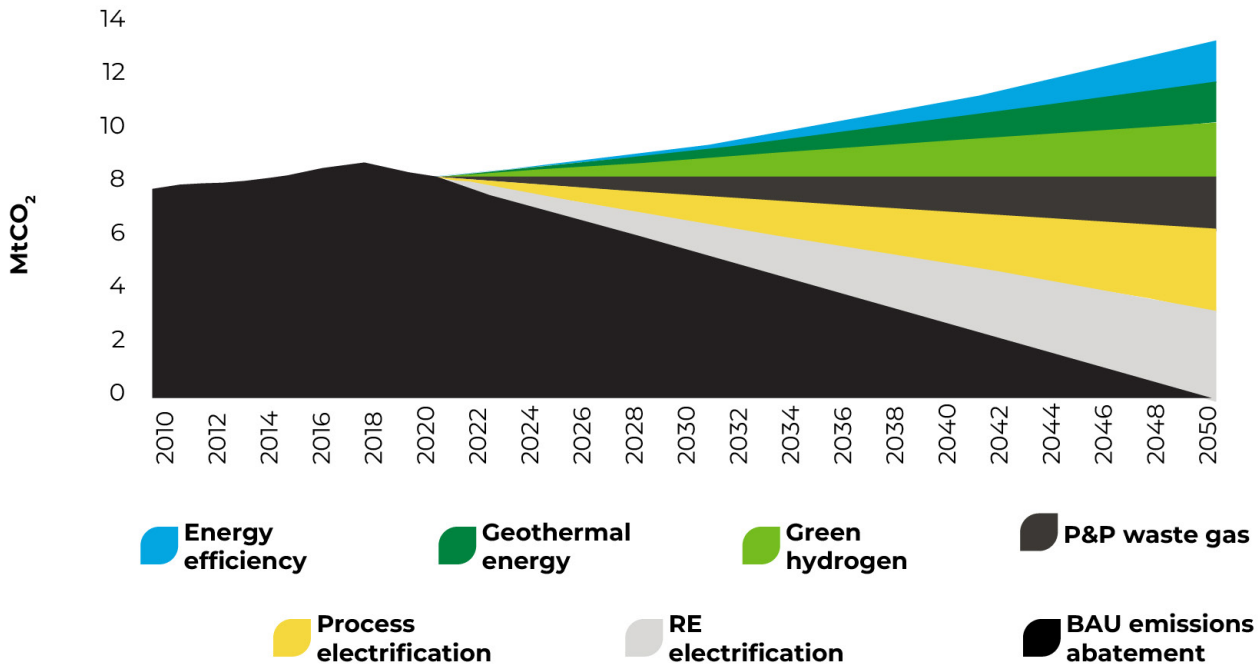
Figure 45. Emission Reductions from Paper Production



Source: Produced in-house

Of the total emissions reductions (Scopes 1 and 2), 25% comes from electrification with renewable energies. This is followed by process electrification (23%), gasification from waste and clean hydrogen (15% each), and geothermal and energy efficiency (11% each), respectively, as shown in the figure below.

Figure 46. Zero-Emission Paper Production by 2050



Source: Produced in-house

5.4.2.1 Paper Industry CO_2 Reduction Costs

Among the assessed paper industry measures, clean hydrogen has the highest investment cost at USD $1,267/t and approximately USD $500 million to adapt processes and technologies in the region. To achieve a positive benefit-cost differential, the price of clean hydrogen will have to be reduced by 12.5% to reach around US$3.5/kg.

The investment cost for process electrification, geothermal, and electrification with renewable energies are estimated to be, respectively, USD $695/t, $622/t, and $423/t, with cost-benefit differentials of more than USD $20/t. Equipment adaptations and implementing new infrastructure for these three measures would require USD $18.630 billion, with 70% for geothermal energy, 25% for electrification with renewables, and 5% for process electrification.

Producing gas from waste paper and energy efficiency measures would have the lowest investment cost (USD $130/t and USD $40/t, respectively). Using frequency controllers in pumping equipment, fans, and thermocompressors generates the highest benefit per ton of product, relative to its investment cost. The table below shows the paper industry measure's economic valuation.

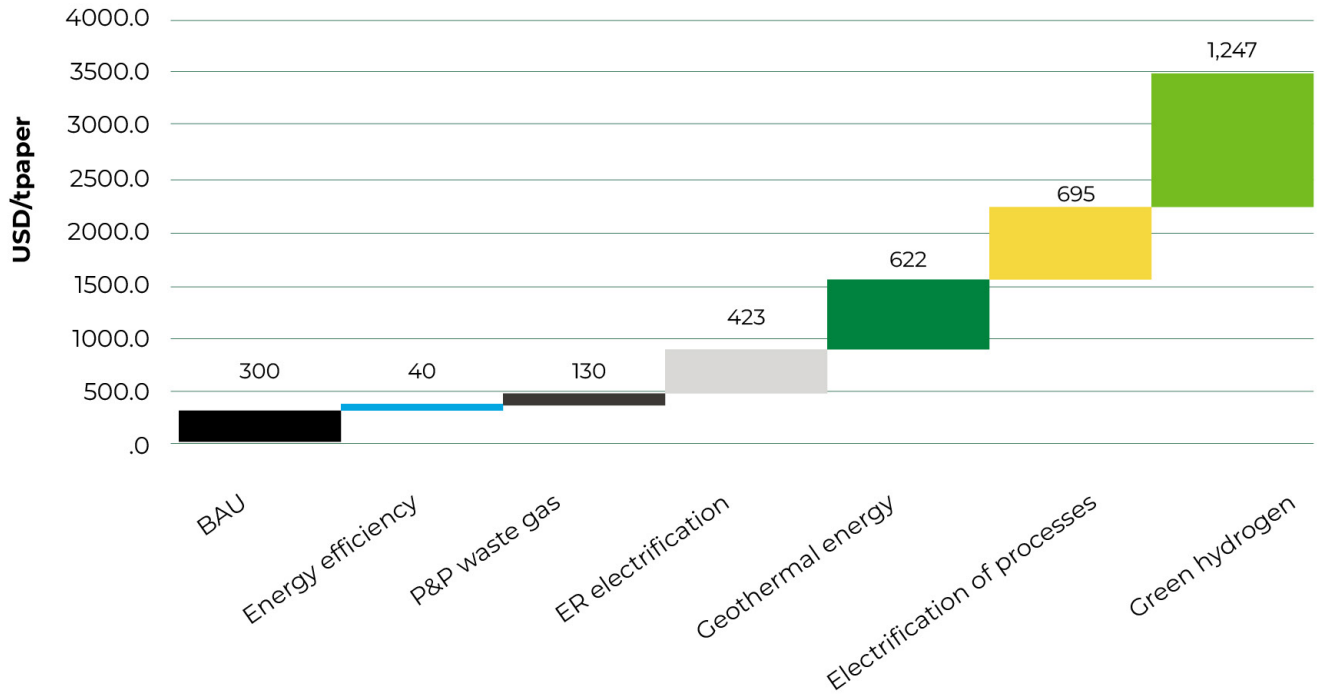
Table 20. Levelized Investment, Operating, and Profit Costs by Paper Industry Measure

Measure	Present Value of the Investment	Operating Costs	Benefits			Benefit-Cost Differential
			Energy Savings	Emissions Avoided	Total	
Clean Hydrogen	1,247	157	-26	7	-19	-176
Process Electrification	695	84	46	2	48	48
Geothermal	622	20	45	1	46	26
Renewable Electrification	423	33	18	2.2	20	20
Industrial Waste Gas P&P	130	8	18	1	19	11
Energy Efficiency	39.9		16.9	1.4	18.3	18.3
Shoe Press	*26.6*		*4.2*	*0.3*	*4.6*	*4.6*
Condensing Boilers	*8.6*		*4.2*	*0.3*	*4.6*	*4.6*
Thermocompressors	*3.8*		*4.2*	*0.3*	*4.6*	*4.6*
Frequency Converters (pumps, fans, compressors)	*0.8*		*4.2*	*0.3*	*4.6*	*4.6*

Source: Produced in-house

Paper produced with zero emissions would cost an estimated USD $3,157/t, far higher than the USD $300/t under a BAU scenario. Clean hydrogen is responsible for 40% of the expected cost increase, followed by process electrification (22%), geothermal (20%), electrification with renewables (13%), gas from waste (4%), and energy efficiency (1%). The figure below shows each paper industry measure's incremental decarbonization costs.

Figure 47. Cost of Zero-Emission Paper Production in LAC by 2050

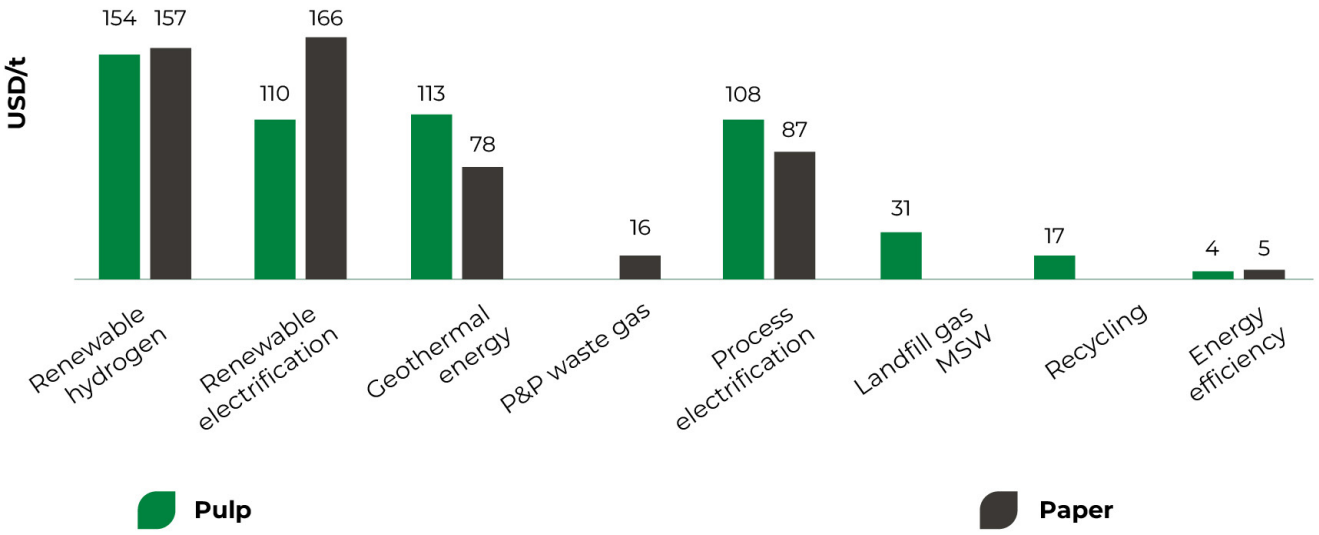


Source: Produced in-house

5.4.3 Levelized Cost of CO_2 Emissions Reduction

Pulp and paper industry levelized CO_2 emission reduction costs range between USD \$4/tCO_2 and USD \$170/tCO_2 . Among the measures evaluated, clean hydrogen and electrification from renewables have the highest decarbonization costs, while the lowest are obtained for energy efficiency measures, as shown in the figure below.

Figure 48. Levelized Cost of CO_2 Reduction, by Industry



Source: Produced in-house

Vertically integrating the pulp and paper industries reduce the levelized cost of emissions reduction for LAC by 20-30%, through integrating heat-consuming processes and recovering waste energy from pulp production for use in other processes, such as paper drying.

The pulp industry has a high potential to decarbonize its own operations and contribute to emissions reductions in other sectors. Kraft pulp mills have greater potential to achieve emissions neutrality or even act as carbon sinks, as it is able to generate its own energy using biomass residues from upstream processes. Under the right market conditions, the pulp industry could produce electrofuels, such as clean hydrogen and syngas[194], and even feedstocks for other industries. For example, gas production from black liquor gasification, can be a raw material for chemicals (Bajpai, 2016). BLG can be integrated with combined cycle technology (BLGCC) to produce significantly more electricity than conventional boiler/steam turbine systems, and even generate surplus power for other industries. Moreover, lignin from pulping can replace oil and coal to produce a variety of bio-based plastics and lightweight materials, such as carbon fiber[195]. Under favorable electricity price scenarios, the pulp and paper industry could expand its activities into the electricity market, clean fuel production, and chemical inputs.

[194] https://acrobat.adobe.com/link/track?uri=urn%3Aaaid%3Ascds%3AUS%3A1ba37a0d-0b59-4827-b420-58190bc3d662&viewer%21megaVerb=group-discover
[195] https://www.energimyndigheten.se/arkiv-for-resultat/Resultat/lignin-en-restprodukt-redo-for-nya-anvandningsomraden/

6. Investments Under the Paris Agreement

6.1 Universally Aligned Investments

Paths to decarbonizing the pulp and paper industry and that are universally aligned with the Paris Agreement (PA) include: (i) the anticipated, planned, and organized replacement of carbon-intensive production processes; (ii) renewable or low-emission electrification of kilns, use of alternative fuels for heat generation in pulp and paper manufacturing processes; iii) implementing efficiency measures to reduce process energy intensity, including the use of more efficient equipment and pulp and paper recycling; and iv) introducing new technologies to reduce direct process emissions, such as carbon capture, use, and storage (CCUS).

Therefore, investment measures that are considered universally aligned with the PA include those that: i) their economic feasibility does not depend on fossil fuel consumption, processing, or transportation; ii) their economic feasibility does not depend on fossil fuel subsidies; and iii) the operation does not significantly depend on the direct use of fossil fuels. The table below shows the pulp and paper industry measures that are universally aligned with the PA.

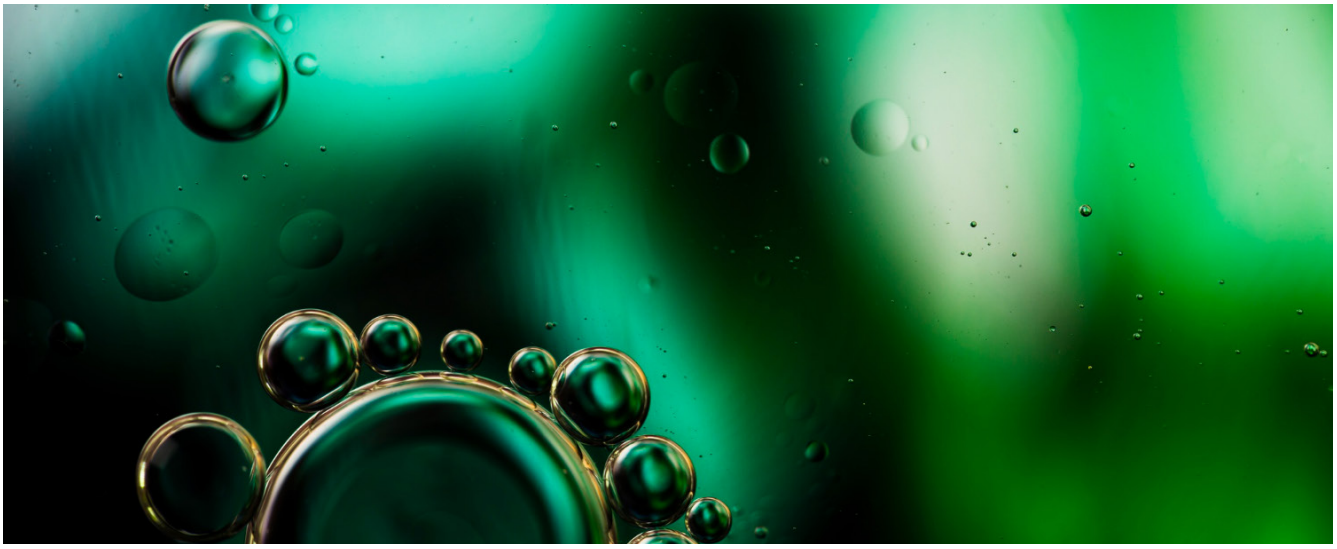


Table 21. Measures Applicable to the Pulp and Paper Industry Universally Aligned with the PA

Measures	Conditions and Guidelines
Implementing energy efficiency improvements in pulp and paper manufacturing processes	Using higher energy performance technologies reduces the energy intensity of the processes and, therefore, are universally aligned with the PA.
Displacing conventional fuels with green hydrogen to generate heat for paper drying	Green hydrogen is universally aligned with the PA because it displaces fossil fuel consumption. Producing hydrogen with renewable electricity maximizes emission reductions.
Electrifying paper drying using renewable electricity	Electrifying energy demand with renewable energy is universally aligned with the PA. Implementing renewable electrification displaces fossil fuel use and related emissions.
Producing renewable electricity for self-consumption	Producing renewable electricity is universally aligned with the PA. Implementing renewable electricity can mitigate 100% of the indirect emissions associated aluminum industry electricity consumption.
Produce biogas from pulp and paper wastewater and gasification of biomass, black liquor, or industrial wastes	Biogas is universally aligned with the PA, as it directly replaces fossil fuel use.
Using geothermal energy for pulp and paper process heat	Geothermal energy is universally aligned with the PA, if any CO_2 that is produced along with the steam is reinjected (binary system). Geothermal steam directly displaces fossil fuels for heat generation in the pulp and paper industry.

Source: Produced in-house

6.2 Unaligned Investments

According to the IDB Group Sustainable Energy Sector Guidelines (GN-2613-1), the IDB Exclusion List of the Environmental and Social Policy Framework (ESPF)[196], and the IDB Invest Environmental and Social Sustainability Policy (ESSP), those investments inconsistent with the PA include activities related to the exploration and production of coal, oil, and gas.

For the pulp and paper industry, this includes consuming energy from fossil fuels and processes that release carbon when treating raw materials. The table lists measures applicable to the pulp and paper industry that are not considered universally aligned with the PA.

[196] The Exclusion List contains activities that are incompatible with the IDB Group's commitments to address climate change in coal, oil and gas issues.

Table 22. Measures Applicable to the Pulp and Paper Industry that Are Not Aligned with the PA

Measures	Conditions and Guidelines
Fossil fuel-based heat generation	Using fossil fuels to generate heat for pulp and paper manufacturing processes is not aligned with the PA. Developing this infrastructure supports continued carbon emissions.
Fossil fuel-based power generation plants	Electricity generation plants based on fossil fuels are not aligned with the PA. Developing this infrastructure supports continued carbon emissions.

Source: Produced in-house

6.3 Investments Requiring Review

This section considers investments that have the potential to align with the PA. These investments must demonstrate tangible changes and benefits in displacing carbon-intensive production processes, consistent with industry policies and national climate change objectives. The table below describes the measures that require validation to be universally aligned with the PA.

Table 23. Pulp and Paper Industry Activities that Require Validation of Their Alignment with the PA

Measures	Conditions and Guidelines
Blue hydrogen	Blue hydrogen is extracted from natural gas fields. If it can be produced without also releasing underground CO2, it would be in line with the PA. Producing blue hydrogen under zero-emission conditions raises costs, and, thus, is not competitive for industry project developers.

Source: Produced in-house

7. Policy Roadmap for Individual Countries

The pulp and paper sector plays a critical role in packaging, hygiene products, publishing, and the expanding bioeconomy. As the fourth-largest industrial consumer of energy, it must shift toward low-carbon production to stay competitive. Achieving decarbonization presents both energy and process hurdles, given the industry's high heat demands, varied operations, and potential for circularity. Unlocking this transition will require significant investment, strong policy support, and ongoing research and innovation to drive technological change.

In this context, this section presents a roadmap, as summarized in the table below, that governments can follow to decarbonize the pulp and paper industry. Recommendations are based on the pathways identified in this chapter, such as adopting cleaner, lower-carbon energy alternatives; energy-efficiency measures across kraft pulp, mechanical pulp, and paper production; deploying CCUS where suitable; and increasing the use of recycled materials in pulp production.

Table 24. Summary of Pulp & Paper Decarbonization Roadmap for LAC Countries

Period	Goals
2025–2030	Publish national pulp & paper decarbonization strategies to 2050; map and update environmental, energy, and waste regulations; establish recycling targets and mandates in public procurement; create regulatory sandboxes for biogas, landfill-gas, and gasification demonstration projects; prioritize "no-regrets" efficiency measures in kraft pulp, mechanical pulp, and paper plants; and support feasibility studies on industrial symbiosis, biomass availability, and low-carbon infrastructure.
2031–2037	Adopt embodied-carbon criteria in procurement; introduce disclosure on energy, emissions, and recycled content; permit CO_2 transport/storage networks and set interconnection rules for renewable gas injection; scale biomass and biogas fuel switching; commission first commercial electric boilers and heat pumps; launch first CCS demonstrations; broaden concessional finance, introduce CfDs for CCS/hydrogen, expand tax credits, and explore PPPs; and harmonize recycled-fiber standards, share CCS/gasification lessons, and build regional markets.
2038–2045	Increase emissions-intensity standards and recycled-content thresholds; align trade policies with global low-carbon rules; develop liability and insurance frameworks for CCS; set end-of-life paper recovery obligations; deploy CCS at scale in boilers and kilns; expand electrification; foster industrial symbiosis and provide transition packages for affected communities; shift to private/blended finance, focus public funds on just transition, repowering, and grids; and scale reskilling, harmonize CO_2 and hydrogen safety/MRV, and integrate regional fiber logistics.
2046–2050	Tighten performance standards to near-zero; require high recycled content and full recovery obligations; align border measures and certification with global carbon requirements; operate on low-carbon heat (hydrogen, biogas, electrification, geothermal) and renewables; maintain CCS where residual emissions persist; integrate AI-driven optimization; and consolidate regional governance and standards; share benchmarks and position LAC as a global hub for sustainable pulp and paper.

7.1 Vision and Baseline

Pulp and paper assets in LAC differ in scale, fuel mix, and export orientation. The kraft chemical process dominates pulp production, although other processes are also present. To position themselves in a low-carbon future, governments should first assess their role in domestic and global value chains: whether as pulp exporters, producers of paper and board, recyclers, or import-dependent markets.

The next step is to establish a comprehensive baseline. This should include mapping mill locations and technologies; steam and electricity demand; performance of recovery boilers and other machinery; and the availability and cost of low-carbon fuels, such as biomass residues, wastewater biogas, landfill gas, or hydrogen. It should also assess renewable resource potential, CCUS opportunities, and recycling infrastructure, particularly collection systems, sorting capacity, and fiber quality losses. While trade exposure to low-carbon standards is lower than in some other industries, it remains important to evaluate these risks alongside sustainability considerations for pulp exports.

Such a baseline provides the foundation for tailored strategies that connect industrial, energy, waste, and trade policy with emissions reduction and long-term competitiveness. Depending on the size and structure of the sector within each country, pulp and paper can be addressed within a broader industrial decarbonization strategy, but setting dedicated targets for this industry remains important.

7.2 2025–2030: Foundations and Early Demonstration Projects

7.2.1 Policies and Regulations

Governments should publish national pulp and paper decarbonization strategies extending to 2050. These strategies can include modeled scenarios, abatement curves, policy cost curves, funding gaps, and just transition measures that address social considerations.

It is essential to map the regulations that affect the sector and to update environmental, energy, and waste regulations to enable several key measures. These include: (i) low-carbon fuel switching, such as hydrogen safety codes and biogas injection and use; (ii) sustainable biomass sourcing standards; (iii) electrification permits for boilers and heat pumps, if required; (iv) geothermal exploration, where available; and (v) CCUS readiness (monitoring, liability, transport, and storage permitting).

While some countries already have recycling policies and government mandates requiring the use of paper containing recycled material or natural fibers not derived from wood, it remains important to establish recycling targets and mandates in public paper procurement. These targets should be based on the current baseline and can be increased every five years.

Finally, governments can create regulatory sandboxes to demonstrate emerging technologies, such as wastewater biogas, landfill gas, and biomass gasification, as well as other innovative solutions.

7.2.2 Projects, Technologies, and Infrastructure

Governments should prioritize "no-regrets" efficiency measures that can be implemented across pulp and paper production processes. In kraft pulp production, this includes adopting technologies, such as cold blowing in batch digestion, improving the efficiency of black liquor evaporation, and using oxygen-enriched combustion where it is both safe and beneficial. For mechanical pulp production, governments can encourage optimization in refining processes, including improvements in specific energy use and consistency. Support for demonstrating biopulping technologies, which biologically pre-treat wood chips to reduce refining energy requirements, will also play an important role. Additional measures include upgrading or adding condensing boilers and implementing real-time energy management systems that integrate metering, analytics, and operator dashboards.

Governments can also support the launch of demonstration projects for low-carbon technologies. These may include wastewater biogas capture and upgrading, municipal solid waste landfill-gas supply to mills, and black liquor or industrial waste gasification. The targeted use of electric boilers and heat pumps for medium-temperature duties can also be tested.

During this phase, governments can also initiate feasibility studies on industrial symbiosis opportunities, such as clustering pulp and paper mills with other industries to share infrastructure for heat, steam, and carbon dioxide utilization. They can support assessments of regional biomass availability and competing uses to ensure long-term sustainable supply chains.

7.2.3 Funding and Incentives

To promote the mentioned efficiency measures, governments can provide accelerated depreciation or tax credits for the plants that introduce them, based on emissions reductions. MDBs can provide concessional loans, guarantees, and green bonds for a first-of-a-kind (FOAK) efficiency retrofits, biogas, gasification, and electrification investment that would otherwise struggle to secure private capital due to their risk profile. With the support of MDBs, governments can also provide results-based grants for verified energy savings and recycled-fiber quality improvements, among others.

7.2.4 Capacity Building and Regional Cooperation

During this phase, it is important to train industry and regulators on low-carbon technologies, including hydrogen safety, biogas handling, gasification, electrified heat, and CCUS. At a regional level, coordination can begin on recycled-fiber trade, to develop common fiber-quality and contamination standards, and to harmonize testing.

7.3 2031–2037: Scaling and Infrastructure

7.3.1 Policies and Regulations

During this phase, governments can adopt embodied-carbon criteria in public procurement for printing, writing, tissue, and packaging paper products. For example, governments could require that printing paper used in public offices must have a maximum embodied carbon intensity or a minimum percentage reduction in embodied carbon relative to the national average baseline. Disclosure and reporting requirements for energy intensity, emissions intensity, and recycled content by product grade can be introduced to strengthen transparency and accountability. In addition, governments can establish permitting systems for CO_2 transport and storage networks, as well as interconnection rules for landfill-gas and renewable gas injection.

7.3.2 Projects, Technologies, and Infrastructure

Governments can support the scaling of thermal fuel switching with sustainable biomass, upgraded biogas from wastewater and landfill streams, and demonstration projects for hydrogen use in suitable burners and kilns. During this phase, first commercial-scale electric boilers and industrial heat pumps for medium-temperature duties can also be promoted, while expanding geothermal applications where resources exist. Real-time energy management systems can evolve into advanced digital platforms. Further upgrades to mechanical presses and waste-heat integration can reduce steam demand in dryers. Large-scale black liquor and industrial waste gasification lines can be deployed. Governments may also facilitate launch of the first large CCUS demonstration projects, with shared compression and transport infrastructure linked to emerging CO_2 hubs.

7.3.3 Funding and Incentives

Concessional lending and green bonds can be broadened to support deployment. Governments may introduce contracts for difference (CfDs) or carbon contracts to de-risk CCUS and hydrogen projects. Investment tax credits can be expanded for electrified heat and high-efficiency equipment. Dedicated credit lines may also be created for recycling infrastructure, covering collection, sorting, and de-inking, alongside fiber-quality upgrades. PPPs can be explored for financing CO_2 pipelines, recycling hubs, biomass hubs, and landfill-gas capture networks, helping reduce the upfront cost burden for individual companies.

7.3.4 Capacity Building and Regional Cooperation

At this stage, governments can harmonize recycled-fiber and de-inking standards. Lessons from CCUS demonstration projects, gasification projects, and electrified heat applications may be shared regionally. Governments can also help establish regional marketplaces for recycled fiber and biogenic fuels, and coordinate logistics for cross-border CO_2 transport and biomass supply.

7.4 2038–2045: Transformation and Deployment

7.4.1 Policies and Regulations

Governments can increase emissions-intensity performance standards by product grade and minimum recycled-content thresholds for all paper products. Customs and trade policies may be aligned with global low-carbon standards to reduce leakage risks. Long-term liability frameworks and insurance mechanisms for CCUS storage can be developed to provide certainty for operators. End-of-life paper recovery obligations may also be placed on municipalities and producers to ensure circularity.

7.4.2 Projects, Technologies, and Infrastructure

This phase can focus on deploying CCUS at scale on recovery boilers and lime kilns where residual emissions remain. Electrification of medium-temperature heat can be expanded, alongside site-wide heat cascading and steam optimization. Black liquor and industrial waste gasification can mature into a reliable baseload fuel supply for the sector. Governments may also foster industrial symbiosis, enabling shared biomass sourcing, steam networks, and the use of residues from neighboring industries. Transition packages can be created for communities affected by fossil fuel phase-out or technology shifts. At the same time, demonstration projects for next-generation processes, such as enzyme-assisted pulping and advanced drying technologies can be supported.

7.4.3 Funding and Incentives

Private and blended finance can increasingly drive investments at this stage, with public support focusing on just-transition funds, repowering of older facilities, and grid and transmission upgrades that allow high renewable penetration. Performance-based incentives tied to verified emissions reductions and recycled-content delivery may be prioritized.

7.4.4 Capacity Building and Regional Cooperation

Governments can scale reskilling programs in areas such as CCUS operations, hydrogen and biogas systems, and advanced automation. Regional cooperation may focus on harmonizing safety and MRV protocols for CO_2 transport, storage, and hydrogen. Fiber trade and logistics can be integrated across borders to balance seasonal fluctuations and quality needs.

7.5 2046–2050: Consolidation to Net-Zero

7.5.1 Policies and Regulations

In the final phase, governments can tighten performance standards to achieve near-zero emissions across all paper grades. High recycled-content requirements and comprehensive end-of-life paper recovery obligations may become universal. Border adjustment measures and certification systems can be aligned with international carbon requirements. Product standards may codify durability, recyclability, and low-carbon attributes.

7.5.2 Projects, Technologies, and Infrastructure

By this stage, pulp and paper production can operate predominantly on low-carbon heat sources, including hydrogen, biogas, electricity, and geothermal, powered by renewable electricity. CCUS may remain in place for residual process emissions. Real-time energy management can be fully integrated with AI-driven optimization systems. Closed-loop fiber cycles can be achieved, with high capture rates and minimal quality loss supported by advanced sorting, de-inking, and fiber rejuvenation technologies.

7.5.3 Funding and Incentives

Financing can increasingly focus on operations and maintenance optimization, reinvestment cycles, and securing competitive renewable power tariffs. Targeted innovation grants may continue for breakthrough processes in next-generation drying and pulping. Just-transition measures can remain in place where workforce and community support are still needed.

7.5.4 Capacity Building and Regional Cooperation

Governments can consolidate regional governance of low-carbon standards and certification, ensuring consistency across markets. Shared benchmarks and open data platforms may be promoted to drive continuous improvement. By this stage, Latin America and the Caribbean can position itself as a global hub for sustainable pulp, paper, and recycled fiber, exporting both products and technical expertise.

8. Recommendations for LAC

Decarbonizing the LAC pulp and paper industry requires support for demonstration programs for emerging technologies, investment in renewable energy capacity, expanded access to climate finance funds, and further studies to inform investment decision-making.

New analyses in three key areas would be particularly beneficial in the near term:

- **Decarbonization scenarios for the pulp and paper industry in LAC.** This consists of expanding the analysis in this chapter to model possible technology adoption strategies in order to identify their impact on reducing regional direct and indirect pulp and paper industry emissions. First, the LAC pulp and paper industry's current Scope 1 and Scope 2 mitigation trajectory must be defined within the Paris Agreement framework. Next, the identified decarbonization alternatives' contributions must be evaluated against the previous baseline BAU scenario. This analysis will identify the potential impact of the selected options on the industry's emissions reduction by mid-century.

- **Economic valuation of the measures to construct an emission abatement curve.** This valuation seeks to estimate the economic benefits of implementing the identified decarbonization alternatives. Analysis involves adjusting industry-wide estimates of the costs associated with adopting each technology to LAC's specific circumstances. Economic valuation will help identify the most cost-efficient alternatives for decarbonizing the LAC pulp and paper industry and identify options to improve the economic performance of technically feasible alternatives, including through synergies with other sectors. Economic valuation will also identify the impact of evaluated decarbonization alternatives on pulp and paper costs. Assessment will be the primary input to create an emissions abatement curve showing the cost per measure and its impact on emissions reduction by 2050 in LAC.

- **Identify the funding gap.** Estimating the financing needed to implement decarbonization alternatives is key to understanding financial needs, strategically planning, raising resources, and making informed decisions. This analysis involves assessing the aggregate financing needed to decarbonize the entire pulp and paper industry in the region by 2050, the financing that is currently available, and the resulting gap. Assessing the possible causes of these gaps and defining the routes to overcome them is essential.

STEEL

1. INTRODUCTION

The steel value chain stretches from iron ore extraction through steel recycling and multiple metallurgical processes to finished products used in buildings, machinery, vehicles, whitegoods, and industrial and consumer products. Iron and steel production is a major global industry, accounting for 3.6 Gt of CO_2 emissions in 2022[197]. Within Latin America and the Caribbean (LAC), steel production is concentrated in six countries (Brazil, Mexico, Argentina, Colombia, Chile, and Peru) and contributes 2.9% of global steel industry emissions.

The Paris Agreement (PA) aims to achieve net zero greenhouse gas emissions (GHGs) by 2050 to prevent an average 1.5°C increase in global warming over pre-industrial levels. However, decarbonizing the steel industry faces considerable technical and economic constraints and would require significant investments.

In its commitment to align its operations with the Paris Agreement, the IDB Group aims to promote steel industry decarbonization in Latin America and the Caribbean through technical assistance and lending operations that align with its sector strategies and climate change impact goals in the region's countries. In this context, this chapter describes crude steel production routes and identifies opportunities for decarbonization in Latin America and the Caribbean.

This chapter first describes the processes used to produce steel, the global and regional markets for steel, the industry's environmental impact, technological options for decarbonization, and implications for Latin America and the Caribbean. It then describes investments that support decarbonization. Finally, it recommends accelerating the decarbonization of the steel industry in Latin America and the Caribbean and provides a roadmap that can be used by countries wishing to decarbonize their steel industry.

[197] Calculated from World Steel Association steel production and emissions intensity figures.

2. PRODUCTION PROCESSES

This section describes the different routes used to produce crude steel, from materials preparation through ironmaking to steelmaking. It then examines the energy intensity of the different steel production routes and the fuels used at each stage.

2.1 Crude Steel Manufacturing Stages

Crude steel, the basic material used to manufacture steel products, is composed of iron, carbon, and other elements such as chromium, copper, phosphorus, manganese, molybdenum, nickel, silicon, vanadium, and titanium, among others. The carbon content (typically between 0.02% and 2%) and the other elements give crude steel specific properties tailored for its final use.

Crude steel is produced from iron ore through chemical and metallurgical processes. These processes can be divided into three stages: materials preparation, ironmaking, and steelmaking. Each of these stages is described below.

2.1.1 Stage I. Materials Preparation

Crude steel production begins with preparing key input materials, including iron and coke (to provide the needed carbon). To prepare the iron, iron ore is crushed, homogenized, and mixed with limestone, coke breeze, slag-forming agents, and fluxes at high temperatures to produce iron sinter or iron pellets.

To produce coke, coal is heated at high temperatures in a coke oven in the absence of air to remove volatile matter, resulting in a solid material composed mainly of carbon.[198]

[198] https://worldsteel.org/about-steel/about-steel/steelmaking/

2.1.2 Stage II. Ironmaking

Iron can be produced through a blast furnace (BF) or through the direct reduction of iron (DRI). Typically, a BF transforms iron sinter and coke into pig iron with a carbon content of approximately 4%, although in Brazil some smaller BFs use charcoal in place of coke to provide the needed carbon, which results in lower GHG emissions. Iron, coke, and limestone are added in layers into the upper part of the BF. In the lower part, air and fuels (hydrocarbons, renewables) are introduced to heat the materials and facilitate the coke's combustion, which produces more heat as well as carbon monoxide gas. The heat then melts the iron sinter while the carbon monoxide gas removes oxygen from it through a chemical process. This produces molten pig iron, which has fewer impurities than the iron sinter and a carbon content of approximately 4%. The molten pig iron and slag (waste materials) flow to the bottom of the BF for collection.

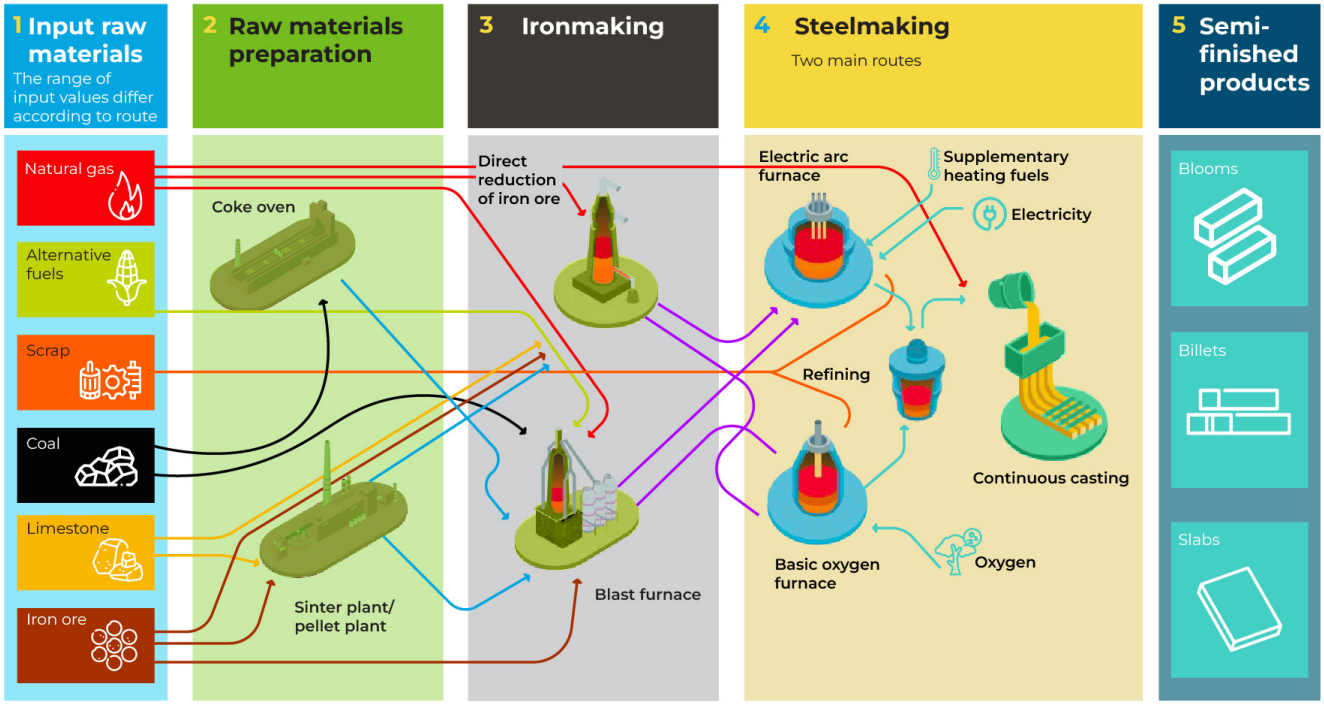
DRI transforms iron into an intermediary product known as sponge iron in a solid state. This is achieved by combining iron pellets and a mixture of carbon monoxide and hydrogen (known as the reducing gas) in a reactor. The gas chemically reacts with the ore to reduce the ore's oxygen content to produce sponge iron, which is then pressed into briquettes known as hot briquetted iron (HBI). The reducing gas can be generated from natural gas, syngas, or from the partial combustion of coal, similar to coke production. The chemical reactions in DRI require high temperatures, but not high enough to melt iron. The DRI process thus requires less energy than BF ironmaking.

2.1.3 Stage III. Steelmaking

Pig iron or sponge iron is then used as raw material in crude steelmaking following two main routes: the basic oxygen furnace (BOF) and the electric arc furnace (EAF). Both processes melt the iron inputs and add oxygen and other elements to achieve the desired chemistry for the steel product. Both processes also typically melt steel scrap along with the iron inputs, permitting a high degree of recycling, especially for EAF. For a BOF, the materials are heated by burning a fuel, while an EAF applies high voltage electricity directly to the materials to melt them.

The produced steel is then refined to remove most residual impurities. Steelmaking culminates with a continuous casting process in which the molten steel is poured into open-bottomed, water-cooled molds to create standardized semi-finished shapes (known as slabs, billets, and blooms). The following diagram outlines the steelmaking process, starting with the material preparation process.

Figure 1. The Steelmaking Processes



Source: Elaboration based on World Steel Association[199]

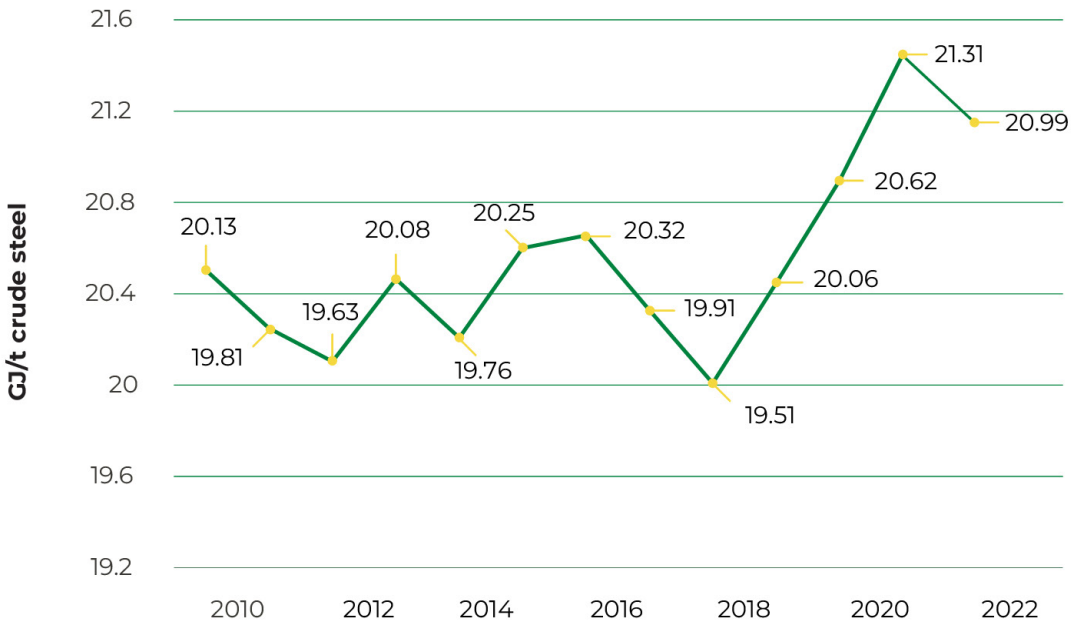
About 70% of global steel production uses the BF-BOF route, and about 29% uses the EAF route. Variations and combinations of production routes account for the rest. Although steel is highly recyclable, most steel products have a useful life that lasts for decades. Therefore, more than just recycled steel scrap is required to meet growing steel demand.

2.2 Energy Intensity

In 2022, the steel sector consumed, on average, 20.99 gigajoules (GJ) of energy per ton of crude steel produced. Within this average, the energy intensity varies significantly depending on the production route. Producing steel from iron ore requires eight to ten times more energy than using scrap steel as the raw material due to the need to heat and process the iron ore. According to International Energy Agency data (IEA, 2020), steelmaking has an energy intensity of 21.4 GJ/t using the BF-BOF route and 17.1 GJ/t using the DRI-EAF route, while recycling steel scrap into new steel products using an EAF requires only 2.1 GJ/t. The figure below shows the evolution of global steel production energy intensity from 2010 to 2022.

[199] https://worldsteel.org/about-steel/about-steel/steelmaking/

Figure 2. Energy Intensity of Global Crude Steel Production (2010-2022)

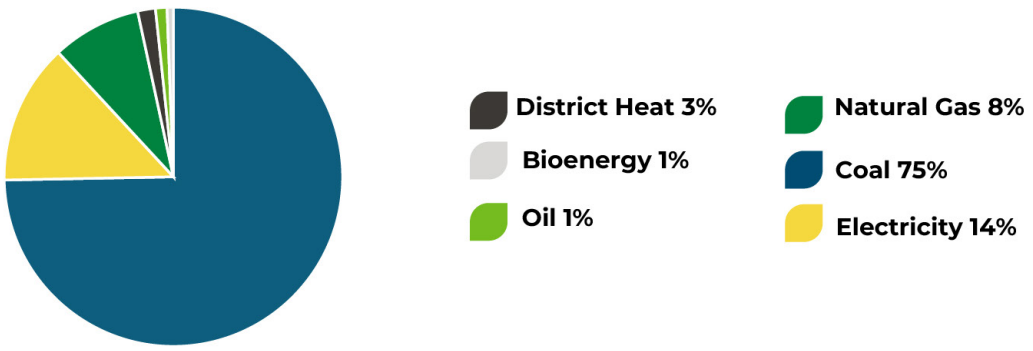


Source: Elaboration based on statistics from the World Steel Association (2021b, 2022a, 2023)

2.3 Steel Production Fuel Matrix

Coal is the main energy source used for steel production, accounting for 73% of the total for 2022 (IEA, 2023). Electricity and natural gas account for a further 22% of the total, as shown in the figure below.

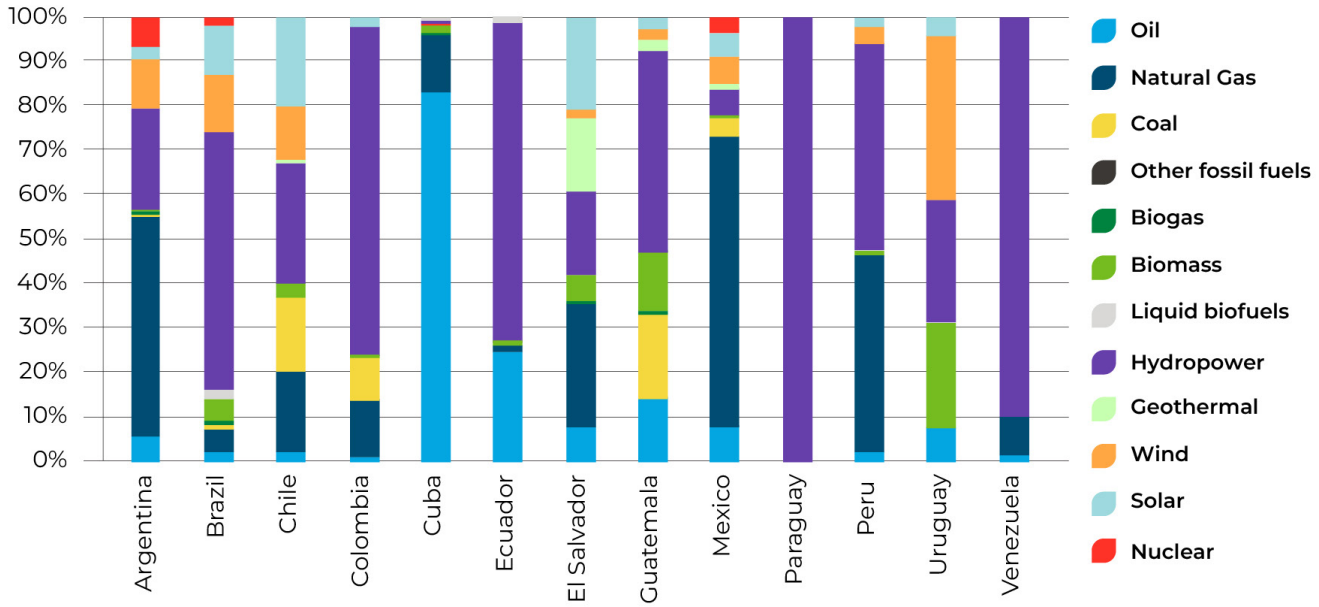
Figure 3. Energy Matrix for Global Steel Production (2022)



Source: Prepared in-house based on IEA (2023)

The energy matrices for electricity generation of the main steel-producing countries in LAC, including Brazil, Argentina, and Mexico, have a higher proportion of non-fossil energy (such as hydroelectric, nuclear, and bioenergy) than the global average (see Figure 4 below). This implies that indirect GHG emissions (scope 2) in some of the largest steel producers in the region are also lower than the global average.

Figure 4. Energy Matrix for Electricity Production in LAC (2023)



Source: Elaboration based on data from the OLADE sieLAC database.

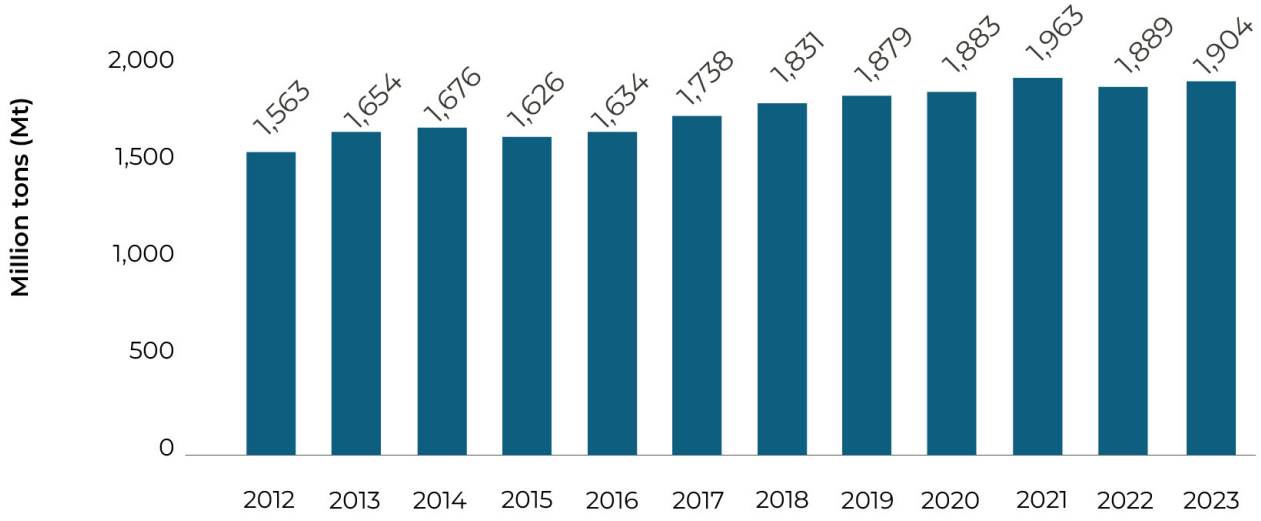
Furthermore, the region has areas with high renewable energy use, such as Argentina and the Chilean Patagonia with wind energy and northern Chile, Argentina, Peru, and some areas of Brazil with solar energy, enabling renewable energy to be generated at competitive prices, although transmission constraints, tariff policies, and institutional issues must be considered.

3. GLOBAL AND REGIONAL MARKETS

3.1 Global Production

Global crude steel production has grown by 21% in the last twelve years, from 1,563 Mt in 2012 to 1,904 Mt in 2023. Increased steel demand is driven by economic growth, technological development, and urbanization, particularly in emerging markets where significant investments are being made in infrastructure and construction. The figure below shows annual global crude steel production from 2012 to 2023.

Figure 5. Global Crude Steel Production (2012-2023)



Source: Prepared in-house based on the 2025 World Steel Association statistics[200]

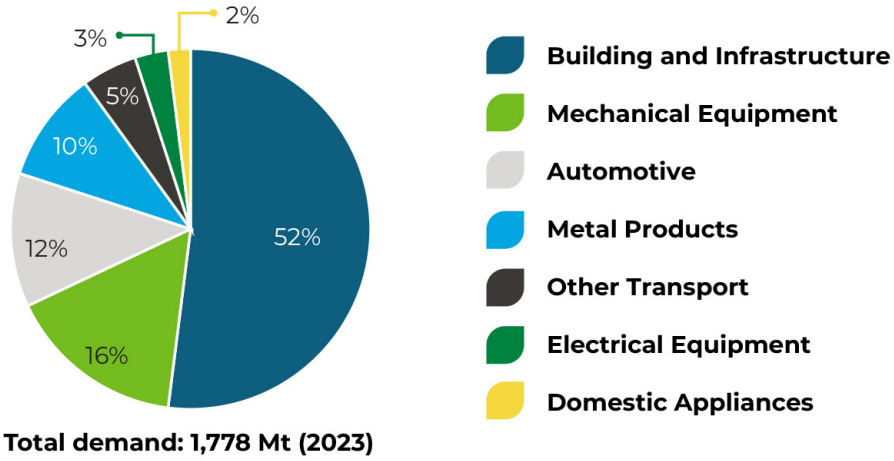
[200] https://worldsteel.org/steel-topics/statistics/world-steel-in-figures/

3.2 End Uses

Crude steel is used to produce a variety of rolled products such as sheets, coils, bars, wire rods, structural beams, and rails. These products are used in the automotive, construction, transportation, energy, packaging, tools, and machinery industries, among others.

In 2023, the construction sector (buildings, housing) and infrastructure (energy, roads, water, and sanitation) accounted for 52% of global steel demand, followed by mechanical equipment (16%), automotive (12%), and tools (10%). Other means of transportation (trains, ships, airplanes), domestic appliances, and electrical equipment make up the remaining 10%, as shown in the figure below.

Figure 6. Percent Share of Steel Demand by Sector (2023)

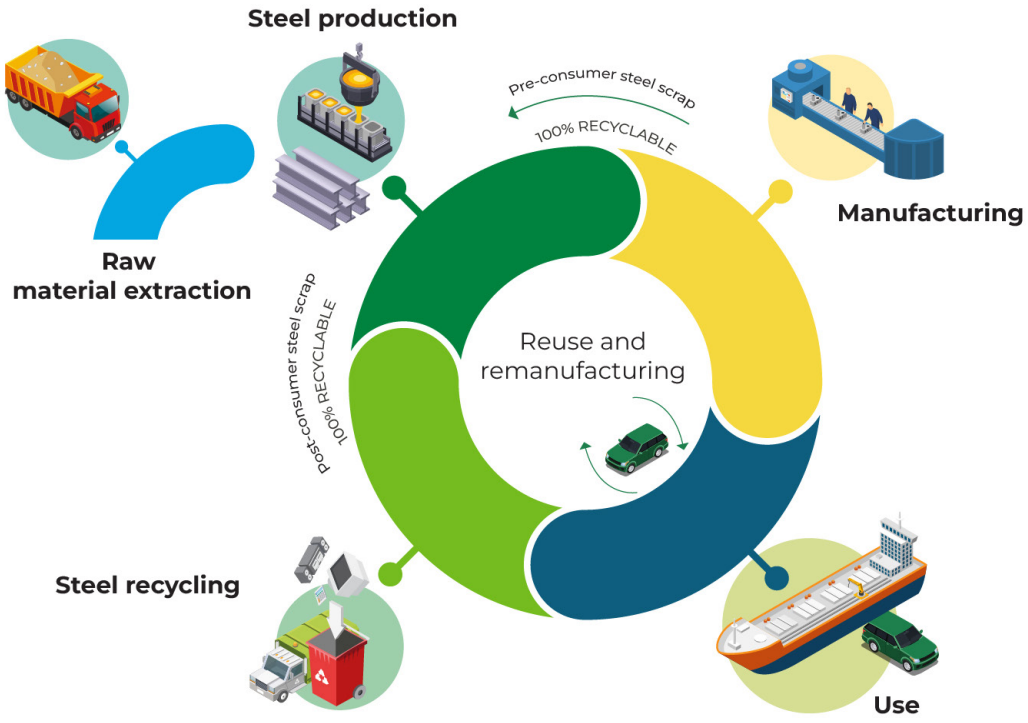


Source: Prepared in-house based on World Steel Association statistics

3.3 Lifecycle

Steel's lifecycle is dependent on its final application. Sectors that provide short-term services, such as packaging, have relatively short lifecycles (less than two years) and simpler value chains. This facilitates recycled steel use integration and circularity. Other industries, such as construction and infrastructure, have longer lifecycles, with periods of at least 50 years before the steel can be recycled. This requires a well-established value chain for recovery, processing, and smelting. The figure below illustrates the life cycle of steel in different applications.

Figure 7. The Life Cycle of Steel



Source: Elaboration based on World Steel Association[201]

Around 630 Mt of steel scrap is globally recycled annually (BIR, 2022), equivalent to 33% of the total crude steel production recorded in 2023 (1,904 Mt). Roughly 38% of recycled steel scrap is pre-consumer[202] generated during the manufacturing and processing of steel products before they reach end consumers. The remaining 62% is post-consumer scrap purchased on the market (BIR, 2022).

3.4 Steel Industry in LAC

This section describes the region's steel industry and analyzes its evolution over time, highlighting each steel-producing country, the major manufacturing routes, leading steel-producing companies, and regional steel trade. It then examines the industry's future and the challenges the region must address.

[201] https://worldsteel.org/steel-topics/life-cycle-thinking/
[202] Waste (circulating scrap) from the steel industry (lumpy metal debris) formed during the smelting process.

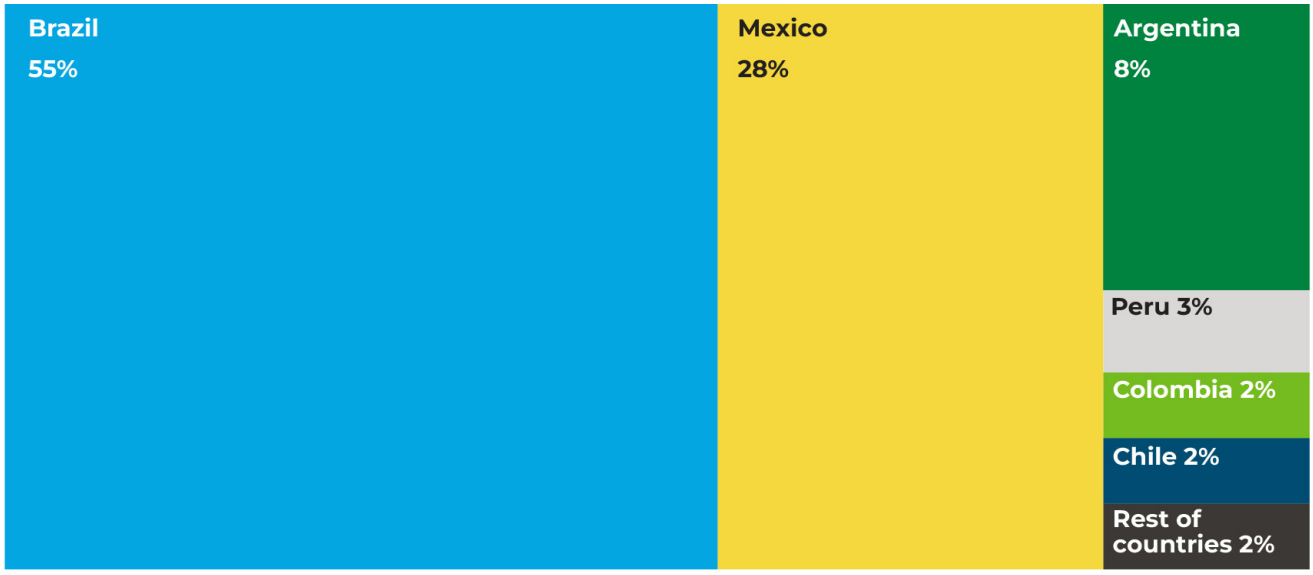
3.4.1 Producing Countries

In the early 1970s, crude steel was produced in eight Latin American countries: Argentina, Brazil, Chile, Colombia, Mexico, Peru, Uruguay, and Venezuela. In 1974, regional production totaled 17 Mt. The largest producers were Brazil, with a share of 44% (7,5 Mt), Mexico with 30% (5,1 Mt), Argentina with 12% (2 Mt) and Venezuela with 6% (1 Mt). In 1975, Cuba began production (298,000 t). Trinidad and Tobago joined in 1980 with a production of 3,200 t, followed by the Dominican Republic in 1986 (100,043 t). Paraguay joined the list of producers the following year with 13,167 t. Almost a decade later (in 1995), Ecuador and El Salvador joined the group of producers with 94,927 t and 34,641 t, respectively. Finally, Guatemala joined in 2000 with a crude steel production of 167,000 t.

In 2016, the Point Lisas Iron and Steel plant in Trinidad and Tobago closed, halting the country's steel production. The EAF-DRI plant was sold in June, 2023 and the new owners plan to revive the plant using renewable hydrogen to produce steel with low CO_2 emissions.

In 2023, the remaining 13 crude steel-producing countries in the region produced 58.32 Mt of crude steel, representing 3.06% of global steel production (1,904 Mt). Brazil, Mexico, Argentina, Colombia, Chile, and Peru account for 98% of the region's production, as shown in the figure below.

Figure 8. Production of Crude Steel in LAC (2023)



Source: Prepared in-house based on the World Steel Association 2023 statistics[203]

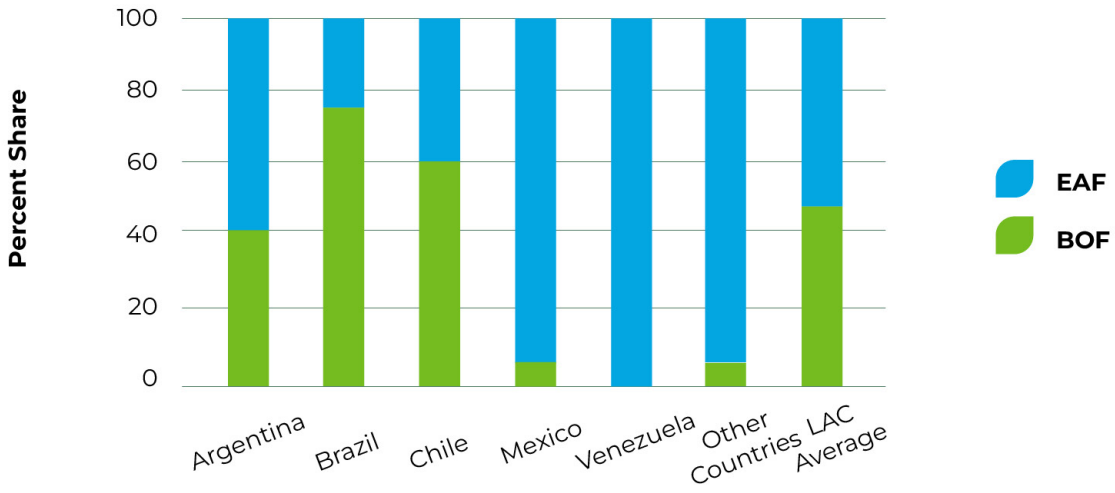
[203] https://worldsteel.org/steel-topics/statistics/annual-production-steel-data/?ind=P1_crude_steel_total_pub/CHN/IND

3.4.2 Major Manufacturing Routes

The Latin American steel industry uses diverse production methods, depending on each country's comparative and strategic advantages, available resources, and market needs. Iron production in LAC is dominated by BF, which produces pig iron. Of the total primary iron produced in 2023, pig iron reached an average share of 78%, while the remaining 22% corresponded to sponge iron produced by DRI. Brazil is the region's leading producer of pig iron, with an 87% share, while Mexico produces 73% of the region's sponge iron (World Steel Association, 2025).

Crude steel production in LAC is largely balanced between BOF and EAF. In 2023, BOF accounted for 49% of total LAC steel production while EAF accounted for 51% (see Figure 9 below). Within individual countries one technology tends to dominate. EAF accounted for 100% of Venezuelan crude steel production (although no actual production is reported for the country in 2023), 93.4% of Mexican production, and 93.2% of production in other smaller producing countries. BOF accounted for 75.9% of production in Brazil and 61.5% in Chile. Argentina had the most balanced production with 42.9% BOF and 57.1% EAF.

Figure 9. Share of Crude Steel Production in LAC (2023)



* Other countries include Cuba, El Salvador, Ecuador, Guatemala, Paraguay and Uruguay

Source: Prepared in-house based on the World Steel Association statistics (2024) and data from Aco Brasil

In the case of other countries in the Latin American region, Cuba, Ecuador, El Salvador, Guatemala, Paraguay, Uruguay, and Venezuela, produce crude steel exclusively using the EAF route (ALACERO, 2023a).

3.4.3 Companies

In Latin America and the Caribbean, the steel industry is largely integrated from iron ore extraction to manufacturing crude steel and finished steel products. Other relevant companies process semi-finished steel into finished products, such as beams, sheets, and tubes. To a lesser extent, electrical steel manufacturers, in partnership with recycling companies, use steel scrap melting furnaces to produce new products.[204]

[204] Electrical steel (silicon steel) is a type of steel manufactured for electrical and electronic applications. This type of steel has enhanced magnetic and electrical properties, making it highly suitable for manufacturing electromagnetic components and devices.

At least 50 regional companies operate more than 80 crude steel-producing mills (Madías, 2014), with a combined installed capacity of nearly 100 Mt (CRU, 2022). Most steel producers are concentrated in Brazil, with 11 companies operating 31 plants. Mexico is the next largest with nine companies operating 17 plants, followed by Colombia, with five companies, and Argentina and Ecuador, with four companies each.

Table 1. Main Crude Steel Producers in LAC

Country	Companies
Argentina	Acindar S.A. (AcelorMittal Group)
	Gerdau Sipar
	Siderar S.A.I.C. (Ternium S.A.)
	Siderca S.A.I.C. (Techint Group)
Brazil	Aço Verde do Brasil - AVB
	Aperam Sudamericana
	ArcelorMittal Aços Longos
	ArcelorMittal Tubarão
	ArcelorMittal Pecém
	Companhia Siderúrgica Nacional (CSN)
	Gerdau Aços Especiais S.A.
	Gerdau Açominas S.A.
	GV do Brasil
	Companhia Siderúrgica do Atlântico
	Villares Metals S.A.
	Siderúrgica Norte Brasil S.A. (SINOBRAS)
	Ternium Brasil
	Gerdau Aços Longos S.A.
	Usiminas
	Vallourec Soluções Tubulares do Brasil S.A.
	ArcelorMittal Sul Fluminense
	SIMEC
Chile	Gerdau AZA S.A.
	Siderúrgica Huachipato S.A. (CAP Acero)
	Diaco S.A. (Gerdau S.A.)
Colombia	Acerías Paz del Río S.A. (Votorantim)
	SIDENAL
	SIDOC
	Ternium Colombia
Cuba	ACINOX (Empresa Siderúrgica José Martí)
Ecuador	ADELCA
	ANDEC
	NOVACERO
	TALME
El Salvador	CORINCA
Guatemala	Siderúrgica Sidegua Masagua
Mexico	AHMSA
	ArcelorMittal México
	Deacero
	Gerdau Corsa
	Grupo Acerero
	Grupo Simec
	Tenaris TAMSA
	Termium México
	Tyasa
Paraguay	Aceros del Paraguay S.A. (ACEPAR)
Peru	Aceros Arequipa
	Empresa Siderúrgica del Perú (Gerdau S.A.)
Uruguay	Gerdau Laisa S.A. (Gerdau S.A.)
Venezuela	Complejo Siderúrgico de Guayana C.A.
	Complejo Siderúrgico Nacional S.A. (CSN)
	Siderúrgica del Orinoco C.A. (SIDOR)

Source: Prepared in-house based on information from the steel associations of each country.

These mills use a variety of processes to manufacture steel. The main production routes are:

- scrap-based electric steelmaking, which has 55 plants in operation;
- blast furnaces and basic oxygen converters, present in 13 plants; and
- electric steelmaking with direct reduction using natural gas, used in 8 mills.

Although electric steelmaking plants make up the vast majority, around 50% of production volume follows the blast furnace and basic oxygen converter (BF+BOF) route.

In addition to conventional steel production routes in Latin America, different routes are also used to help diversify industrial processes. These routes include charcoal-fired furnaces (currently in use in Brazil) and oxygen steelmaking, scrap-based induction furnaces, and direct reduction using coal, among others. These secondary routes demonstrate the Latin American steel industry's adaptability and versatility, allowing for different production methods and resources to meet market demands and take advantage of available regional resources.

3.4.4 Exports and Imports

As shown in the table below, Latin American rolled steel exports (not including welded tubes, strips, or wire rods) declined by 38% between 2017 and 2024. Brazil showed a 61% decrease in exports. Peru saw the second largest decline at 26%, while in Argentina the reduction was 25%. Mexico's exports declined 18% during the period. Chile's exports nearly doubled, however, and the region's smaller producers also showed a decrease of almost 18%.

Table 2. Rolled Steel Exports (Thousands of Tons)

Country	2017	2018	2019	2020	2021	2022	2023	2024
Argentina	706	886	981	659	741	536	479	530
Brazil	5,267	4,228	3,914	2,618	2,738	3,650	2,427	2,046
Chile	99	211	236	203	317	301	290	158
Colombia	79	81	55	40	48	112	54	100
Mexico	3,745	3,821	3,469	3,254	4,107	4,976	3,370	3,065
Peru	236	227	204	133	222	239	227	175
Venezuela	0	0	6	7	13	11	2	2
Others	887	656	591	571	792	630	730	728
LAC Total	**11,019**	**10,110**	**9,457**	**7,484**	**8,977**	**10,456**	**7,579**	**6,804**

Source: Prepared in-house based on information from ALACERO Latin America in figures (2024).

As shown in the table below, Latin American rolled steel imports (not including welded tubes, strips, or wire rods) increased by 12% between 2017 and 2024. During this period, steel imports declined in Argentina (-43%), Peru (-15%), and Colombia (-4%). However, these declines were outweighed by increased imports in the region's largest markets, Brazil (109%), Mexico (13%), and Chile (3%), as well as Venezuela (64%) and the smallest markets aggregated as "other" in the table (6%).

Table 3. Rolled Steel Imports (Thousands of Tons)

Country	2017	2018	2019	2020	2021	2022	2023	2024
Argentina	1,021	941	628	571	997	983	938	586
Brazil	1,995	1,961	1,797	1,636	3,492	2,685	3,872	4,164
Chile	1,719	1,864	1,940	1,502	2,356	1,621	1,608	1,769
Colombia	2,200	2,487	2,414	1,769	2,693	2,205	1,883	2,109
Mexico	11,112	10,130	10,154	8,823	11,715	10,346	12,552	12,512
Peru	2,378	1,778	1,742	1,711	2,431	2,009	1,744	2,012
Venezuela	108	39	22	14	23	87	111	177
Others	4,587	4,715	4,359	3,782	5,257	4,460	5,187	4,869
LAC Total	**25,122**	**23,915**	**23,057**	**19,807**	**28,965**	**24,396**	**27,895**	**28,199**

Source: Prepared in-house based on information from ALACERO Latin America in figures (2024).

Export and import data show a trade imbalance in the region's steel industry, with a high dependence on imports to meet domestic demand. This scenario challenges the competitiveness of the countries' steel production and highlights the need to evaluate strategies that encourage local production and reduce dependence on imports.

3.4.5 Forecasted Demand Projections

On the heels of the global economic disruptions caused by COVID-19, steel consumption has continued to grow due to a recovery in demand, an increase in the industrial production and manufacturing index, and a rebuilding of end-consumer and distribution chain inventories.

According to ECLAC estimates (2022), crude steel demand will continue to rise as emerging economies continue developing and undergo a demographic transition from rural to urban areas. For many emerging economies, this means steel demand is expected to grow more rapidly than their populations. This trend does not hold for all countries, however: Brazilian per capita steel demand has been relatively steady at close to 100 kg per inhabitant since the 1980s despite a real per capita GDP growth of 50% in the same period.

By 2028, the global steel market is projected to grow by 2.5% per year on average. Given steel's importance as one of the world's primary materials and its essential role in driving economies, the sector is anticipated to both significantly impact and be reciprocally impacted by global trends (ALACERO, 2022b).

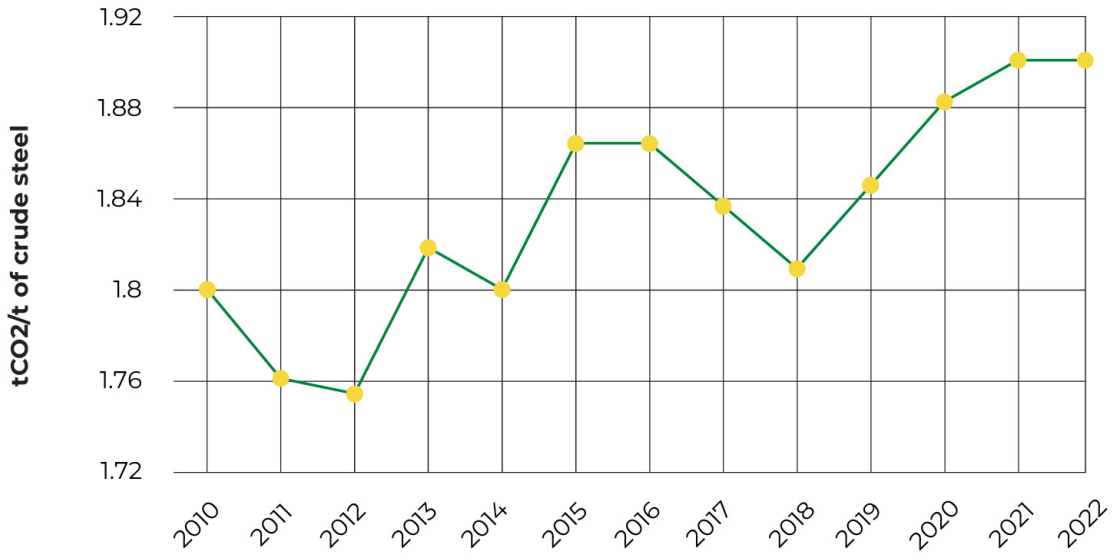
4. ENVIRONMENTAL IMPACT OF THE INDUSTRY

This section looks at the steel industry's contribution to CO_2 emissions at the global and regional levels, providing a framework for understanding its environmental challenges.

4.1 Global

Steel manufacturing has a considerable carbon footprint, emitting an estimated 3.6 Gt of CO_2 globally in 2022[205]. From 2010 to 2022, emissions per unit averaged 1.84 tons of CO_2 per ton of steel, peaking in 2021 and 2022 at 1.91 tCO_2/t[206] (see the figure below).

Figure 10. Emission Factors for World Crude Steel Production (2010-2022)



Source: Prepared in-house based on the World Steel Association statistics (2021b, 2022a, 2023).

[205] Calculated from World Steel Association steel production and emissions intensity figures.
[206] Including direct and indirect emissions.

On average, 70% of crude steel production emissions are direct (Scope 1, released directly through the production process), and the remaining 30% are indirect (Scope 2, released from inputs to the production process that are outside of the manufacturer's direct control) (IEA, 2020). Both direct and indirect emissions factors are influenced by the steel production route and the treatment of electricity inputs.

The average total emission intensity of the BF-BOF route as calculated by the IEA is 2.2 tCO_2/t. This is 7.3 times higher than the IEA's estimated 0.3 tCO_2/t average total emissions from the EAF route using only scrap steel. Combining the EAF route with DRI-produced sponge iron instead of scrap increases average total emissions to 1.4 tCO_2/t but remains 37% lower than BF-BOF. In addition, the BF-BOF route contributes more to direct emissions than the other production routes.

These estimates are based on steel production energy intensities in final energy terms. The World Steel Association's (WSA) methodology estimates steel production energy intensities in primary energy terms. This difference is most pronounced for electricity inputs, as the WSA methodology uses a 37% conversion efficiency factor to calculate the primary energy required to produce the electricity used in the steel production process.

The table below compares the estimated GHG emissions from steel production using the two methodologies. The differences are most pronounced in the scrap-EAF process in which electricity accounts for nearly all of the production energy required.

Table 4. Global CO_2 Emission Factors According to Crude Steel Production Route and Source

		BF-BOF		Scrap-EAF		DRI - EAF	
Source	**Type of emission**	tCO_2/t	%	tCO_2/t	%	tCO_2/t	%
IEA (2020)	Direct	1.20	55%	0.04	13%	1.00	71%
	Indirect	1.00	45%	0.26	87%	0.40	29%
	Total	2.20	100%	0.30	100%	1.40	100%
WSA (2024)	Total	2.32		0.7		1.43	

Source: Elaboration based on IEA (2020a) and World Steel Association (2024)

4.2 Emissions from Latin America

In LAC, the average emission factor for crude steel production is 1.66 tCO_2/t (CRU, 2022), 9% less than the world average. This difference is due to a higher share of steelmaking using the EAF route as well as a more significant share of renewable energy in the electricity generation matrix (CRU, 2022).

Latin America produces 57.9% of its steel using the EAF route—only North America and Africa have a higher regional share (CRU, 2022). This trend results from the wide availability of low-cost electricity and natural gas in countries such as Argentina, Mexico, and Venezuela, which favor DRI and EAF production. In countries with higher cost natural gas, such as Brazil, these technologies are less prevalent.

Total CO_2 emissions associated with crude steel production in the region were an estimated 102.8 Mt in 2022. Direct emissions (Scope 1) account for 93.37% of total emissions (96 Mt, or 1.55 tCO_2/t of steel produced), while indirect emissions (Scope 2) account for the remaining 6.63% (6.8 MT, or 0.11 tCO_2/t of steel produced).

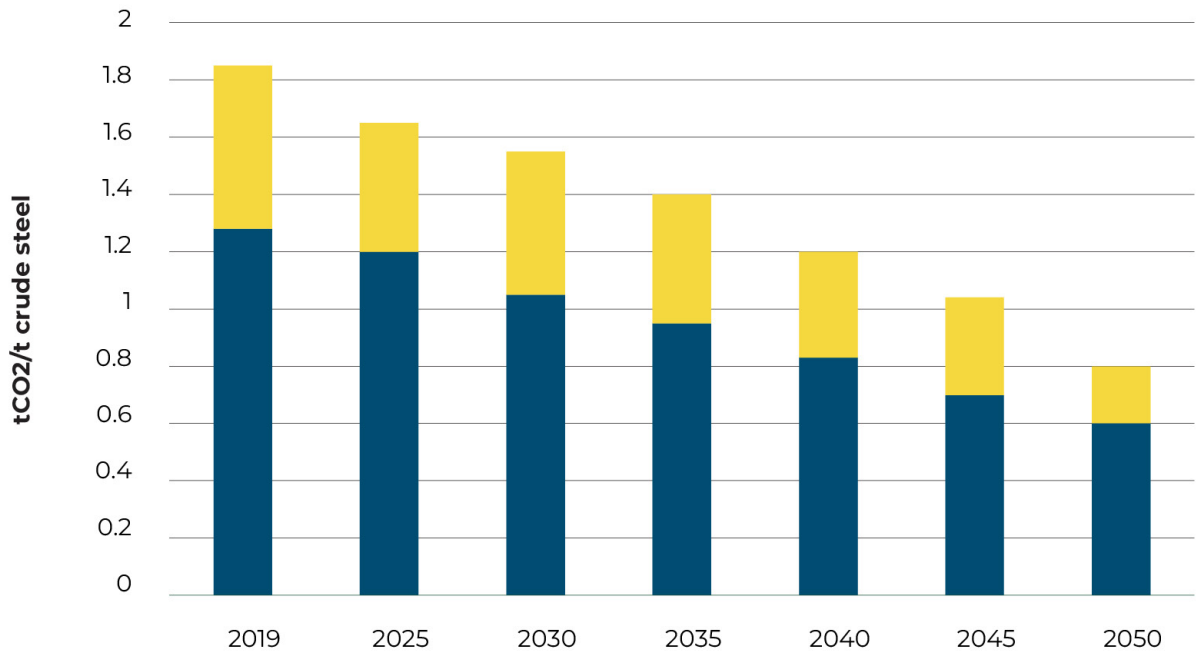
Disaggregating emissions by production route shows that BOF production in LAC generates approximately 1.91 tCO2/t of crude steel, while EAF-based production generates about 0.55 tCO_2/t of crude steel or 29% of the carbon intensity of BOF production per ton produced. Although the EAF process is more electricity intensive and therefore represents higher Scope 2 emissions, the Scope 1 emissions associated with this steelmaking route are 82% lower (CRU, 2022).

5. DECARBONIZATION IN LAC

5.1 Global Decarbonization Scenario

To meet Paris Agreement targets, the IEA estimates that the steel industry must reduce its direct and indirect emissions by at least 50% by 2050 and achieve continuous reductions towards zero emissions (see Figure 11 below). This scenario would reduce emissions intensity from 1.85 tCO_2/t of crude steel in 2019 to 0.8 tCO_2/t by 2050. It would require significant investment and policy support to enable a technological transition towards widespread deployment of production routes with reduced carbon emissions. These routes could include a shift toward EAF, carbon capture, utilization, and storage (CCUS), and other measures that prevent and/or mitigate direct CO_2 emissions, such as hydrogen-based production, bioenergy use, and renewable energy (IEA, 2020a).

Figure 11. Global Decarbonization Scenario for the Steel Industry in 2050



Source: Prepared in-house based on IEA information (2020a).

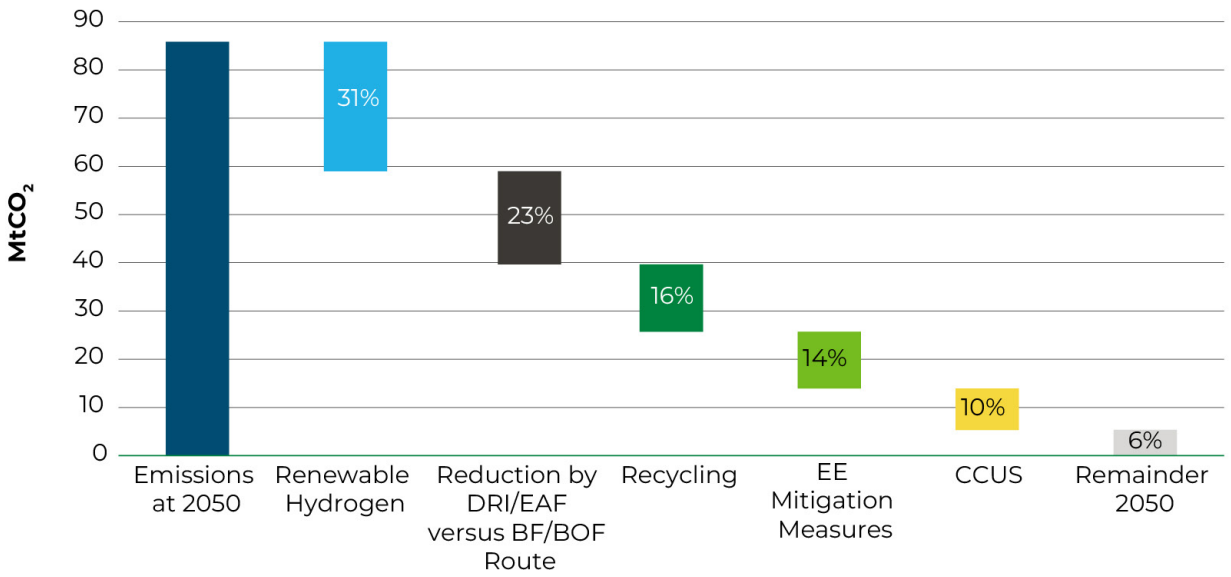
5.2 Industry Decarbonization Routes in LAC

Reducing greenhouse gas emissions in the steel industry poses a complex challenge due to various technical realities of steelmaking (De Pee, 2018). First, 45% of raw materials CO_2 emissions cannot be significantly reduced by a change in fuels but rather require process changes. Second, 35% of emissions come from burning fossil fuels to generate high-temperature heat. Switching to alternative fuels, such as electricity from renewable sources, would require significant furnace design changes. Third, processes across the steelmaking value chain are highly integrated, meaning that changes in one production stage often require changes in others. Finally, production facilities have a long service life, so reducing emissions will require changing processes at existing sites through costly upgrades or closing sites before the end of their economic life.

Mitigating and innovative strategies and technologies can be implemented to reduce emissions from existing infrastructure. Policies supporting unprofitable facilities could be changed to allow them to close. Investment and financial support for infrastructure renewal and modernization can also help. This can include support for increasing energy efficiency through improved process integration and applying emission-reducing technologies, such as replacing natural gas with hydrogen or installing carbon capture, use, and storage (CCUS) technologies. Furthermore, a change in inputs or raw materials, such as a higher proportion of scrap or higher quality iron ore, and incremental fuel switching and blending can also help reduce CO_2 emissions in the industry.

Given the variety of circumstances in the LAC region, energy efficiency, hydrogen deployment, and CCUS are promising options for reducing direct and indirect emissions from the steel industry. The figure below shows how different technologies can help mitigate total emissions from the leading steel-producing groups.

Figure 12. Steel Industry Decarbonization Route in LAC



Source: Prepared in-house based on E3G (2021) data.

Through several strategies, steel production in the LAC region can move towards net-zero emissions by 2050. Energy efficiency and increased scrap recycling could reduce emissions by 14% and 16%, respectively. Another promising option is the use of hydrogen in blast furnaces, especially given the region's capacity to generate hydrogen from renewable energy. This approach could reduce emissions by around 31%. Solutions such as CCUS, though also under consideration, face challenges due to their high costs and intermediate technological maturity. However, they could have an impact of around 10%. The table below details the decarbonization options available to each steel production route.

Table 5. Decarbonization Options for the Steel Industry

Basic production routes	Trends	
	Mitigating	Innovative
Blast Furnace/Oxygen Converter (BF-BOF)	• Heat recovery from coke cooling • Energy efficiency of BF auxiliary equipment • Replace natural gas injection with biomethane or methanol. • Replace pulverized coal injection with blue H_2. • Substitute fossil coal with Biomass.	• Partially replace BF-BOF using mineral feed (sinter-pellets) with equivalent obtained by carbon-free DR (renewable H2). • Replace BF with special furnace systems that incorporate electricity co-generation. • Replace BF with DRI using renewable H_2. • Capture, store, and use CO_2 (CCS/CCU)
Direct Reduction (DRI)	• Substitute natural gas for reduction with biomethane. • Use methanol as an H_2 carrier. • Capture and use CO_2 in other industries. • Energy efficiency using heat recovery • Improve the metallization coefficient.	• DR process with hydrogen (renewable H_2) • Use methane pyrolysis with low-carbon electricity to produce "turquoise hydrogen" and solid carbon for use in EAFs
Electric Arc Furnace (EAF)	• Electrify using renewables. • Computerized management of furnace and energy demand • Energy efficiency with heat recovery • Predominant use of scrap with renewable energy sources.	• Scrap supplement feeding with alternative steelmaking processes using green H_2 as a reductant alone or combined with green H_2 • DR systems using H_2 and EAF using renewable energies and biomass

Source: Prepared in-house.

As described above, optimizing current production processes such as BF-BOF, DRI, and EAF while introducing technological innovations for cleaner and more efficient production is a promising approach to steel industry decarbonization that can be tailored to each country's specific situation. This approach will require significant changes in the status quo, including new infrastructure to allow substituting fossil fuels with biomethane, renewable hydrogen, and renewable energy; capital investment at the plant level to improve energy efficiency through heat recovery and computerized furnace management; and policy and commercial coordination to increase steel scrap availability for use as raw material in EAF. In addition, more technologically unproven approaches are contemplated, such as CCUS and the introduction of co-generation systems that reuse furnace heat energy for electricity generation. These mitigation options could contribute significantly to reducing the carbon footprint of the global steel industry if they are given the required policy, technical, and financial support.

5.2.1 Mitigation Trends

The following are the main CO_2 emission mitigation strategies for the steel industry. They include technologies covering a wide range of readiness for commercial use, capital costs, and operating costs.

5.2.1.1 Substitute natural gas with biomethane

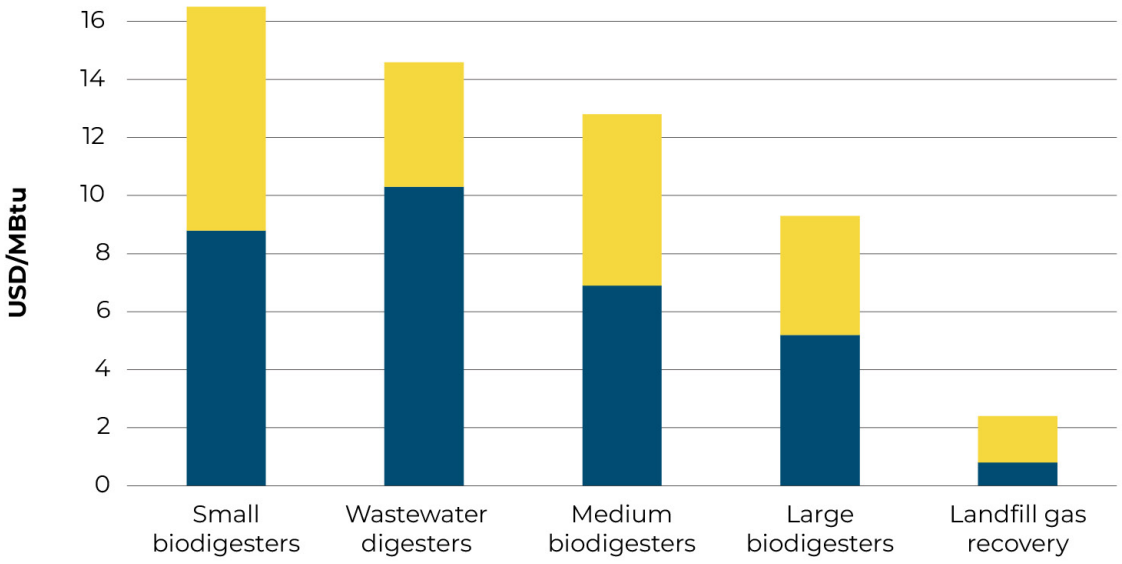
Biomethane, also known as "renewable natural gas", is a nearly pure source of methane that is produced by "upgrading" biogas (IEA, 2020b).[207] While some countries are considering natural gas as a bridge fuel, helping to reduce emissions in the short term while renewable and low-carbon alternatives scale up, biomethane, by contrast, represents a further step toward decarbonization. It is renewable and can be produced from various sources, including agricultural waste, food waste, sewage, and other types of organic waste. Once produced, biomethane can be used in the same way as natural gas. The three leading technologies for its production are biodigesters, landfill gas recovery systems, and wastewater treatment plants. In all cases, biomethane must be treated to remove contaminants and moisture before use.

Biomethane is an alternative to natural gas that does not require changes to existing transmission and distribution infrastructure or end-user equipment, making it compatible with industrial applications. It can be used as a substitute for natural gas injection in blast furnaces or as a reducing agent in direct reduction processes. Biomethane use in the steel industry currently has an estimated TRL of between 5 and 6 (Draxler et al., 2021). In Brazil, the steel company Ternium uses landfill-produced biomethane to replace more than 30% of fossil natural gas consumption. The biomethane is injected into the industrial complex's low-pressure gas pipeline and used for heating in the blast furnace, steel mill, coking plant, and sintering sectors.[208]

The figure below shows average biogas production costs according to raw material and facility size.

[207] The process that removes CO2 and other pollutants present in biogas.
[208] https://www.ternium.com/en/media/news/ternium-pioneers-the-use-of-renewable-gas-in-steel--09158714319

Figure 13. Biogas Production Costs



Source: Prepared in-house based on IEA information (2018).

The costs associated with using biomethane in the steel industry include the costs of converting biogas to biomethane and transporting it from the production or processing site to its destination. Various conversion technologies exist, including membranes, adsorption, biofiltration, absorption/scrubbing, cryogenic refining, and biological enrichment. To increase the use of biomethane in the steel industry, regulations must allow for the injection of biomethane into public natural gas networks so that the industry is not limited by its proximity to biomethane production sites. Although there is no generalized regulation in LAC, Chile allows biogas from the La Farfana wastewater plant to be injected into the distribution network. If policies and infrastructures are implemented to encourage this practice, biomethane could be an essential technological option for decarbonizing steel production. It would not require significant changes in existing blast furnace processes or direct reduction systems based on natural gas.

Despite its benefits, the supply of biomethane is still an issue, with very few operational plants in the region. To change this scenario, regulatory frameworks and targeted policies are needed, such as Brazil did in 2024 by approving a legislation named “Combustível do Futuro”, which created a blending mandate for biomethane (an important demand sign to the market).

5.2.1.2 Use ammonia as a hydrogen carrier

Despite its high cost and transportation difficulties, hydrogen is emerging as a key energy resource in the global energy market. Technical difficulties that affect its commercialization include its low energy density at ambient temperatures and pressures. One possible solution currently used is to compress hydrogen (above 200 bar) to transport it through pipelines, tanks, or ships. Another option is to liquefy hydrogen at a temperature of -253°C to reduce its volume to 1/800 parts, which implies a very high extra cost.

Low-carbon ammonia produced with hydrogen is therefore an attractive alternative for hydrogen transport. According to Wood Mackenzie’s analysis of global hydrogen supply projects, around 85% of installed capacity is intended to produce ammonia.

Ammonia has three advantages over hydrogen as an energy carrier for exports. First, as a liquid its high energy density at low pressures is three times higher than that of compressed hydrogen and 1.5 times that of liquefied hydrogen. This helps to optimize long-distance transport by requiring fewer ships to move the same amount of energy. Second, ammonia is a mature technology. Ships for transporting compressed hydrogen have not yet reached widespread commercialization, with only small volumes being transported. The ammonia industry has extensive experience in its production, storage, and transport, enabling new capacity to be quickly developed. Third, the ammonia industry is large and has established supply chains. A global-scale ammonia plant can produce 2 million tons per annum (mtpa) and total global production is on the order of 180 Mtpa. Roughly 20 Mtpa is currently traded via ships. The ammonia industry is also largely integrated with the production of derivatives such as urea and ammonium nitrate (Wood Mackenzie, 2022).

5.2.1.3 Use methanol as a hydrogen carrier

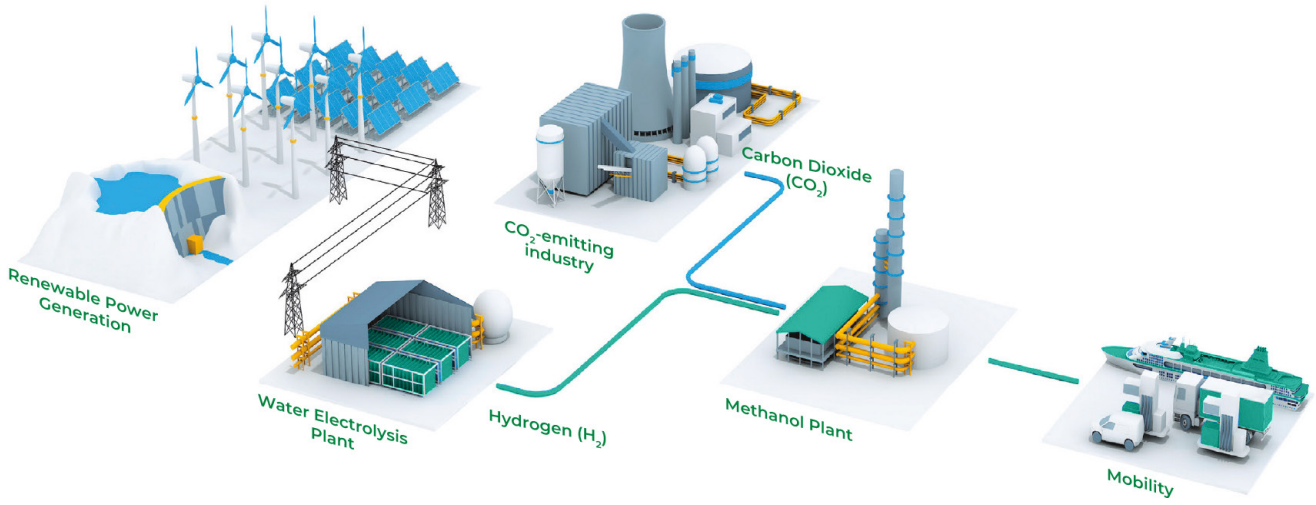
Methanol (CH3OH) is a liquid chemical produced from a mixture of hydrogen, carbon dioxide (CO_2), and carbon monoxide. It is a viable option for transporting hydrogen due to its ease of storage, logistics, and safety compared to pure hydrogen. In addition, methanol can be used directly instead of coal as a reducing agent in steelmaking.

Although methanol combustion produces fewer CO_2 emissions than coal combustion, it still has some emissions, so it is not a completely carbon-free solution. Methanol can be classified according to its manufacturing method and resulting CO_2 emissions reduction:

- brown methanol, produced from coal and with no reduction in CO_2 emissions;
- gray methanol, produced from natural gas and with a minor reduction in CO_2 emissions;
- blue methanol, synthesized from CO2 from natural gas combustion emissions, which reduces CO_2 emissions by 15%-25%;
- biomethanol or green methanol, which is an ultra-low CO_2 chemical produced from sustainable biomass; and
- e-methanol, synthesized from carbon dioxide and hydrogen produced from renewable electricity.

The production of e-methanol requires hydrogen and carbon, which can come from sources such as water electrolysis combined with CO_2 capture from industrial emissions or direct carbon capture in the air. The figure below outlines the e-methanol production sequence.

Figure 14. Diagram of E-Methanol Production



Source: Elaboration based on Thyssenkrupp Uhde

Green methanol and e-methanol have the potential to reduce CO_2 emissions by up to 95%. In the case of e-methanol, this reduction is only possible if the hydrogen used in production comes from water electrolysis using renewable electricity and if the CO_2 used comes from a non-carbon-emitting source, such as direct air capture (DAC).

These biofuels have great potential to reduce emissions from the steel industry. However, processes are still being developed to use methanol directly in sponge iron production via the DRI route, which is still at an experimental stage (Andersson et al., 2020).

The cost of green methanol or biomethanol production depends on the feedstock, investment, and conversion process efficiency. Despite the lack of cost data due to low current production, biomass data, and municipal solid waste data, feedstock costs are estimated to range between 0 and USD 17 per Gigajoule.. With a feedstock cost of 6 USD/GJ, biomethanol costs would range between 320 USD/ton and 770 USD/ton.

E-methanol costs are highly dependent on the cost of hydrogen and CO_2. The cost of CO_2 depends on the source from which it is captured, such as biomass or industrial processes. Currently, e-methanol production costs USD 800/ton to USD 1,600/ton, assuming that CO_2 is obtained from bioenergy carbon capture and storage (BECCS) for USD 10-50/ton. If CO_2 is sourced through direct air capture at a current cost of between USD 300/t and USD 600/t, e-methanol production costs would be between USD 1,200/t and USD 2,400/t. With the decreasing costs of renewables, the cost of e-methanol is expected to decrease to levels between 250 USD/t – 630 USD/t by 2050 (IRENA & MI, 2021).

5.2.1.4 Electrify using renewable sources

A promising solution for steelmaking decarbonization is to switch to EAF supplied with electricity from renewable energy sources. Companies can significantly reduce their GHG emissions by replacing fossil fuels traditionally used in steel production such as coal and electricity generated from fossil sources. In 2019, the steel industry accounted for 5.5% (1,230 TWh) of global electricity demand (IEA,

2020a) which produced 661 MtCO2 (based on a 0.538 kg CO_2 /kWh global average electricity emission factor). Approximately 25% of this electricity was used in electric furnaces to produce iron by DRI and scrap into steel. Most of the remainder was used in semi-finishing and steel-finishing processes.

LAC's electricity production matrix has a high share of renewable energy, especially hydroelectric power. As a predictable energy source, hydropower is well aligned with EAFs, which operate continuously 24 hours a day. In addition, hydropower generation costs are competitive with other renewable generation technologies, as shown in the table below.

Table 6. CAPEX and LCOE[210] of Electricity Generation Technologies (2022)

	Capital cost (USD/kW)			LCOE (USD/kWh)		
	Min	Max	Weighted Average	Min	Max	Weighted Average
Solar Photovoltaic	569	1,878	876	0.030	0.120	0.049
Onshore wind	677	3,389	1,274	0.017	0.145	0.033
Hydro energy	950	5,800	2,881	0.016	0.225	0.061
Bioenergy	1,000	6,000	2,162	0.050	0.125	0.061
Offshore wind	2,128	13,136	3,461	0.058	0.240	0.081
Geothermal	2,300	4,812	3,478	0.050	0.085	0.056
Concentrated solar power	4,274	4,274	4,274	0.118	0.118	0.118

Source: Elaboration based on IRENA (2023)

5.2.1.5 Use scrap as a production input with renewable energy

Steel production from scrap, also known as secondary production, is a low-cost process that reduces GHG emissions by eliminating the need for iron ore and coal. Instead, an electric arc furnace melts steel scrap to convert it into new steel. Currently, the technological maturity of scrap use in the industry reaches a level of 8-9, at the stage of successful operation (Draxler et al., 2021).

Scrap-based EAF steel production produces approximately 1/7th to 1/8th of the CO_2 emissions of the BF-BOF route. Combining renewable electricity supply for EAFs and other steel finishing processes can produce steel with very low CO_2 emissions.

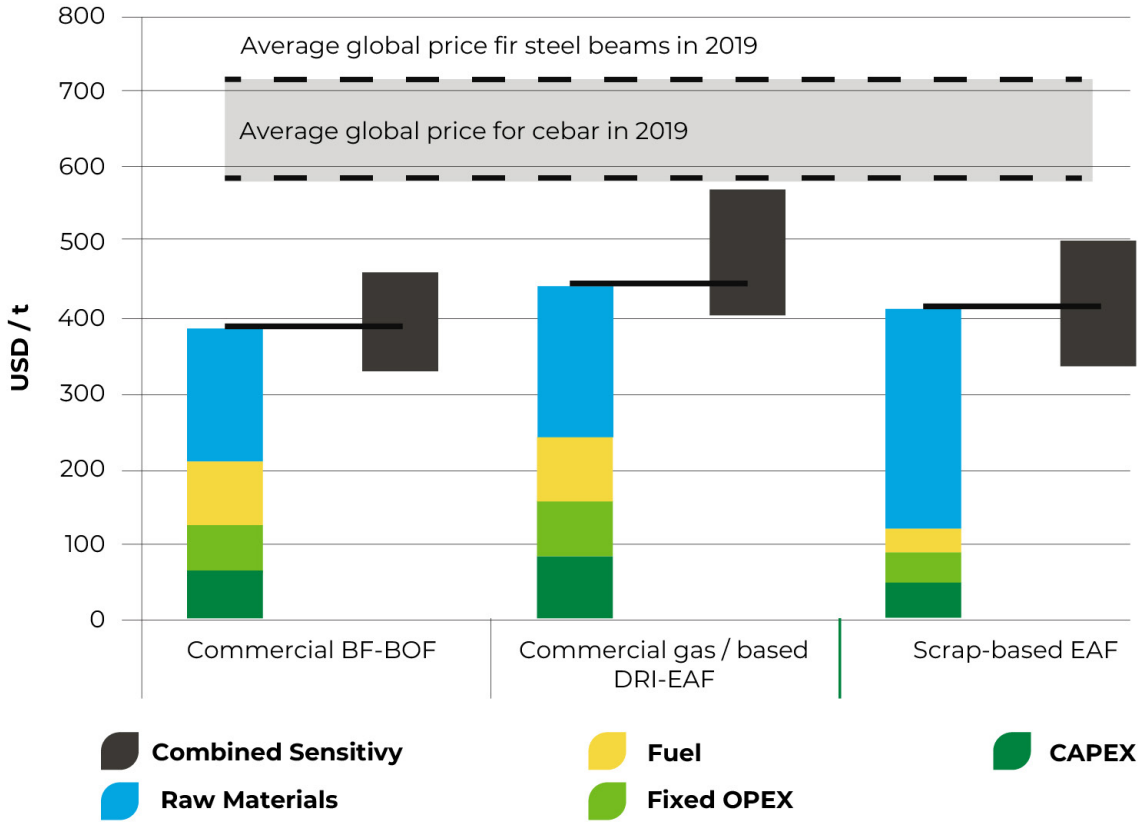
Increasing scrap-based steel production requires a continuous supply of electricity from renewable sources at competitive prices and a sufficient supply of suitable steel scrap. Many LAC countries lack the required volume of quality scrap steel or electricity generation infrastructure to guarantee steady renewable energy supply.

Steel production from scrap is economically competitive with BF-BOF processes. The cost of production through the scrap-EAF route depends mainly on the price of steel scrap and, to a lesser extent, on the cost of electricity. According to a recent study (Nicholas & Basirat, 2021), the levelized cost of steel production from scrap and renewable energy in 2021 was estimated to be USD 572/ton in

[209] Levelized Cost of Energy.

the USA, USD 551/ton in Germany, and USD 642/ton in China. By 2050, lower renewable energy costs are expected to further decrease these figures. In addition, the initial CAPEX for an EAF is lower than that of integrated BF-BOF steel mills, as there is no need to build an ironmaking plant or material preparation facilities such as a coke oven or sintering facility. The figure below shows the overall average cost of steel production according to the route used.

Figure 15. Average Cost of Steel Production by Route



Source: Elaboration based on Nicholas & Basirat (2021)

The demand for scrap is higher when its price relative to the cost of iron ore is low. Market studies of scrap in the United States indicate that its supply level changes significantly when prices exceed the historically high value of USD 250-300 per ton (IEA, 2020a). This incentive has a variable impact in different regions depending on overall availability and labor costs.

The steel industry can realize the full potential of circular economy approaches by implementing policies and incentives focused on increasing the availability of quality scrap and, subsequently, the countries' steel recycling rates. Specifically, national or sectoral regional authorities should consider introducing steel recycling targets and implementing higher recycled steel content requirements for steel-intensive products, policies to reduce steel scrap exports and retain it for domestic use, and incentives to encourage the use of recycled steel.

5.2.1.6 Substitute fossil coal with biomass (BF-BOF)

Biomass can be an option to reduce emissions from blast furnaces and reduction processes. Depending on the type of biomass used, this option is currently assessed at technological readiness levels (TRL) ranging from 2 to 7 (Draxler et al., 2021). Wood-associated biomass is the most studied and used feedstock in the steel industry today, and various thermochemical conversion processes can be employed to improve its properties. The IEA indicates that bioenergy is considered carbon neutral because the carbon released during combustion has previously been in the atmosphere and will be recaptured when the plants grow back, provided it is produced sustainably.[210]

Biochar can replace the pulverized coal injected directly into blast furnaces. For example, the Torero Partnership project is testing the use of biochar to partially replace coal in ArcelorMittal's furnace in Ghent, Belgium, with an estimated CO_2 emissions reduction of between 5% and 28% according to the World Steel Association (2021). This option is not feasible in larger blast furnaces and is limited by biochar availability, but it could play a niche role in reducing CO2 emissions from smaller existing furnaces.

Biomass can also partially replace coke in the steel-making process. Using biomass to replace 2 to 10% of the required coke and higher percentages in sinter, blast furnace charge, and blast furnace injection can result in up to 40% savings in blast furnace GHG emissions (Mousa *et al.*, 2016).

As a short-term decarbonization initiative within integrated coke plants, Gerdau Ouro Branco in Brazil developed BIOCOKE, which inserts up to 2% biomass to replace coal in the coke plant. This initiative has reduced emissions by 32 kgCO2e/t of steel and reduced costs by roughly USD 3/t of coke.[211]

Other forms of biomass, such as wheat, corn, and sunflower field residues, can be converted to charcoal at a lower cost. Production costs can be reduced by upgrading and optimizing existing processes, maximizing the biomass value chain and considering logistics, integrating with the steel plant, effectively utilizing by-products, and implementing industrial symbiosis (Mousa *et al.*, 2016). However, technical limitations may prevent charcoal from reaching an industrial scale to decarbonize the industry effectively, as it will likely only be viable for smaller furnaces.

A well-designed and efficiently operated supply chain, equipped with appropriate technological solutions at each stage and supported by effective coordination across all aspects, comparable to the supply chains supplying raw materials to the steel industry, is essential for the widespread adoption of biomass as an energy source in the LAC steel sector. Usable biomass sources must be qualified and certified as sustainable in environmental, economic, social, and governance terms by commonly accepted certification systems such as Forest Stewardship Council (FSC) for planted forests and their products or Global Gap for agricultural residues. Finally, the best technologies and practices established in international technical standards must be used in both biomass and raw material supply and biomass-derived product extraction mechanisms for producing adequate quality products.

5.2.2 Main Innovative Trends

Compared with traditional BF-BOF and DRI-EAF steelmaking routes, three innovative routes have been identified that may become technically and commercially available in the near future. The first route adds CCUS technology to a natural gas-based DRI reactor to capture and store CO_2 generated during iron reduction. This technology is in commercial operation in the United Arab Emirates (UAE), the United States, Belgum, and Mexico. The Al Reyadah CCUS Project[212] in the UAE has an estimated emissions reduction of 80% (Correa et al., 2021). In Mexico, two plants operated by Ternium captured a total of 270,000 tons of CO_2 in 2024 and sold it for use in the beverage industry.

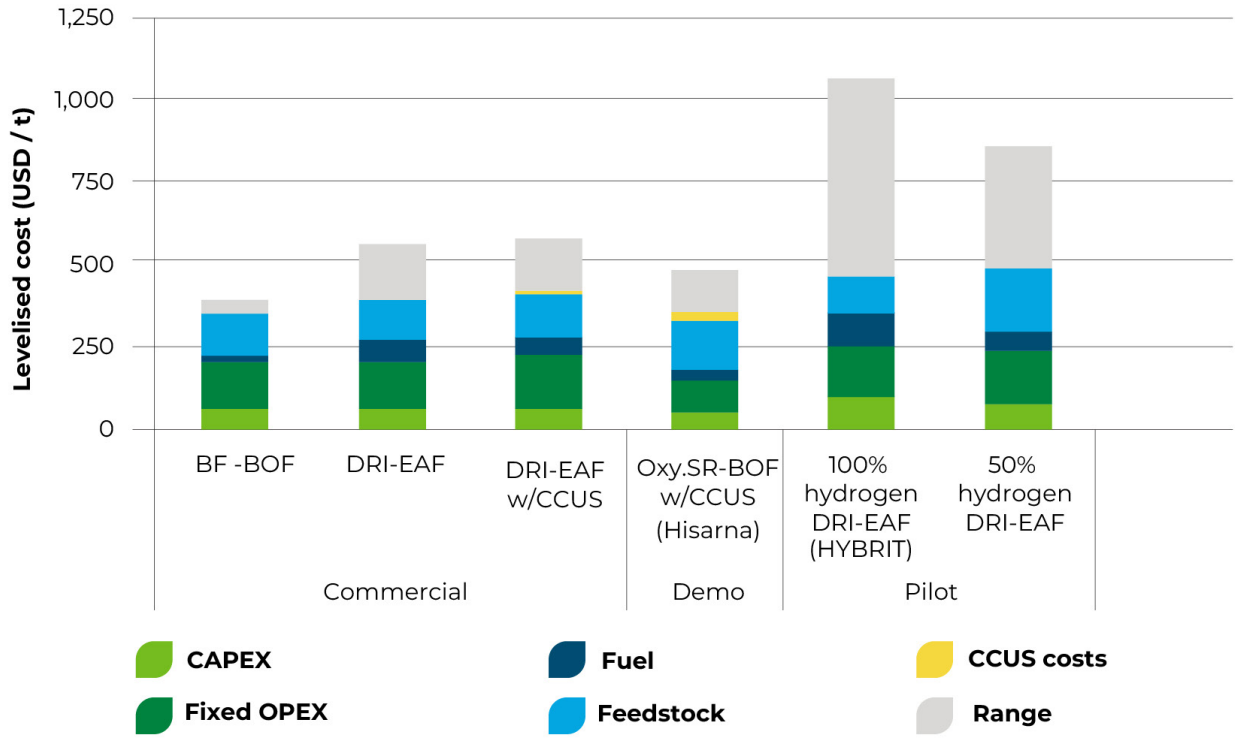
[210] https://www.ieabioenergy.com/bioenergy-a-sustainable-solution/
[211] https://worldsteel.org/es/case-studies/sustainability/gerdau-biocoke/
[212] https://www.cslforum.org/cslf/sites/default/files/documents/AbuDhabi2017/AbuDhabi17-TW-Sakaria-Session2.pdf

The second route is HIsarna technology (applicable to the BF-BOF route), which combines direct reduction (without sintering) and the smelting process to directly produce molten pig iron using coal (without coke), thereby improving energy efficiency. According to experimental data from a test facility built at Tata Steel in the Netherlands in 2010, applying HIsarna technology can reduce GHG emissions by roughly 20% alone and by over 80% if combined with CCUS (TATA Steel, 2020).

The third identified route is H2/DRI-EAF, which uses hydrogen as the sole reducing gas to produce sponge iron. Emissions can be mitigated if this route is coupled with using carbon-free electricity to produce hydrogen and operate the EAF. This route is currently at a demonstration scale in Sweden (HYBRIT Project[213]) and at a pilot scale in Germany (ThyssenKrupp[214], ArcelorMittal[215], Salzgitter[216]) and Austria (Voestalpine[217]). In some countries, the use of natural gas in hydrogen-ready plants while renewable H2 is widely available can be an alternative.

The DRI-EAF route combined with CCUS or hydrogen could increase levelized production costs compared to the traditional DRI-EAF route. This is mainly due to switching to more expensive fuels and the high CAPEX required for the transition. However, these additional costs could be offset in the long term as CCUS and hydrogen technologies develop and mature and the costs associated with CO_2 emissions increase. The figure below compares the levelized costs of these three options with the two traditional steelmaking routes (Nurdiawati & Urban, 2021).

Figure 16. Levelized Steel Production Costs by Route



The range refers to the range of total levelized costs across all regions, with the lower end of the range broken down for each technology.

Source: Elaboration based on IEA, 2019.

[213] https://www.hybritdevelopment.se/forskningsprojekt-1/
[214] https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/green-hydrogen-for-green-steel-made-in-duisburg--steag-and-thyssenkrupp-are-planning-joint-hydrogen-project-91317
[215] https://corporate.arcelormittal.com/media/case-studies/hydrogen-based-steelmaking-to-begin-in-hamburg
[216] https://salcos.salzgitter-ag.com/en/
[217] https://www.voestalpine.com/greentecsteel/en/breakthrough-technologies/

Electricity is the main cost component for producing hydrogen using electrolyzers. The H2/DRI-EAF route will need a low-carbon electricity price of USD 5 per 35/MWh (which translates to hydrogen costs between USD 0.7 and 2.0 per kgH2, assuming high-efficiency electrolyzers and low capital costs) to compete with the CCUS-equipped natural gas-based route over the long term (IEA, 2019).

Steel industry decarbonization must consider multiple factors, including available resources, production routes, geographic locations, energy costs, and geopolitical conditions. The most appropriate decarbonization strategy will depend on each steel industry's specific circumstances. Supportive government policies, technical analyses based on good-quality information, and resources to promote research and development are essential.

5.2.3 Potential Business Synergies

Synergies between Latin American companies may help accelerate the steel industry's decarbonization. For example, companies that produce biomass as a waste product can collaborate on projects that substitute biomass for coal in steel production processes. Other biofuels, such as organic waste biomethane, can also replace natural gas consumption. Partner companies can co-invest in infrastructure to create the economies of scale needed to produce biomethane at competitive prices.

Using methanol as a hydrogen carrier is another area where companies can collaborate. Methanol produced from renewable sources and other integrated solutions, such as carbon looping, can be used as a way to store and transport hydrogen. Joint investment in methanol production and use can increase methanol supply at prices competitive with fossil fuel prices.

Steel producers can also establish strategic alliances with electric utilities or independent power producers to facilitate and reduce the cost of using electricity from renewable sources. One way to achieve this is through long-term supply contracts: the power developer is assured of stable demand and price for its product, and the steel company is assured of a continuous clean energy supply at stable prices.

Another approach is joint development of renewable projects. Steel producers and utilities can combine their resources to develop renewable energy generation projects specifically designed to supply steel plants. This includes installing wind or solar farms near production plants to reduce transmission and distribution losses and associated costs. Through collaboration, these companies can leverage synergies, share risks, and reduce the costs associated with transitioning to greater renewable energy use in steel production processes.

Steel producers can achieve significant synergies by promoting circular economy practices. Companies can collaborate with collection and recycling service providers to establish more efficient methods and expand scrap collection coverage. This includes implementing incentive programs to motivate suppliers and end consumers to participate in the recycling process.

Companies can collaborate on improving scrap classification and separation processes to obtain a higher-quality product suitable for use in steel production. This implies investing in advanced technologies and equipment that separate different types of scrap more accurately and eliminate unwanted contaminants.

Another way to increase the reuse of steel scrap is by encouraging circular economy practices in collaboration with other sectors. Steel producers can establish partnerships with industries such as construction, automotive, and electronics to facilitate collecting and recycling of end-of-life metal products. This involves developing scrap exchange systems and promoting the use of recycled steel products.

To this end, ResponsibleSteel certification, together with implementation of the ISO 59000 circularity standards, would play a key role in strengthening synergies between the steel industry and other recycling and sustainability sectors. By adhering to ResponsibleSteel standards, companies in the steel industry would demonstrate their commitment to responsible and sustainable practices, encouraging collaboration and trust with other industries interested in sustainability. ISO 59000 standards provide a solid framework for efficient resource management, encouraging materials reuse and reducing waste. This shared focus on sustainability and the circular economy would optimize the steel value chain while promoting innovation and the development of joint solutions that drive the transition towards a more sustainable industrial model.

6. ALIGNMENT OF INVESTMENTS WITH THE PARIS AGREEMENT

Aligning steel industry investments with the Paris Agreement (PA) mitigation goals requires operations to be consistent with each country's low-GHG-emission development strategy. One approach to evaluating investment alignment identifies whether investments are "universally aligned" or "universally non-aligned" with the PA's mitigation goals. For those not falling into either category, a detailed analysis is required to evaluate the project against specific criteria.

This ensures that investments:

i. Do not contradict each country's Nationally Determined Contributions (NDCs), GHG emission reduction plans, or sectoral pathways.

ii. Do not "lock in" GHG emissions levels that are likely incompatible with 2050 net-zero emissions targets by ensuring that all technical and financially feasible alternatives with lower GHGs are evaluated.

iii. Where appropriate, include strategies to manage climate transition risks that may jeopardize the investment's economic viability and/or result in locked-in or stranded assets.

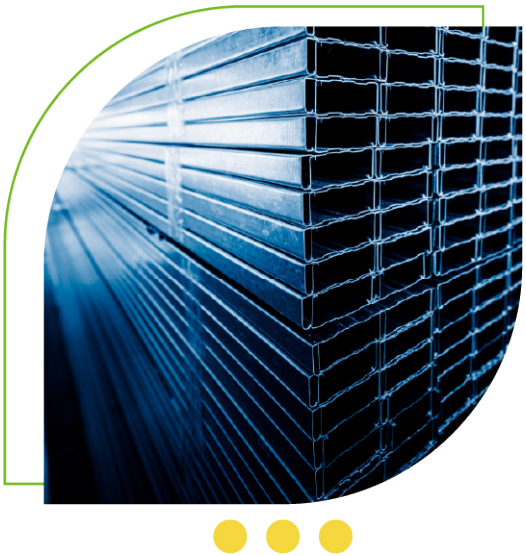
The table below assesses the technology options described above to determine their alignment with the PA's mitigation goals.

Table 7. Alignment of Mitigation and Innovation Trends with PA Criteria

Mitigation Trends	Alignment with PA criteria
Replace natural gas with biomethane	Universally aligned as it replaces energy and/or reduces elements from fossil fuels. If the source biomass were to decompose anaerobically without collecting the methane produced, there is an additional positive effect since methane has approximately 28 times more GHG power than CO2 from biomethane combustion.
Use methanol as a hydrogen carrier	Universally aligned as it replaces energy and/or reduces elements from fossil fuels, where possible: - Green Methanol: produced from sustainable biomass (biomethanol). - E-Methanol: synthesized with carbon dioxide and hydrogen produced from renewable electricity.
Renewable energy electrification	Universally aligned as it replaces: - Electric power from fossil fuels used for steel production: o In direct use in EAF. o In electric energy for other operations in other routes. - Fossil coal with renewable hydrogen as a reducing element.
Use scrap with renewable resources	Universally aligned when used in the EAF route as it avoids the direct energy required for steel production using the alternative BF- BOF route and its associated GHG emissions. Emissions reduction is even more significant if the electrical energy comes from renewable sources.
DRI H2 with renewable hydrogen and EAF with renewable electrical energy	Universally aligned as they replace energy and/or reduce elements from fossil fuels. If biomass is added, it must come from adequately certified sustainable sources.
HIsarna with CCUS	Not universally aligned as the process itself has CO2 emissions from fossil carbon, but when combined with CCUS, if this alternative is viable, emissions are reduced by 90% and it can be considered aligned.
Natural gas DRI with CCUS	DRI NG with CCUS is not universally aligned because the process itself has CO2 emissions from natural gas and emissions from electricity generation. However, combined with CCUS in the DRI and electricity from renewable sources, emissions are reduced by 85% and it can be considered aligned.

Source: Elaboration based on IDB Methodology - Alignment of Investments with the Paris Agreement.

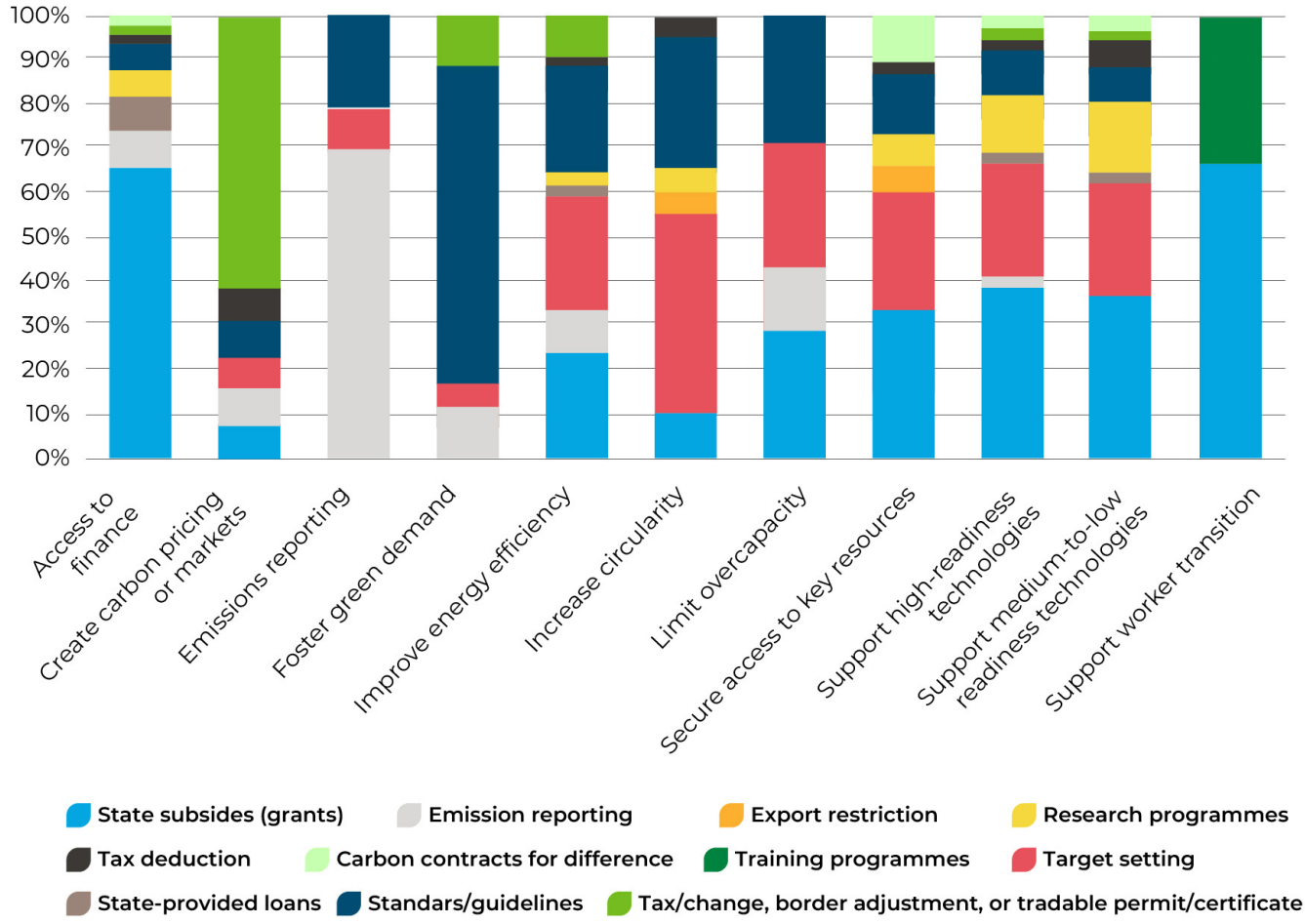
7. POLICY ROADMAP FOR INDIVIDUAL COUNTRIES



The steel industry provides thousands of jobs and is vital to economic development, but its competitiveness will depend on its ability to adapt to new technologies and carbon reduction targets and measures such as the Carbon Border Adjustment Mechanism (CBAM) in Europe. While the industry in LAC would like to shift toward low carbon technologies, it requires government support on both supply and demand sides. Significant investment and policy support is needed to enable a technological transition to low carbon steel. Furthermore, the development of carbon border adjustment mechanisms adapted to local contexts and market conditions will be crucial to safeguarding competitiveness and advancing the decarbonization of the regional steel sector.

Producing countries across the world have distinct policy objectives and are implementing a range of policies for steel decarbonization, as shown in the next figure. Currently most policies are non-binding and directed at the supply side to reduce emissions in steel production (Climate Club, 2024). To advance to net-zero, binding and demand-side policies must also be implemented.

Figure 17. Share of Instruments Used by Objective



Source: Elaboration based on Climate Club (2024)

Although many industrial decarbonization policies can be horizontal as they apply to multiple sectors, this section focuses on steel-specific policies. It presents a roadmap, summarized in the table below, suggesting specific actions that governments can pursue. The policy recommendations are based on the technological pathways outlined above for steel decarbonization, which include expanding recycling, shifting toward EAF, replacing natural gas with hydrogen or biomethane, increasing energy efficiency, and installing CCUS technologies. These broad recommendations are intended to provide each country a menu of options from which to choose to tailor their strategy using the policies and incentives that best complement their unique circumstances and goals.

Table 8. Summary of the Steel Decarbonization Roadmap for LAC Countries

Period	Goals
2025–2030	Design national steel decarbonization strategies to 2050; adapt regulations; expand scrap programs; identify champion companies; design and launch early demostration projects supported by the Climate Investment Funds (CIF) in Brazil & Mexico or with concessional loans in other countries; seek regional cooperation and coordination with EU on CBAM, and to develop regional cross border adjustment mechanisms to protect regional industries.
2031–2037	Introduce embodied-carbon standards in procurement; require emissions disclosure; retrofit plants for efficiency and H_2-readiness; expand advanced scrap recycling; scale up proven measures; launch CCUS demonstration projects; broaden concessional lending, green bonds and CfDs; co-finance renewables, grids, hydrogen hubs and CO_2 storage; strengthen regional cooperation.
2038–2045	Mandate emissions-intensity performance standards; set minimum recycled-content rules; retire inefficient BFs; deploy large-scale H_2-based; scale CCUS; support workers and communities with transition packages; expand industrial symbiosis and next-gen demonstration projects; shift to blended/private finance; deepen regional cooperation on H_2-and CO_2 logistics.
2046–2050	Tighten performance standards to near-zero; mandate high recycled-content thresholds and full recovery of vehicles and construction scrap; complete transition to H_2-DRI/EAF and CCUS routes; focus finance on O&M optimization, reinvestment and competitive renewables/H_2 pricing; position LAC as global hub for sustainable steel.

Source: Produced in-house

7.1 Vision and Baseline

Steelmaking in Latin America varies in plant age, production technology, energy supply, and market orientation. For governments seeking to draft effective steel decarbonization roadmaps, the first step is to establish their national position within the global and regional steel value chain—whether as producers, importers, exporters, or end-use consumers—and to articulate the role they aspire to play in a low-carbon steel value chain.

For producing countries, this requires a detailed mapping of existing production pathways, such as BF or DRI for ironmaking, or BOF or EAF for steelmaking. This includes assessing the carbon footprint and energy sources of the steel they source, the use of transitional fuels like natural gas, the resilience of their supply chains, and the implications of evolving trade policies. Producing countries that are also exporters must analyze the requirements of importing countries and how they may evolve in the future. Nonproducing countries, meanwhile, should focus on mapping their role as importers, consumers, and traders within the steel value chain. This baseline analysis will enable governments to design tailored, pragmatic roadmaps that align industrial, energy, and trade policies to safeguard competitiveness and long-term industrial resilience.

7.2 2025–2030: Foundations and Early Demonstration Projects

7.2.1 Policies and Regulations

During this first phase, governments should design national steel decarbonization strategies to 2050 that reflect their objectives, role in the low-carbon steel value chain, energy systems, industrial and labor structures, natural resource availability (renewables, natural gas, geological storage), and financial capacity. These strategies should include modeled scenarios of technology adoption, development of an emission abatement curve to prioritize actions by cost-effectiveness, and an assessment of funding gaps. Germany, Japan, Korea, and United Kingdom already have a steel decarbonization roadmap in place (Climate Club, 2024), which can serve as guidance.

National scrap recycling programs, targets, and guidelines should be introduced to stimulate demand and improve material circularity. Countries should also conduct a comprehensive review of existing frameworks to ensure they enable, rather than hinder, the deployment of early decarbonization pathways. This includes updating safety and infrastructure regulations to permit the transport, storage, and use of alternative gases such as hydrogen and biomethane, as well as establishing rules for CCUS. Governments should also establish and actively promote industrial regulatory sandboxes for innovative technologies and business models in controlled conditions.

7.2.2 Projects, Technologies and Infrastructure

Demonstration projects should also be designed and launched in this period. Each country should also identify champion companies, meaning large domestic or multinational steel producers with both the willingness and resources to advance decarbonization early and implement demonstration projects. Specific technological pathways that can be adapted as appropriate to each country are found in section 5.1.

Governments should promote early adoption of no-regrets measures such as energy efficiency, optimizing of current production processes, renewable energy sourcing for EAFs, and synergies between industries. Technologies that require minimal retrofitting, such as biomethane substitution in blast furnaces or DRI processes, should also be encouraged.

Pre-development studies for CO_2 storage capacity, hydrogen hubs, and grid expansion should be initiated to prepare the ground for scaling in later phases.

7.2.3 Funding and Incentives

On the financing side, Brazil and Mexico are positioned to lead with the support of the CIF Industry Decarbonization Program. Other producing countries can access concessional loans, blended finance structures, and guarantees to advance their own demonstration projects by providing financial support for low-carbon technologies. MDBs can design country-specific instruments to de-risk investment, such as guarantees and results-based grants tied to verified emission reductions, and mobilize capital from climate funds. Countries should also fund research and development programs for low-carbon technologies, particularly those at lower TRLs, such as exploring the use of methanol as a substitute for coal in steelmaking reduction processes.

Circular economy and steel scrap recycling programs should be funded in both producing and non-producing countries to strengthen supply chains and reduce reliance on imported scrap. Some of the incentives that are being implemented by governments in this area include tax deductions, state subsidies and grants, research programs, and export restrictions (Climate Club, 2024). National scrap collection and recycling programs should align with ISO 59000 circularity standards and encourage

industrial symbiosis initiatives that valorize by-products such as slags, gases, and biomass. Creating market incentives to keep steel scrap within the region to reduce exports and to use recycled content in construction and infrastructure projects will further stimulate demand for circular materials.

7.2.4 Capacity Building and Regional Cooperation

MDBs can facilitate knowledge exchange and support the development of regional standards and guidelines, as well as early coordination with the EU on CBAM, and to develop regional cross border adjustment mechanisms to protect regional industries. Countries should harmonize definitions of low-carbon steel, recycling, and waste management, create common measurement tools, and enable cross-border trade in scrap and secondary materials. Capacity building should also include training in the different decarbonization pathways, steel-specific policymaking, circular economy, certification processes, and implementation of monitoring, reporting, and verification processes.

7.3 2031–2037: Scaling and Infrastructure

7.3.1 Policies and Regulations

In this phase, governments should begin introducing embodied-carbon standards in public procurement to create stable demand for low-carbon steel. Regulations should require emissions-intensity disclosure from domestic producers and importers while establishing permitting frameworks for CO_2 transport infrastructure. Electricity planning rules should also prioritize industrial decarbonization loads if they do not compete with residential loads. Carbon pricing for steel production can also begin to be implemented.

7.3.2 Projects, Technologies and Infrastructure

During this period, the focus will shift from pioneer projects to scaling proven solutions. Producing countries should prioritize energy efficiency retrofits in existing plants, introduction of co-generation systems that reuse furnace heat energy for electricity generation, and expansion of advanced scrap recycling systems. Countries with natural gas-based DRI plants should begin to retrofit them to be hydrogen-ready, and large-scale hydrogen DRI–EAF demonstration projects should be launched in locations with abundant renewable resources. CCUS demonstration projects should also be deployed in regions with suitable geology and shared CO_2 hubs in early stages of development.

7.3.3 Funding and Incentives

Governments and MDBs should broaden concessional lending, expand green bond frameworks, and co-finance renewable energy, transmission, and hydrogen hubs in strategic industrial regions. Instruments such as contracts for difference (CfDs) can de-risk high-cost projects like hydrogen DRI and CCUS, provided they are fiscally sustainable and time-bound. Public–private partnerships for industrial infrastructure such as hydrogen pipelines and CO_2 networks should also be promoted. Innovation through research and development programs and funding for low-carbon technologies should continue.

7.3.4 Capacity Building and Regional Cooperation

Countries should harmonize certification schemes, monitoring, reporting and verification standards, and recycling rules to enable regional integration. Cooperation should focus on creating regional scrap markets, coordinating logistics for hydrogen and CO_2, and sharing lessons from early demonstration projects.

7.4 2038–2045: Transformation and Deployment

7.4.1 Policies and Regulations

By the late 2030s, governments should mandate emissions-intensity performance standards for steel, introduce minimum recycled-content requirements in key end uses, and align trade policies with global low-carbon standards. Non-producing countries should strengthen their role as enablers by scaling procurement of low-carbon steel for infrastructure and facilitating regional logistics for hydrogen and scrap.

7.4.2 Projects, Technologies and Infrastructure

By this phase, steel-producing countries must move to the deployment of transformative technologies. Steel-producing countries should begin retiring inefficient blast furnaces and deploying large-scale hydrogen DRI–EAF plants. CCUS should be scaled in facilities where renewable hydrogen is not yet viable, and industrial symbiosis projects should be expanded regionally. Governments should continue to support next-generation demonstration projects, such as HIsarna technology, to keep future technology options open. Transition packages should accompany the retirement of stranded assets to protect workers and communities.

7.4.3 Funding and Incentives

Funding will increasingly come from private capital as technologies mature, with concessional support tapering off. Public incentives should focus on transition finance to convert existing assets and on just-transition funds to support affected workers and communities. International partnerships and MDBs funding will remain essential for financing large-scale infrastructure projects.

7.4.4 Capacity Building and Regional Cooperation

Reskilling programs, community engagement initiatives, and harmonized regional safety protocols for hydrogen and CO_2 should be scaled up. Working teams to revise regulations and standards should continue.

7.5 2046–2050: Consolidation to Net-Zero

7.5.1 Policies and Regulations

In the final phase, performance standards should tighten to near-zero emissions. Governments should mandate high recycled-content thresholds and enforce full recovery of end-of-life vehicles and construction materials. Trade and customs policies should be fully aligned with global carbon requirements.

7.5.2 Projects, Technologies, and Infrastructure

By this stage, Latin America's steel industry should predominantly be hydrogen-based DRI–EAF plants and CCUS-equipped facilities. Residual emissions should be offset through carbon removals, and supply chains should be optimized through regional integration of scrap, DRI, and HBI flows.

7.5.3 Funding and Incentives

Financing will focus on maintaining competitiveness through O&M optimization, reinvestment cycles, and continued just-transition support for affected regions. Financing in research and development and training programs should also continue. Ensuring competitive renewable electricity and hydrogen pricing through regulatory reforms will be critical for long-term viability.

7.5.4 Capacity Building and Regional Cooperation

Regional governance of standards and certification systems should continue, alongside benchmarking and data sharing to ensure continuous improvement. Latin America should also position itself as a global knowledge hub for sustainable steel production, exporting expertise to other regions.

By 2050, Latin America's major steelmaking countries should collectively secure a position as global leaders in low-carbon steel, while maintaining economic competitiveness. Non-producing countries should be aligned with regional net-zero steel value chains, ensuring that their procurement, recycling, and trade policies reinforce the competitiveness of the regional steel sector.

8. NEXT STEPS AS A REGION

Advancing steel industry decarbonization in LAC requires expanded access to climate finance funds and further studies to inform investment decision-making.

New analyses for the region in four key areas would be particularly beneficial in supporting LAC steel decarbonization efforts:

1. **Decarbonization scenarios for the steel industry in LAC.** This consists of modeling potential technology adoption strategies to identify their impact on reducing regional direct and indirect steel industry emissions. First, the LAC steel industry's current scope 1 and scope 2 mitigation trajectory must be defined within the Paris Accord framework. Next, the identified decarbonization alternative's contributions must be evaluated against the previous baseline BAU scenario. This analysis will identify the potential impact of the selected options on the industry's emissions reduction by mid-century.
2. **Economic valuation of the measures to construct an emission abatement curve.** This valuation seeks to estimate the economic benefits of implementing the identified decarbonization alternatives. The analysis involves compiling and evaluating the costs associated with adopting each technology in LAC, including the initial investment and operating costs. It then estimates the benefits of fuel cost savings and carbon offsets. The economic valuation will help identify the most cost-efficient alternatives for decarbonizing the LAC steel industry and identify options to improve the economic performance of technically feasible alternatives, including through synergies with other sectors. The economic valuation will also identify the impact of the evaluated decarbonization alternatives on steel costs. The assessment will be the primary input to create an emissions abatement curve showing the cost per measure and its impact on emissions reduction in 2050.
3. **Calculation of the funding gap.** Estimating the financing needed to implement the decarbonization alternatives is key to understanding financial needs, strategically planning, raising funds, and making informed decisions. This analysis involves assessing the aggregate financing needed to decarbonize the entire steel industry in the region by 2050 and assessing financing that is currently available for closing the gap. Here it is essential to explain the possible causes of these gaps and define pathways for closing them.

At the regional level, these studies can inform the more detailed country-level analysis described in the policy section above. Establishing a regional baseline and common set of data and analysis will help ensure individual countries' decarbonization strategies grounded in a coherent set of regional assumptions and promote the sharing of information and best practices across the region.

CONCLUSION

The heavy industries described in this report—aluminum, cement, pulp and paper, and steel—will be difficult, but not impossible, to decarbonize.

Many of the technologies described in the preceding chapters are already commercially available and widely used. Examples include electricity and heat from renewable sources, energy efficiency measures, and circular economy practices that reuse waste from one industry to produce materials in another. These practices can have lower operating costs than traditional energy sources or production methods. To enable wider use of these options, policy makers and finance providers should reduce barriers, such as upfront investment costs, incomplete regulations, or limited supply chains.

Other technologies have been shown promising through their use in other sectors or regions. These include electrifying heat production and using ammonia or methanol as a hydrogen carrier. Targeted studies and financial support can help adapt these technology options to the LAC market or relevant industry. Sharing best practices and cross-industry or cross-geographical learnings can also be encouraged through regional and sectoral gatherings, associations, and data portals.

For some options, the underlying technologies are well understood but require extensive supporting infrastructure or are more expensive than current technologies. For example, renewable hydrogen is currently far more expensive than gray hydrogen and increasing co-processing of municipal solid waste or biomass residues to a substantial share of heavy industry's energy needs would require new gathering and processing logistics in many markets. Aligning regional policies to encourage cross-border initiatives can help new markets reach scale and reduce costs more quickly. Procurement targets, recycling mandates, minimum content requirements, and contracts-for-differences can also help create markets and reduce costs as new supply chains are being established.

Other technologies, however, remain unproven outside of laboratories and demonstration projects. Examples include inert anodes for aluminum electrolysis and applying CCUS technologies to new industries. Closing the final gaps to reach net-zero by 2050 may require technological breakthroughs to deploy these options on an industrial scale or at affordable costs. LAC governments should support the research and development, and the regulatory sandboxes to test enabling policies, that are needed to unlock tomorrow's breakthroughs today.

Bridging the gaps to achieving the heavy industry decarbonization described above and throughout this report requires close coordination among industry champions, policy makers, regulators, and financiers. Creating country- and industry-level baselines and roadmaps are important first steps to establishing a common understanding, vision, and approach to decarbonization among all stakeholders.

LAC countries and industries are well positioned to take the lead in deploying heavy industry decarbonization technologies and adapting global best practices to the region's unique circumstances and challenges. Their ability to set a clear pathway to net-zero emissions and adjust to the challenges they will face along the way will play an important role in their future competitiveness in global markets, as well as their ability to meet economic and development needs.

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Focus on Aluminum, Cement, Pulp & Paper, and Steel