A ROADMAP FRAMEWORK FOR INDUSTRIAL DECARBONIZATION IN LATIN AMERICA AND THE CARIBBEAN

Ali Hasanbeigi, Global Efficiency Intelligence

Cecilia Springer, Global Efficiency Intelligence

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Prepared for the Inter-American Development Bank by:

Ali Hasanbeigi, Global Efficiency Intelligence

Cecilia Springer, Global Efficiency Intelligence

Coordination:

Vanderleia Radaelli, Lead Specialist, Competitiveness, Technology, and Innovation (CTI) Division, Inter-American Development Bank (IDB); Coordinator, Climate Change Cluster, CTI Division, IDB

Alison Cathles and Sandra López, Specialists, CTI Division, IDB

Nathália Amarante Pufal, Gina Cárdenas, and Carlai Netto, Consultants, CTI Division, IDB

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Inter-American Development Bank
1300 New York Avenue, N.W.
Washington, D.C. 20577
www.iadb.org

Executive Summary[*]

This report delves into the intricate landscape of industrial energy use and emissions in the Latin America and the Caribbean (LAC) region and explores potential avenues for decarbonization across key industrial subsectors. It presents a robust conceptual framework to empower stakeholders in LAC countries to develop sector-specific roadmaps for commercial and emerging industrial decarbonization technologies. Specifically, it explores three top energy-using industrial subsectors: food and beverages, iron and steel, and cement. It conducts a comprehensive review of existing international decarbonization roadmaps, focusing on the abovementioned subsectors, spotlighting technologies and strategies pertinent to the LAC region. These technologies are categorized under five pillars of industrial decarbonization: energy efficiency; material efficiency; electrification; low-carbon hydrogen (GLCH) derivatives, feedstocks and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS). These technologies are pivotal for emission reduction and also play a crucial role in enhancing climate resilience in various sectors.

The report's conceptual framework (Figure 1) is modular and universally structured so that it can be adapted to a variety of industrial subsectors and countries. It begins with a detailed analysis of the economic and energy profiles of specific industrial subsectors. It then identifies and classifies potential decarbonization technologies and develops various scenarios reflecting the ambitions and realities of each sector. These insights inform the construction of a decarbonization model to forecast energy use and emissions under different scenarios. The result is a cohesive decarbonization roadmap with recommendations for government and industry, considering existing policies and potential opportunities and ensuring a contextual and data-driven approach adapted to the needs of the LAC region.

The frameworks presented in this report are important for addressing the urgent challenges of industrial decarbonization in LAC. By offering tailored decarbonization roadmaps, the report provides decision makers with practical tools to navigate the complexities of transitioning toward sustainable industrial practices. This is crucial given the region's unique socio-economic and environmental characteristics and its levels of technological readiness. The policy gap analysis underscores the necessity for more comprehensive and integrated approaches to industrial decarbonization policies.

A multi-step approach ensures that the roadmap is firmly rooted in context and informed by available data, synthesizing insights into cohesive, actionable strategies for industrial decarbonization. The report provides sample outlines for using the framework to develop decarbonization roadmaps for the three industrial subsectors studied: iron and steel, cement, and food and beverages. The findings contribute to advancing

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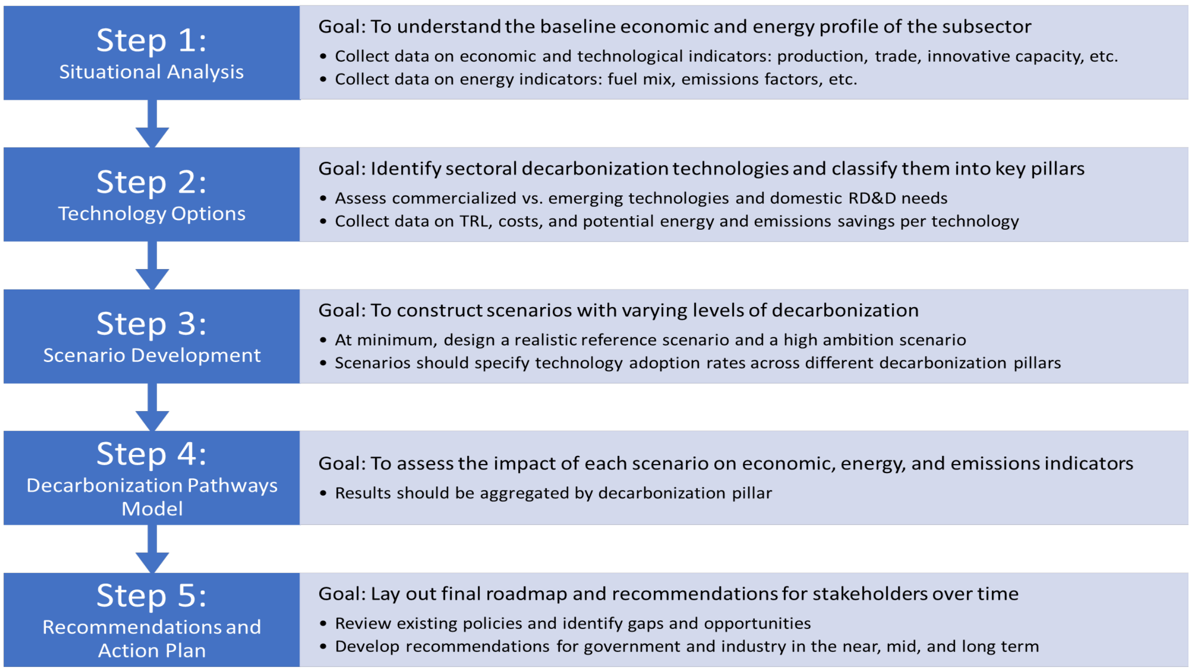
sustainability goals and will play a pivotal role in mitigating climate change impacts, thus ensuring a more resilient and prosperous future for the LAC region.

Figure 1: Schematic of Conceptual Framework for Developing Sector-specific Industrial Decarbonization Roadmaps



Source: Authors' elaboration.

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1. Introduction

Climate change is manifested as a global rise in temperature of 1 degree Celsius since pre-industrial times. This warming is causing more frequent and intense extreme weather events. The Paris Agreement aims to limit this increase to 1.5 degrees by the end of the century. To do so will require a 50 percent reduction in emissions in the next decade and net-zero emissions by 2050. Industrial decarbonization, a critical component of this effort, poses both structural and technical challenges. Industrial production entails a large and diverse number of materials transformations, from the extraction of raw materials to the manufacturing of final products. Industrial decarbonization will require a wide range of technology solutions across increasingly complex supply chains. The emissions reductions needed will require approaches that are transformational rather than incremental, especially considering the anticipated growth in product demand across many countries and regions. Despite these challenges, industrial decarbonization holds the potential to enhance manufacturing productivity and cost competitiveness on a global scale by developing innovative products and meeting growing demand.

Although the LAC region contributes less than 5 percent of global emissions, it is highly vulnerable to climate impacts (EIB, 2023). Decarbonizing the industrial sector in LAC is pivotal for environmental resilience, sustainable development, productivity, and competitiveness. However, the industrial sector is emissions-intensive. Emissions from heavy industry account for 20 percent of the region's global emissions (Gischler et al., 2023), but the sector is hindered by information gaps, policy fragmentation, and limited research and development investments.

Strengthening public sector capacity and coordination is vital for promoting greener technologies, fostering industrial modernization, and ensuring competitiveness. By doing so, governments can effectively implement such policies. Although LAC countries committed to the Paris Agreement and their individual Nationally Determined Contributions (NDCs), translating these commitments into actionable steps for industrial decarbonization along the value chain remains a challenge. Governments are still crafting emissions reduction legislation and industry-specific net-zero policies, while also identifying potential investments in decarbonization-related research, education, and training. On the corporate side, large firms are expected to make organizational changes, invest in technological innovations, and coordinate with smaller firms in the supply chain. However, they often face barriers due to information asymmetry and lack of awareness. Furthermore, lead firms in high-emissions sectors lack the necessary information, tools, and support to choose the most suitable technologies for decarbonization.

This report presents a comprehensive technological evaluation of low-carbon technologies for industrial subsectors in the LAC region. It includes a conceptual framework for creating sector-level roadmaps for both commercial and emerging industrial decarbonization technologies to aid in the enhancement of decarbonization of high-emissions industries while considering climate resilience in selected countries and specific industrial sectors within LAC.

The report begins by analyzing energy use and emissions in a variety of industrial subsectors in LAC countries. It focuses on three industrial subsectors: food and beverages, iron and steel, and cement, which are the three top energy-using subsectors critical for industrial decarbonization in LAC countries with available data.[1] Next, it presents a comprehensive review of existing industrial decarbonization roadmaps for each subsector, identifying key technologies and policies for industrial decarbonization, as well as understanding how each study portrays the role of innovation. Drawing from this review, it presents specific technologies for decarbonization in each subsector, grouped into five pillars of industrial decarbonization for conceptual clarity. A conceptual framework is developed to aid decision makers in each country produce sector-level roadmaps for industrial decarbonization. The report concludes with an analysis of policy gaps in the LAC region and policy recommendations to advance industrial decarbonization while capturing other economic and environmental benefits.

A new roadmap framework is essential to steer industrial decarbonization efforts in the LAC region. This report introduces a conceptual framework grounded in thorough research, incorporating diverse technologies and strategies aligned with the five pillars of industrial decarbonization: energy efficiency; material efficiency; electrification; low-carbon fuels, feedstocks and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS). While structured for wide relevance, the framework has a modular design, enabling it to be customized to meet specific requirements, especially within the three aforementioned subsectors.

A pivotal feature of this framework is its focus on evaluating the science, technology, and innovation landscape in each subsector or country, facilitating an appraisal of its readiness for technological adoption. The need for this framework arises from the imperative to provide a systematic and adaptable approach that addresses the unique challenges and opportunities within the LAC region, ultimately promoting effective and tailored industrial decarbonization strategies.

2. Country and Industry Subsector Selection Process

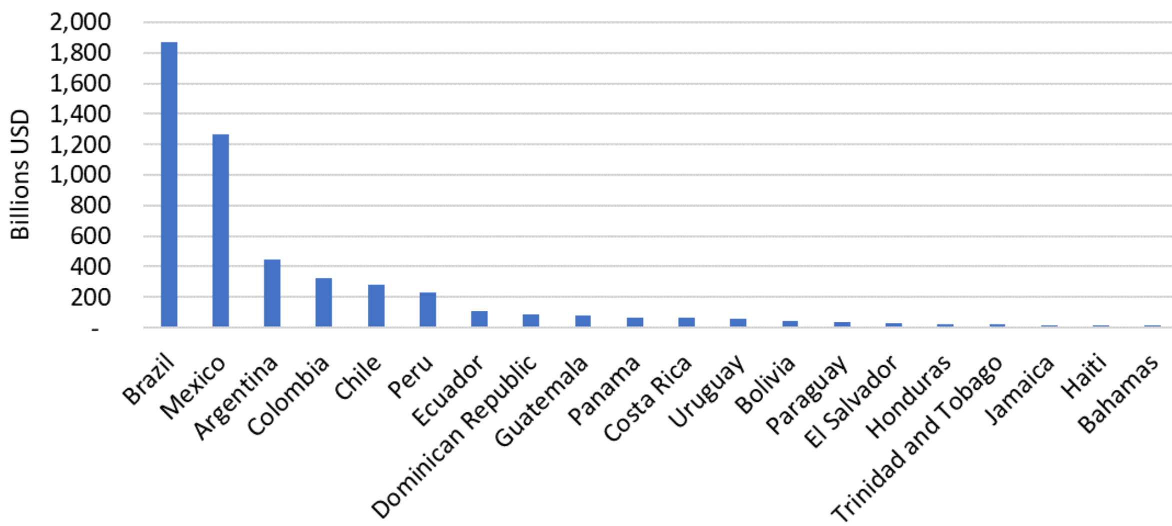
To identify key subsectors for decarbonization in the LAC region, energy use and emissions were analyzed across a range of LAC countries. The selection process for the countries and subsectors involved compiling data from multiple sources. 2019 was chosen as the base year for this analysis to maximize data availability and mitigate fluctuations in energy use and emissions attributable to the COVID-19 pandemic.

[1] It is important to note that data availability and analysis are key for policymaking. Assessing data availability should be a key first step for development an industrial decarbonization roadmap, and data availability varies across LAC countries.

2.1. Country Analysis

The selection processes began by identifying the top 20 IDB member countries in the LAC region. Brazil, Mexico, Argentina, Colombia, and Chile had the top five highest GDPs in 2019, based on World Bank GDP data (Figure 2).

Figure 2: Top 20 Latin American and Caribbean Countries by GDP (in current US$) in 2019



Source: World Bank (2023).

These top 20 countries were analyzed to understand the contribution of their industrial sector to the overall economy based on a number of metrics and indicators of maturity of the national innovation system and other proxies for technological capabilities (Table 1). The share of industry value added ranged from 17 to 38 percent, with Uruguay having the lowest share and Trinidad and Tobago the highest among the selected countries. The top five countries by industry value added as a share of GDP are Trinidad and Tobago, Paraguay, Ecuador, Mexico, and Peru. A number of countries also have a high share of manufactured goods in their total exports, the top five being Mexico, El Salvador, Guatemala, Costa Rica, and the Dominican Republic. In terms of indicator proxies for innovation and technological capability, the economic complexity index developed by the Harvard Growth Lab ranks countries based on the diversity and complexity of their exports, with a higher ranking being more favorable. The index ranks countries from 1 to 133, based on available data, and the highest rank is 1, representing the country with the most complex economy in that year.

Table 1: Indicators on Industry and Technological Capability in Selected LAC Countries

	Industry and Manufacturing Economic Indicators		Innovation and Technological Capability Indicators		
Country (in order of 2019 GDP)	Industry value-added (% of GDP)	Share of manufactured exports in total exports	Economic complexity ranking (lower = better, range 1-133) (2019)	High-technology exports (% of manufactured exports) (2019)	Research and development expenditure (% of GDP) (2019)
Brazil	19%	25%	57	14%	1.2%
Mexico	31%	75%	20	20%	0.3%
Argentina	23%	13%	79	5%	0.5%
Colombia	26%	16%	66	9%	0.3%
Chile	27%	11%	77	8%	0.3%
Peru	30%	8%	100	4%	0.2%
Ecuador	33%	5%	120	6%	NA
Dominican Republic	29%	31%	72	6%	NA
Guatemala	22%	36%	85	5%	0.0%
Panama	28%	NA	45	0%	NA
Costa Rica	19%	31%	44	18%	NA
Uruguay	17%	8%	61	8%	0.5%
Bolivia	25%	4%	106	3%	NA
Paraguay	33%	8%	88	7%	0.1%
El Salvador	25%	56%	60	5%	0.2%
Honduras	27%	18%	92	2%	NA
Trinidad and Tobago	38%	NA	53	0%	0.1%
Jamaica	19%	1%	71	4%	NA
Haiti	23%	NA	NA	NA	NA
Bahamas	13%	10%	NA	NA	NA

Sources: World Bank (2023), Harvard Growth Lab (2023).

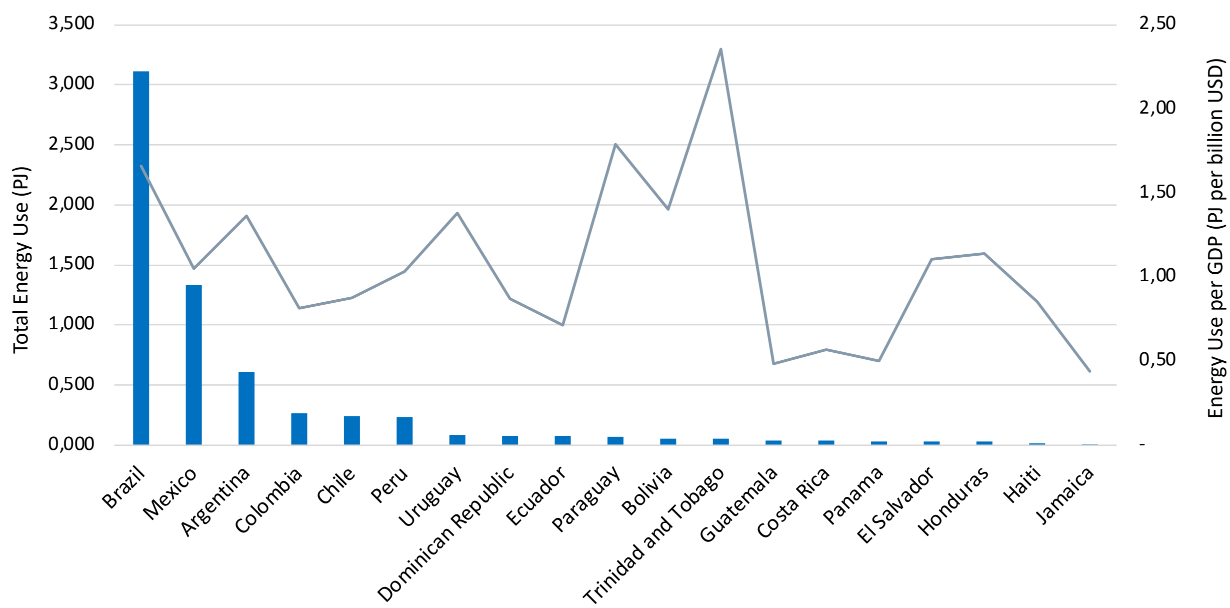
Notes: indicator definitions: Industry (including construction) corresponds to ISIC divisions 05-43 and includes manufacturing (ISIC divisions 10-33). It comprises value added in mining, manufacturing (also reported as a separate subgroup), construction, electricity, water, and gas. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources. Share of manufactured exports in total exports was calculated by assessing the share of merchandise exports in total exports of goods and services, multiplied by the share of manufactured exports in merchandise exports. Economy complexity is discussed above. High technology exports are products with high R&D intensity, such as in aerospace, computers, pharmaceuticals, scientific instruments, and electrical machinery. R&D expenditure is gross domestic expenditures on research and development (R&D), expressed as a percentage of GDP. They include both capital and current expenditures in the four main sectors: Business enterprise, Government, Higher education and Private non-profit. R&D covers basic research, applied research, and experimental development.

Among the 20 countries selected, Mexico, Costa Rica, Panama, Trinidad and Tobago, and Brazil ranked highest in economic complexity. Mexico, Costa Rica, and Brazil had the highest share of high-tech exports (e.g., products with high R&D intensity, such as aerospace products, computers, scientific instruments, and electrical machinery) in all manufacturing exports, while all other countries had less than a 10 percent share for this metric. Brazil spent the largest share of its GDP on research and development, at 1.2 percent, quadruple the share of the next-highest-spending country (Mexico – 0.3%). The indicators from Table 1 suggest different stages of economic development, economic complexity, relative importance of industrial production in the economy, and national innovation efforts, which are important factors for the eventual decarbonization of industry and its potential implications for those economies. The main driver, however, of the eventual country-sector selection was based on emissions data and the availability of emissions data at the sub-sectoral level.

2.2. Subsector Energy and Emissions Analysis

To identify the subsectors to be studied, data from the International Energy Agency were used to calculate total energy use by industrial subsector for each of the 20 countries.[2] This involved extracting raw data on fuel use and electricity use by industrial subsector. Next, total energy use in petajoules (PJ) was calculated based on net calorific value for all fuel types. Notably, the top five countries by GDP also emerged as the top five industrial energy users (Figure 3).

Figure 3: Ranking of Selected Latin American and Caribbean Countries by Industrial Energy Use in 2019

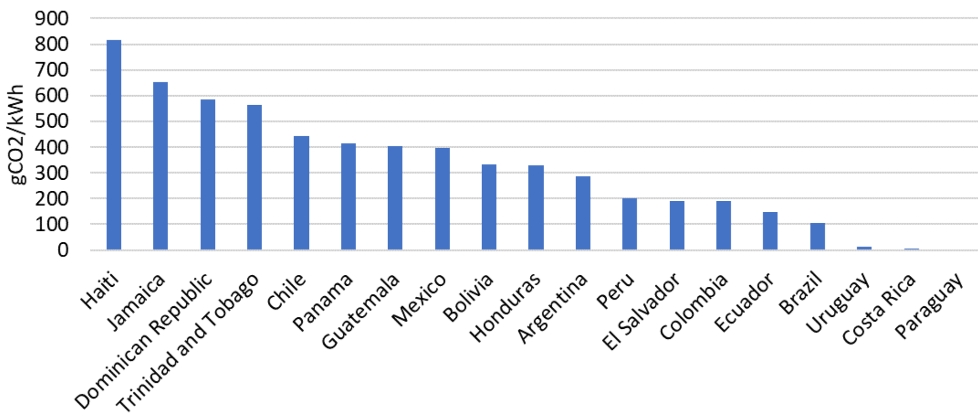


Source: Authors' analysis based on IEA (2022).

[2] Data on the Bahamas were not available.

Using these energy data, total CO_2 emissions were estimated for each subsector based on emissions factor data, including country-specific grid emissions factors. Some LAC countries, especially Caribbean countries, rely heavily on fossil-based electricity, while others, such as Uruguay, Costa Rica, and Paraguay, almost exclusively use low-carbon power sources, especially hydropower (Figure 4).

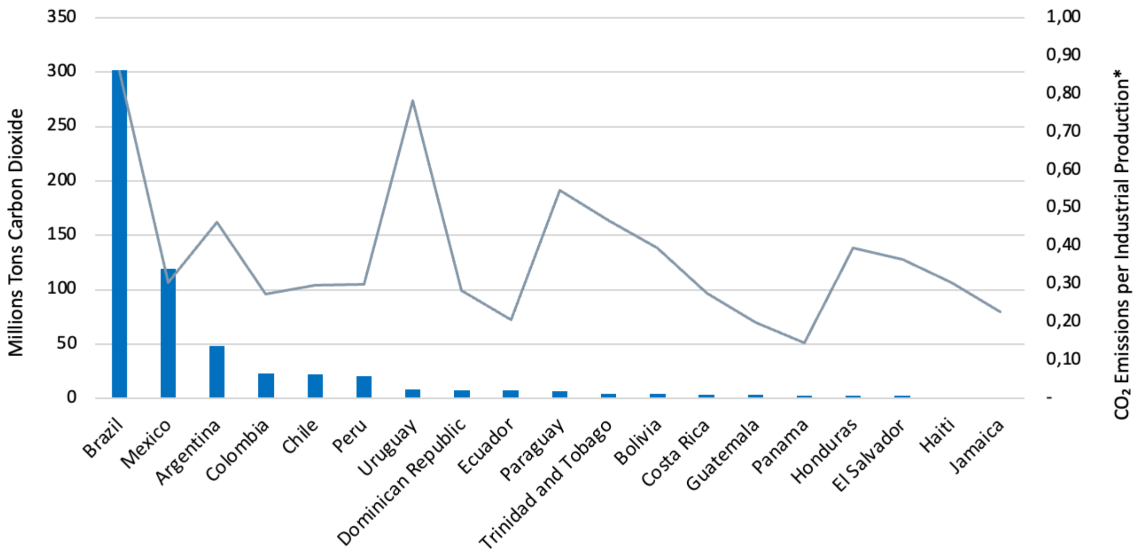
Figure 4: Comparison of Electricity Grid Emissions Factors in Selected Latin American and Caribbean Countries in 2019



Source: IEA (2022).

The top five countries by GDP and industrial energy use—Brazil, Mexico, Argentina, Colombia, and Chile– likewise ranked as the top five industry sector emitters (Figure 5). Despite low grid emissions factors in some countries, the high level of industrial production and non-electricity fuel use played a larger role in determining the countries' emissions rankings.

Figure 5: Comparison of the Industrial Sector's Annual CO_2 Emissions in Selected LAC Countries in 2019



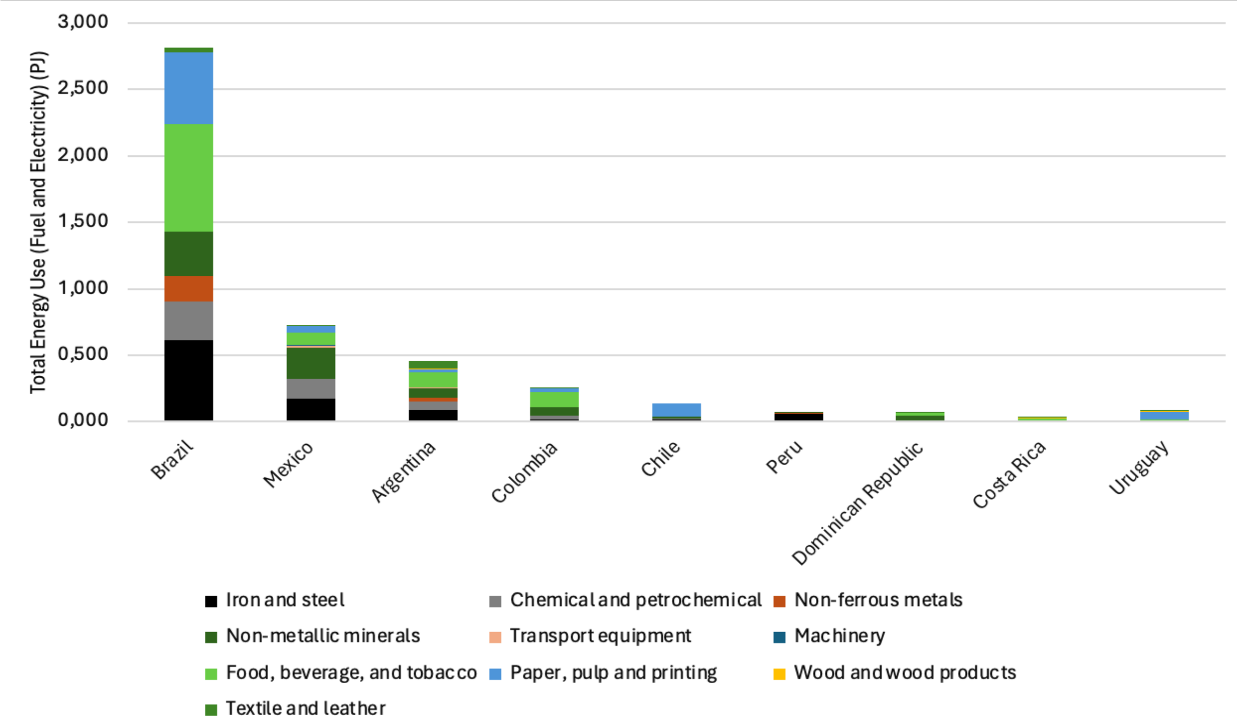
Note: *Industrial Production was estimated using each country's GDP and the 2019 Industry Value Added (% of GDP).
Source: Authors' analysis based on IEA (2022).

Data from nine countries (Brazil, Mexico, Argentina, Colombia, Chile, Peru, the Dominican Republic, Costa Rica, and Uruguay) were sufficiently detailed to conduct further analysis of energy and emissions at the industrial manufacturing subsector level. These nine countries represent diverse stages of economic development, maturity of their national innovation system, climate commitments, and more. The lack of subsector-level energy use data makes comparison beyond these selected countries unfeasible.

Energy use, CO_2 emissions, and CO_2 emission intensity per unit of energy use were estimated for ten subsectors across these nine countries: food, beverages, and tobacco;[3] non-metallic minerals; iron and steel; paper, pulp and printing; chemical and petrochemicals; non-ferrous metals; textile and leather; transport equipment; wood and wood products; and machinery. Notably, the top five energy-using and CO_2-emitting subsectors were food, beverages, and tobacco; iron and steel; non-metallic minerals (mostly the cement industry); paper, pulp and printing; and chemical and petrochemicals (Figures 6, 7, and 8).

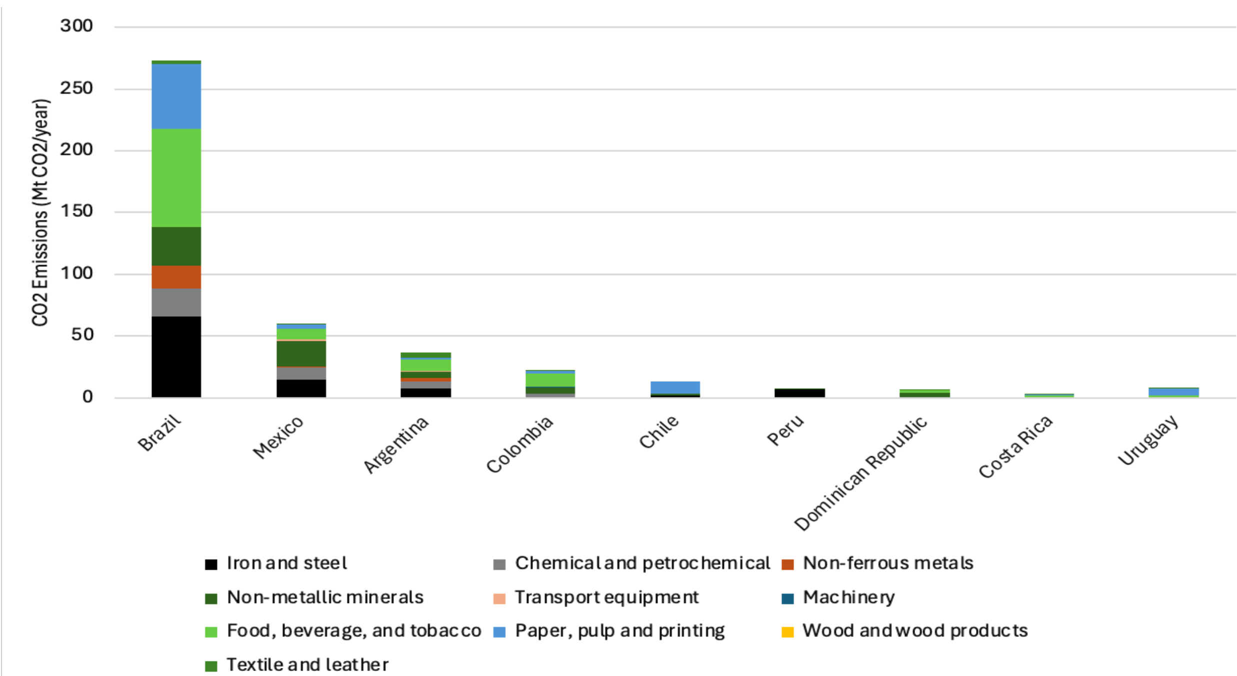
[3] The data analyzed is for "food, beverage and tobacco" although in some instances in the document, we use "food and beverage," a more common term.

Figure 6: Total Energy Use by Subsector in Selected LAC Countries in 2019



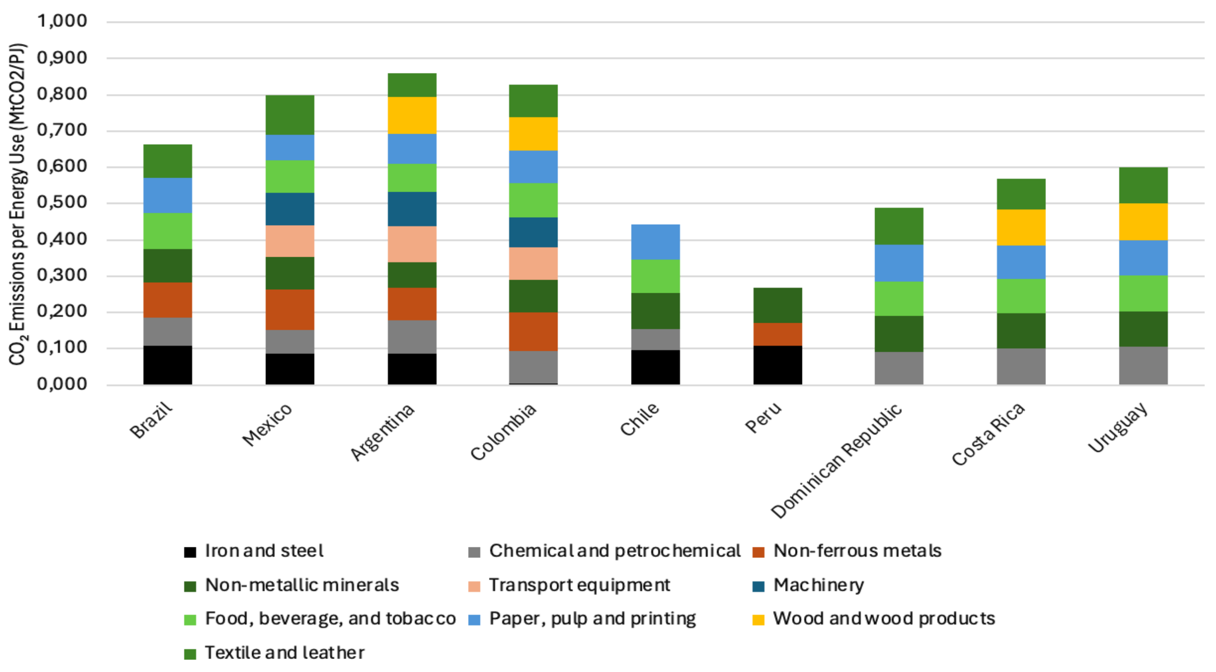
Source: Authors' analysis based on IEA (2022).

Figure 7: CO_2 Emissions per Unit of Energy Use by Subsector In Selected Latin American and Caribbean Countries in 2019



Source: Authors' analysis based on IEA (2022).

Figure 8: Total CO_2 Emissions by Subsector in Selected Latin American and Caribbean Countries in 2019



Source: Authors' analysis based on IEA (2022).

To further narrow down these top energy-using and emitting subsectors, we looked at subsector energy patterns in the four largest countries, Brazil, Mexico, Argentina, and Colombia. In these four countries, iron and steel; food, beverage, and tobacco; and non-metallic minerals (i.e., cement) used the most energy, accounting for over 90 percent of energy use in each subsector across all nine countries. It is important to note that cement production produces significant additional greenhouse gases through process emissions (calcination process), which account for up to 60 percent of total CO_2 emissions in the cement industry, making the total climate impact higher than the estimated emissions solely from fuel and electricity. Table 2 shows the top three CO_2-emitting industrial subsectors for the nine countries with available sectoral energy use and emissions data.

Table 2: Top Three CO_2-Emitting Industrial Subsectors in Latin American and Caribbean Countries with Available Data

Country	#1 Emitting industrial subsector	#2 Emitting industrial subsector	#3 Emitting industrial subsector
Costa Rica	Food, beverage, and tobacco	Wood and wood products	Chemical and petrochemicals
Mexico	Non-metallic minerals (cement)	Iron and steel	Chemical and petrochemicals
Peru	Iron and steel	Non-metallic minerals (cement)	Non-ferrous metals
Uruguay	Paper, pulp and printing	Food, beverage, and tobacco	Wood and wood products
Chile	Paper, pulp and printing	Iron and steel	Non-metallic minerals (cement)
Colombia	Food, beverage, and tobacco	Non-metallic minerals (cement)	Chemical and petrochemicals
Brazil	Food, beverage, and tobacco	Iron and steel	Paper, pulp and printing
Argentina	Food, beverage, and tobacco	Iron and steel	Chemical and petrochemicals
Dominican Republic	Non-metallic minerals (cement)	Food, beverage, and tobacco	Chemical and petrochemicals

Note: Around half of all CO_2 emissions from cement production are process-related emissions from the calcination process. Therefore, the overall CO_2 emissions for the cement industry are higher than the basis of energy-related emissions used for ranking and comparison in this table.
Source: Authors' elaboration.

As a result, the final three subsectors selected for the study are iron and steel; food, beverages, and tobacco; and non-metallic minerals (i.e., cement). Based on this analysis, these three sectors were selected for the roadmap and technology research and conceptual roadmap framework development. Table 3 presents total energy use and estimated CO_2 emissions for the selected three subsectors totaled across the nine countries with available data.

Table 3: Energy Use and CO_2 Emissions From Top Three Industrial Subsectors in 2019

Industrial Subsector	Total Energy Use (Fuel and Electricity) (PJ)	Carbon Dioxide Emissions from Fuel and Electricity (million tons CO_2)	Countries in Which the Subsector is the Highest Emitting Subsector
Iron and Steel	961	96.1	Peru
Food, Beverage, and Tobacco	1,187	113	Brazil, Argentina, Colombia, Costa Rica
Non-metallic Minerals*	747	67	Mexico, Dominican Republic

*Around half of CO_2 emissions from cement production is process-related emissions from the calcination process. Therefore, the overall CO_2 emissions or the cement industry is almost double the energy-related emissions shown in this table.
Source: Authors' analysis based on (IEA 2022).

3. Review of Sector-Specific Roadmaps

Based on the analysis in section 2, the three industrial subsectors selected for the review of sector-specific roadmaps are: food and beverage, iron and steel, and cement. These sectors represent both consumer products and heavy industries recognized as vital to the economies of the LAC region. As the three largest energy-consuming and highest-emitting subsectors in the LAC region, they will play a significant role in the region's decarbonization trajectory.

Based on a thorough review of credible and expert scientific literature and reports, over 30 roadmaps and technology assessments were identified for the food and beverage, iron and steel, and cement industries. The literature reviewed includes academic and industry publications and reports by government and non-governmental organizations and the private sector. The review was designed to extract lessons and insights that can be adapted to the industrial context of the LAC region. The review also aimed to identify roadmaps that emphasized the role of technology and innovation in the industrial decarbonization process. Thus, most of the selected roadmaps are from developed countries or rapidly advancing economies such as India and China.

The in-depth examination of international examples of sector-specific decarbonization roadmaps focused on their methodologies, the role of technology, the role of innovation, and recommended policies. Through a comparative lens, the roadmaps identified demonstrate efficacy in promoting industrial decarbonization. As much as possible, attention was paid to roadmaps catering to industries that resemble those in the LAC region in terms of structure and inherent challenges.

3.1. Food and Beverage Industry

The studies targeting decarbonization technologies within the food and beverage industry (Table 4), focused primarily on developed countries because of the availability of information, reveal an array of methodologies and recommendations for this important sector. A pronounced trend is the emphasis on energy-efficient technologies, including general improvements for lighting, HVAC systems, compressed air systems, motor systems, steam systems, and refrigeration, as well as additional efficiency technologies specific to individual categories of food products.

Table 4: Sample of Studies Reviewed, Food and Beverage Industry

Study Citation	Geography	Methodological Approach	Role of Technology	Role of Innovation	Recommended Policies
Bhadbhade and Patel 2020	Switzerland	Techno-economic modeling of energy efficiency technology adoption	Technologies: Energy efficiency for motors, steam systems, refrigeration, waste heat recovery; measures for specific products	Focuses on commercially available technologies; technical energy efficiency potential was compared to current levels of energy consumption to estimate potential savings	NA
Cameron, Lopez, and Yule, 2021	Europe	Models a roadmap to net zero food production with adoption of different technologies, examines costs and emissions	Technologies largely commercially available (e.g., energy management systems, electrification of heat, fuel switching, energy efficiency)	Models several scenarios that vary based on penetration of clean technologies	Policies: funding for relevant infrastructure, capacity building
Hasanbeigi, Kirshbaum, and Collison, 2023	United States	Bottom-up model of electrification technologies for process heating, assessing energy savings, emissions, energy costs, and additional electricity load	Technologies are largely commercially available - electrification technologies including heat pumps, electric steam boilers, electric dryers, and resistive heating	Assumes 100% adoption of technologies in order to compare maximum potential; models scenarios with more rapid grid decarbonization and lower electricity prices	Policies: financial incentives
U.S. Department of Energy, 2022	United States	Scopes key technology needs and opportunities for various sectors, including food and beverages, incorporating scenario modeling and expert input to lay out a cohesive technical approach	Technologies studied that are commercially available: Energy efficiency (e.g., smart manufacturing and recycling), electrification (e.g., electric boilers, ovens, and fryers; heat pumps; and process electrification)	Includes emerging technology pillars - low-carbon fuels (e.g., hydrogen and biofuels), and CCUS (primarily CO_2 as a feedstock); analyzes technology maturity and market readiness for different	Policies: primarily focuses on RD&D investment and how the U.S. government can increase the efficacy of RD&D support

				decarbonization technologies, and assesses R&D needs for further innovation over time	
Sovacool et al., 2021	Global	Systematic review of literature on the energy and climate impacts of food and beverages	Technologies studied that are commercially available: Energy efficiency, including automation, process management, heat recovery; and adoption of renewable energy	Includes a section on breakthroughs and transformative innovations, including advanced heating and refrigeration technologies	NA
Yuan and Riley, 2023	United States	Review of technologies, barriers, and policies regarding decarbonization of food and beverage production	Technologies studied that are commercially available: Electrification, including heat pumps and boilers	Characterizes technological maturity of heat pumps and electric boilers, as there is variation across specific designs	Policies: electricity market reform, financial incentives for heat pumps, R&D
Food and Drink Federation, 2021	United Kingdom	Develops actions and information primarily for food and beverage producers, including upstream and downstream actions with a focus on manufacturing	Technologies: product design, packaging, manufacturing, and distribution; manufacturing decarbonization technologies include energy efficiency, low-carbon electricity, electrified heating, and switching to sustainable refrigerants	Focuses on commercially feasible actions to meet a 2040 net-zero target	NA

Electrification also emerges as a key decarbonization pillar for the food and beverage sector, highlighting technologies such as heat pumps, electric boilers, and electric heaters and dryers for their large potential in decarbonizing food and beverage production. Several studies conduct modeling scenarios, projecting the potential impacts of these technologies on emissions and costs. Some studies extend the decarbonization purview to broader areas such as product design, packaging, and distribution.

A majority of the research papers focus on commercially available technologies, although several characterize the maturity and market readiness of various decarbonization technologies. In terms of innovation, several studies scope R&D opportunities, identifying areas that need more innovative strides for achieving long-term goals. Some studies highlight breakthrough and transformative innovations, particularly in advanced heating and refrigeration technologies.

The decarbonization roadmaps for the food and beverage sector offer several policy recommendations. Most studies call for bolstered R&D investment, including the amount and efficacy of such investments, and couple R&D with financing for technology deployment and the integration of low-carbon energy supply. Several studies highlight the need to integrate associated infrastructure for decarbonization and capacity building with food and beverage production. The policy suggestions also encompass broader structural changes, such as electricity market reforms and high-level collaboration between government and industry.

3.2. Iron and Steel Industry

This sub-section provides a list of studies that have charted roadmaps for steel decarbonization. The roadmaps vary in their geographical focus, methodological approaches, recommended technologies and policies, and perspectives on the role of innovation. Most of the roadmaps reviewed emphasize the critical role of certain technologies in steel decarbonization. They all underscore energy efficiency improvements as a fundamental first step, with specific attention given to its application in coke-making, blast furnace (BF) ironmaking, basic oxygen furnace (BOF), electric arc furnace (EAF), casting, and rolling processes. The emphasis on material efficiency and recycling further underscores the industry's shift toward circularity and a reduced need for primary steel production where scrap resources are available.

Table 5: Sample of Studies Reviewed, Iron and Steel Industry

Study citation	Geography	Methodological approach	Technology role	innovation role	Recommended policies
Hasanbeigi, Lu, and Zhou, 2023	China	Models of decarbonization pathways for steel by 2050, estimating emissions	Commercially available technologies: material efficiency, energy efficiency fuel switching, and electrification	Includes discussion of emerging technologies (CCS, hydrogen DRI); develops different scenarios that vary by the rate of energy efficiency improvement and adoption of CCUS and new production routes	Policies: emissions trading systems (ETS), R&D
ArcelorMittal, 2021	Global	Based on a net zero by 2050 target, the study lays out several technological pathways and general decarbonization levers	Commercially available technologies: increased use of scrap, clean electricity, and offsetting residual emissions	The study lays out two main pathways for technological development: Innovative DRI and smart carbon. These pathways require emerging technologies for steelmaking transformation (e.g., DRI-EAF) and energy transformation (e.g., BECCS)	Policies: ETS, CBAM, GPP, financial incentives
U.S. Department of Energy, 2022	United States	Scopes key technology needs and opportunities for various sectors, including iron and steel, incorporating scenario modeling and expert input to lay out a cohesive technical approach	Technologies studied that are commercially available: Energy efficiency (e.g., smart manufacturing and recycling)	Analyzes technology maturity and market readiness for different decarbonization technologies, and assesses R&D needs for further innovation over time; considers emerging technologies under several pillars - electrification (e.g., molten oxide electrolysis and	Policies: Primarily focuses on RD&D investment and how the U.S. government can increase the efficacy of RD&D support

Study citation	Geography	Methodological approach	Technology role	innovation role	Recommended policies
				electrowinning), low-carbon fuels (e.g., hydrogen and biofuels), and CCUS (e.g., top-gas recycling, post-combustion CCUS)	
Agora Industry and Wuppertal Institute 2023	Global	Models various net-zero pathways to assess emissions, focusing on making the case for technical feasibility of net-zero iron and steel by 2040	Commercially available technologies: material efficiency, scrap-based steelmaking	Considers two scenarios, a technology mix scenario with moderate improvement in material efficiency and some commercialization of low-carbon technologies; and a global green iron scenario with additional hydrogen DRI deployment and BECCS	Policies: focuses on government and industry actions to scale up hydrogen DRI, including supporting clean energy and raw materials infrastructure, ETS and CBAM, and standards for green steel and embodied carbon (e.g., GPP)
Fan and Friedmann, 2021	Global	Models three hypothetical plants (BF-BOF, EAF, and DRI-EAF) to examine the effects of different technology adoption pathways on decarbonization potential, marginal cost increases, and marginal abatement costs	Primarily focuses on emerging technologies	Hydrogen DRI-EAF ranked as most mature low emissions pathway; assumes adoption scenarios for different categories of emerging technologies and fuels (hydrogen, biomass, zero-carbon electricity, etc.)	Policies: financial incentives, green procurement, production standards
Hall et al., 2022	India	Based on estimated costs for different steel production routes, models two net-zero pathways (by 2050 and by 2070)	Technologies studied that are commercially available: scrap utilization	Primarily focuses on emerging technologies (e.g., CCUS, gas and hydrogen DRI-EAF, MOE; sets technology adoption pathways	Policies: green procurement, product standards, R&D, ETS, CBAM

Study citation	Geography	Methodological approach	Technology role	innovation role	Recommended policies
				based on scenario, net zero by 2050 or 2070)	
International Energy Agency 2020	Global	Full techno-economic modeling of steel production, emissions, costs, etc. through 2050, including a technology module that optimizes by minimizing cost and meeting demand	Commercially available technologies: energy efficiency, fuel switching and electrification	Models a baseline stated policy scenario and a sustainable development scenario with decarbonized electricity and alternative production routes, including emerging technologies using hydrogen and CCUS	Policies: green procurement, financing, retirement, R&D, ETS, CBAM
McKinsey and Company 2020	Europe	Review of decarbonization technologies	Commercially available technologies: energy efficiency, biomass, scrap use	Emerging technologies are studied – CCUS and gas and hydrogen DRI-EAF; projects future declines in green hydrogen prices as a driver of technology adoption	NA
Mission Possible Partnership 2022	Global	Technology model that selects lowest cost technologies to meet demand	Primarily focuses on emerging technologies; includes a baseline scenario, a carbon cost scenario with a carbon price that drives technology adoption, and a technology moratorium scenario with investment only into low-emissions technology	Focuses on emerging technologies like hydrogen, BECCS, CCUS, DRI-EAF with different fuels, electrolysis and electrowinning, SR-EAF	Policies: financial incentives, GPP, CBAM, ETS, carbon standards

Study citation	Geography	Methodological approach	Technology role	innovation role	Recommended policies
Toktarova et al. 2020	Sweden	Models different technology options and resulting emissions and costs over time	Other than switching to the EAF production route, primarily focuses on emerging technologies; sets timeline for different technology adoption scenarios	Focuses on emerging technologies like CCUS, biomass, hydrogen DRI-EAF	Policies: national bioenergy policy, national CCUS strategy, national electrification strategy
Yadav, Guhan, and Biswas 2021	India	Models operations of a hydrogen-based steel plant to estimate costs and emissions	Study focuses on one emerging technology, hydrogen DRI-EAF	Assumes decreasing costs of green steel production through 2050	Policies: R&D, GPP

Abbreviations: DRI = direct-reduced iron; EAF = electric arc furnace; BECCS = bioenergy with carbon capture and sequestration; ETS = emissions trading system; CBAM = carbon border adjustment mechanism; GPP = green public procurement; CCUS = carbon capture, utilization, and storage; R&D = research and development; BF-BOF = blast furnace-basic oxygen furnace; SR = smelting reduction.
Source: Authors' elaboration.

Many studies also focus on electrification, including increasing the share of EAF steelmaking over the BF-BOF route. Most of them incorporate some amount of innovation over time, which allows the cost-effective introduction of currently emerging technologies such as molten oxide electrolysis (MOE), electrowinning, and direct reduced iron using electric arc furnaces (DRI-EAF). Clean hydrogen emerges as a critical technological solution, both as a substitute for carbon-intensive reduction processes and as a fuel. The prominence of hydrogen-based direct reduced iron (DRI) using EAF, often shortened to hydrogen DRI-EAF, is cited across many studies, with some studies featuring it as the most promising or mature low-emissions pathway for steelmaking.

Carbon capture, utilization, and storage (CCUS) is another key technological avenue identified across multiple studies, with applications ranging from top-gas recycling to post-combustion capture. The integration of bioenergy with CCUS (BECCS) and the increased use of scrap metal are often studied in tandem with these technologies to offset residual emissions.

Furthermore, many of the studies reviewed conclude with policy recommendations based on the technologies modeled. For the iron and steel sector, these recommendations tend to focus on different segments of the value chain. Upstream, many studies recommend supplementary governmental support for decarbonization-related infrastructure, such as renewable energy, clean hydrogen, and CCUS production and transport infrastructure. For the midstream step of actual iron and steel production, studies emphasize the need for government support for R&D in advancing emerging solutions, such as by providing direct funding for innovation, as well as other financial incentives through carbon pricing and carbon border adjustment mechanisms (CBAM). Finally, for downstream transformation of product demand, many studies highlight the role of green public procurement (GPP) and policies that improve and standardize the definitions of green steel and set embodied carbon limits.

3.3. Cement Industry

This sub-section reviews decarbonization roadmaps for cement and concrete, focusing on potential technological and policy solutions. Improving energy efficiency has some potential to reduce emissions in this sector, but its impact is limited. The main energy efficiency technologies covered were waste heat recovery, improved grinding techniques, smart manufacturing, and the use of more efficient kilns and fluidized bed kilns. Around half of the CO_2 emissions in the cement industry are process-related emissions from calcination and are not related to energy use.

Table 6: Sample of Studies Reviewed, Cement Industry

Study Citation	Geography	Methodological approach	Technology role	Innovation role	Recommended policies
Karlsson et al., 2020	Switzerland	Models different technology options and resulting emissions and costs over time	Technologies studied that are commercially available: Dry kilns, alternative binders and SCMs, material efficiency	Considers CCUS as an emerging technology; sets timeline for different technology adoption scenarios	Policies: pilot projects, R&D, national bioenergy and CCUS strategies
Rocky Mountain Institute and China Cement Association, 2022	China	Roadmap of decarbonization pathways for China's cement industry, comparing costs of different pathways to zero carbon	Technologies studied that are commercially available: Fuel substitution, energy efficiency (grinding, clinker calcination), SCMs	Emerging technologies: alternative raw materials and CCUS (including carbon-cured concrete); Sets timeline for technology deployment from 2020 to 2060	Policies: ETS, GPP, green finance
U.S. Department of Energy 2022	United States	Scopes key technology needs and opportunities for various sectors, including cement, incorporating scenario modeling and expert input to lay out a	Technologies studied that are commercially available or near-term: Energy efficiency (e.g., smart manufacturing and innovative chemistries), electrification (e.g., precalciner	Emerging technologies: low-carbon fuels (e.g., hydrogen and biofuels; solar thermal) and CCUS (e.g., oxycombustion, calcium looping, and indirect calcination with CCUS)	Policies: Primarily focuses on RD&D investment and how the U.S. government can increase the efficacy of RD&D support

Study Citation	Geography	Methodological approach	Technology role	Innovation role	Recommended policies
		cohesive technical approach	and full kiln electrification)		
U.S. Department of Energy 2023	United States	Draws from expert consultations to evaluate technology and business models to reach net zero cement	Lists “currently deployable measures” as clinker substitution, energy efficiency, and alternative fuels	Emerging technologies: CCUS, alternative production methods (alternative feedstocks, alternatives to traditional rotary kiln production), alternative binder chemistries, and earlier-stage SCMs, hydrogen fuel blends and electrification	Policies: standards and shared data; technical and financial support for technology adoption; GPP; RD&D
GCCA 2022	Global	Forecasts emissions and emissions reductions to reach net zero for concrete by 2050	Commercially available technologies: design and construction efficiency, alternative raw materials and binders, low-carbon electricity, and carbonation	Includes CCUS as an emerging technology and lays out expected timelines for technology adoption; introduces GCCA’s innovation initiatives, the Innovandi Global Cement and Concrete Research Network and an Open Challenge to pair startups with established GCCA members	Policies: carbon pricing; investment in related infrastructure and low-carbon cement technologies; building demand for low-carbon concrete products through GPP and standards
UK Concrete 2020	United Kingdom	Roadmap model to net negative concrete and cement by 2050, optimizing technology use to meet demand	Technologies studied that are commercially available or near-term: new concrete mixes and designs, alternative raw materials and binders, fuel switching	Assumes ongoing electricity and transport decarbonization in the model, and availability of emerging technologies like zero carbon fuels and CCUS technologies	Policies: GHG accounting, standards

Abbreviations: SCM = supplementary cementitious materials,
Source: Authors’ elaboration.

Across studies, supplementary cementitious materials (SCMs) and alternative raw materials are frequently identified as pivotal for reducing the carbon footprint of cement. The focus on SCMs is coupled with the larger theme of clinker substitution, which uses alternative binders and materials such as alkali-activated materials. Some studies also examined electrification technologies, such as full kiln electrification and precalciner electrification. Many roadmaps paired electrification with a move to low-carbon electricity sources. Fuel switching and the use of low-carbon fuels, including hydrogen and biofuels, are another significant technological area in many cement decarbonization roadmaps.

Finally, the potential of CCUS is greater for cement production than for other subsectors due to the process-related CO_2 emissions inherent to cement production. The roadmaps reviewed contained a number of diverse CCUS strategies, from post-combustion carbon capture to oxy-combustion and calcium looping. The integration of these strategies with indirect calcination and carbon-cured concrete also demonstrates the range of potential CCUS technologies for cement and concrete production.

The roadmaps reviewed treated the role of innovation. Several studies systematically ranked technologies based on their technology readiness level (TRL). Modeling-oriented studies developed scenarios to reflect potential shifts in energy efficiency, clinker substitution, fuel switching, and the incorporation of CCUS over time, and some had sensitivity analyses that incorporated potential fluctuations in demand, cost, and others. These roadmaps frequently include timelines that indicate when specific technologies might penetrate the market, ranging from short-term projections to those spanning up to 2060.

Given the need for further innovation to scale up cement and concrete decarbonization technologies, many cement roadmaps provided policy recommendations around increasing R&D support. This was often linked to recommendations on promoting green finance and pilot projects to catalyze the adoption of low-carbon technologies and practices, especially related to CCUS. In addition, many roadmaps advocate for the inclusion of the cement industry in carbon pricing systems or CBAMs. Finally, initiatives like capacity building, general regulatory frameworks, and standards set the stage for overall decarbonization of the sector.

4. Review of Sector-Specific Decarbonization Technologies

This section presents a comprehensive compilation of decarbonization technologies based on the literature review and additional sources of information. These technologies are at the forefront of global industry practices and bear significant potential for adoption in the LAC region. Beyond their primary function of reducing CO_2 emissions, some of them also offer additional advantages, notably enhancing climate resilience in specific sectors.

For each subsector studied, the industrial decarbonization technologies are organized under five pillars representing the diverse strategies for industrial decarbonization (Table 7). The five industrial decarbonization pillars are briefly explained below and are linked to specific subsectors in the following subsections.

Table 7: Five Pillars of Industrial Decarbonization

Material efficiency	Energy efficiency	Electrification of industrial heat	Low-carbon fuels, feedstocks, and energy sources (LCFFES)	Carbon capture, utilization, and storage (CCUS)
• Higher quality products and materials • Waste reduction • Low-carbon material substitution	• Energy management • Waste heat recovery/ combined heat and power • Systems optimization	• Electric boilers • Heat pumps • Electric heaters and dryers	• Green hydrogen as feedstock or reductant • Alternative feedstocks • Biofuels	• Post-combustion capture • Carbon utilization

Note: Technologies listed under are not a comprehensive or specific sectoral list.
Source: Authors' elaboration.

Pillar 1: Material efficiency

There is significant potential to reduce the carbon footprint of industry via a focus on material efficiency. There are various ways to reduce material demand through optimization of materials consumed in the products at the design stage, the use stage, and the end-of-life stage. Measures such as light-weighting, longer lifetimes, improved product quality, reduced waste during manufacturing, re-manufacturing, repurposing, re-use, and recycling of products fall under this pillar. For certain end uses, there is potential to replace energy-intensive materials such as steel and concrete with alternative materials such as enhanced wood products, composites, and others, especially considering resource availability in the LAC region, to lower the carbon footprint of final products.

Pillar 2: Energy efficiency

The energy efficiency pillar contains many opportunities for near-term decarbonization. In many cases, energy efficiency technologies do not require major changes to industrial processes and can bring immediate reductions in emissions. Energy efficiency technologies should lead to improvements in system efficiencies and recovery of thermal energy, expansion of energy management practices, and smart manufacturing. Near-term energy efficiency improvements should be paired with longer-term decarbonization pathways.

Pillar 3: Electrification

A large share of industrial energy use is for process heating, most of which is provided by fossil fuel combustion. Many commercially available and emerging electrified technologies such as electric boilers and heat pumps can provide process heat. The advantage of electrified process heat comes when decarbonized electricity is used. Given ongoing grid decarbonization in many countries, electrification holds large decarbonization potential.

Pillar 4: Low-carbon fuels, feedstocks, and energy sources (LCFFES)

LCCFES refers to the adoption of low-carbon energy sources such as sustainable biofuels. This pillar also includes low-carbon fuels and feedstocks, such as green hydrogen, which can be used as feedstock in the chemical industry (e.g., ammonia and methanol) or as a reducing agent in the steel industry (H_2-DRI ironmaking). Some technologies from this pillar are expected to be available in the near- to medium-term, while others will require longer-term R&D. Green Hydrogen is a critical component of just energy transition plans in LAC. Recognizing that a one-size-fits-all approach is not applicable, individual countries must design their strategies based on factors such as available resources, existing infrastructure, industrial value chain, domestic hydrogen demand, export opportunities, and geographical location. Incorporating clean hydrogen and its derivatives into industry decarbonization pathways is vital for fostering sustainable growth and mitigating climate change (IDB, 2023).

Pillar 5: Carbon capture, utilization, and storage (CCUS)

CCUS is the longest-term decarbonization pillar in this analysis. Even with full deployment of all of the other decarbonization technologies, this may not be sufficient to reach net-zero industrial emissions. CCUS can be a source for longer-term emissions reductions, especially in carbon-intensive heavy industries such as cement and steel. Carbon utilization can occur via a range of applications through which CO_2 is captured and used either directly (i.e., not chemically altered) or indirectly (i.e., transformed) in a variety of ways (i.e., CO_2 based synthetic fuels, or chemicals).[4] CO_2 utilization should be prioritized in LAC by, for example, using CO_2 as a raw material for methanol production, and its transformation to other fuels or for carbonated beverages. In addition to carbon capture, carbon utilization and carbon storage are necessary for building a fully functional market to support CCUS infrastructure. During the process of scaling up CCUS, it is important to improve the efficiency, economic viability, and safety of CCUS. Examples of CCUS technology include post-combustion chemical absorption of CO_2 and the construction of CO_2 pipelines and other related infrastructure for using, transporting, and storing carbon. Each subsection below summarizes decarbonization technologies for each subsector by classifying the technologies into these five pillars.

4.1. Decarbonization Technologies for the Food and Beverage Industry

Energy efficiency: Numerous energy efficiency technologies are already in commercial use within the food and beverage manufacturing sector, yet there is still room to broaden their application. Several emerging technologies promise notable efficiency improvements, such as waste heat recovery, advanced oven burners, enhancements in steam production, and the principles and tools of smart manufacturing. Smart manufacturing holds promise in process refinement, particularly in the ability to

[4] As defined and described by the International Energy Agency: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-capture-and-utilisation.

optimize performance across different systems, such as through the integration of thermal systems and streamlining the supply chain. Optimizing the supply chain for energy efficiency can also yield co-benefits, such as reducing spoilage and waste and improving product safety through better traceability.

Material efficiency: Product degradation and spoilage are major problems for food and beverage manufacturing. Opportunities exist to reduce this waste through improved processing, handling, and packaging practices that can significantly reduce unconsumed products, with a corresponding reduction in the energy, resources, and emissions that would otherwise be required. There are existing practices and technologies to extend the shelf life of food and beverage products and reduce degradation. In addition, the packaging of food and beverage products is also an energy- and resource-intensive part of the industry, and material efficiency can improve performance, reduce the volume of packaging waste and, where possible, allow for recycling.

Electrification: Food and beverage manufacturing is well-suited for electrification of heating because of the demand for low-temperature process heating in this sector. Electric boilers, hybrid boilers, industrial heat pumps, and the modularization of process heating in food and beverage manufacturing are all part of the electrification pillar. Through the electrification of process heating, ovens and fryers represent a potential avenue for accelerating decarbonization.

Low-carbon fuels, feedstocks, and energy sources (LCFFES): LCFFES decarbonization measures for the food and beverage industry can entail generating renewable energy onsite for processes that use electricity. Furthermore, there can be a general shift toward lower-carbon fuels and by-product biomass. Additionally, innovations such as solar drying offer low-carbon alternatives to traditional methods.

Carbon capture, utilization, and storage (CCUS): Overall, CCUS is not a major decarbonization pillar for the food and beverage industry, given the sheer diversity of food and beverage manufacturing, varying CO_2 sources, geographical differences, and others. Processing food-grade CO_2 for reuse is another potential challenge.

Table 8: Decarbonization Technologies for the Food and Beverage Industry

Decarbonization pillar	Key technologies
Energy efficiency	General • Energy management systems, controls, and maintenance • Improved steam systems through boiler efficiency and steam distribution efficiency • Improved motor system and pump efficiency • Improved refrigeration systems through system management, cooling load reduction, compressor efficiency, and condenser and evaporator efficiency • Improved compressed air systems • Building energy efficiency through improved HVAC systems and lighting Dairy (see Brush, Masanet, and Morrell, 2011) • More efficient pasteurization, homogenization, sterilization, and heat treatment (e.g., pulsed electric fields) • Improved evaporation and evaporator fan controls • Improved spray drying (e.g., DriZoom) Beer (see Galitsky et al., 2003a) • Use of waste heat and compression filters for mashing • Improved wort boiling and cooling • Improved fermentation • Improved filtration and pasteurization • More efficient packaging (e.g., low-pressure blowers for bottle drying) Corn wet milling (see Galitsky et al., 2003b) • Alternative steeping chemistries • Improved fermentation • Mechanical dewatering • More efficient drying (e.g., infrared heating) • Advanced membranes Breakfast cereal (see Kermeli and Worrell, 2018) • Improved weighing and blending • More efficient cooking, toasting, and drying • Improved forming processes Fruit and vegetable processing (see Masanet et al., 2008) • More efficient blanching • Ohmic heating • Pre-cooling before freezing Wine • Ultrasound equipment for speeding grape maceration
Material efficiency	• Improved packaging design • Use of wastewater and byproducts to produce biogas through anaerobic digestion • Use of residues or waste as fuel or for conversion to fuels • Reduce food waste
Electrification	• Electric industrial heat pumps for heating, drying, pasteurizing, etc. • Electric boilers and hybrid electric boilers • Electric dryers (e.g., electric fluidized bed dryer, rotary dryer, ring dryer) • Indirect resistive heating

Decarbonization pillar	Key technologies
Low-carbon fuels, feedstocks, and energy sources	• Onsite renewable energy generation • Use of lower-carbon fuels and by-product biomass • Solar drying
CCUS	• Carbon capture from combined heat and power (CHP) • Utilization of CO_2 for carbonated beverages

Note: Some specific food and beverage types that are more energy-intensive are discussed in further detail with regard to decarbonization technologies.
Source: Authors' elaboration.

4.2. Decarbonization Technologies for the Iron and Steel Industry

Energy efficiency: A variety of energy-efficient technologies are already available to be deployed on a commercial scale in the steel industry. Technologies such as waste heat recovery for different processes, coke dry quenching (CDQ), top-pressure recovery turbine plants (TRT), and many others are commercially available for deployment (Hasanbeigi et al., 2023). Also, cutting-edge technologies can assist with energy management systems, drawing from smart manufacturing and the Internet of Things; such technologies include predictive maintenance and machine learning or digital twins to improve process control (Hasanbeigi et al., 2013). Improved energy efficiency may produce other benefits for the iron and steel industry besides energy savings and decarbonization, including less risk exposure to fluctuating energy costs, increased productivity, and reduction of air pollution.[5]

Material efficiency: For iron and steel production, material efficiency can be a significant decarbonization lever. Multiple strategies exist in each of the product life-cycle stages, ranging from steel product design (e.g., improving design to have lighter products, optimizing to minimize material use, design for longer life, reusability, and ease of high-quality recycling), steel product manufacturing (e.g., improving material efficiency in the production and fabrication processes, increasing material waste recycling), steel product use (e.g., extending the building and product lifetime, intensifying product use, and switching to other low-carbon alternative materials, such as mass timber for certain kinds of buildings), and steel product end-of-life (e.g., increasing building component direct reuse, increasing the recycling rate of steel products, and remanufacturing of steel products). Another important technology classified under material efficiency is scrap-based EAF production. EAF steelmaking can use a wide range of scrap types. Recycling scrap to make steel saves virgin raw materials as well as the energy required for converting them and reduces the CO_2 intensity of steel production.

Electrification: In terms of heating, reheating furnaces can be electrified, and electric induction furnaces can also be scaled up. Ladle and tundish heating can be switched to resistance, infrared, or plasma heating. The use of EAF steel production over the BF-BOF

[5] The IDB publication 'Acelerando la descarbonización de la industria pesada en América Latina y el Caribe' notes that implementing energy efficiency measures in LAC holds significant potential for reducing carbon emissions and progressing towards the goal of achieving net-zero emissions by 2050. Additionally, these measures not only require low investment costs but also have the capacity to achieve a 14 percent reduction in emissions from this industry.

route is also a form of electrification. In terms of grid decarbonization, all processes in steel production that use electricity can lower their emissions by using lower-carbon electricity.

LCFFES: In terms of fuel switching, several alternative fuels, such as natural gas, biomass, biogas, and on a medium-term time horizon, hydrogen, can replace coal or coke as a fuel or reducing agent in the iron and steelmaking processes. Another key technology in this category is green hydrogen-based DRI-EAF steelmaking. If DRI is paired with the EAF to produce steel, it results in lower CO_2 emissions compared to the BF-BOF steel production route, and further reduction of CO_2 emissions can be achieved by utilization of hydrogen produced from renewable energy (green hydrogen) as the energy source and reducing agent for the production of DRI, thus releasing H_2O instead of CO_2. There is a demonstration H_2-DRI plant currently operating in Sweden. Several H_2-DRI plants are under construction around the world, with many more announced to start construction by 2030.

CCUS can be used to decarbonize different steel production routes, such as top-gas recycling in blast furnaces with CCUS, DRI with post-combustion CCUS, and oxygen-rich smelt reduction with CCUS, etc. These CCUS technologies vary greatly in their commercialization status, with most of them currently at the pilot stage. CO_2 could be utilized to produce chemicals, fuels, and construction materials. The main challenges for CCUS technologies are achieving further reductions in costs and improving operational efficiencies as well as having suitable CO_2 transport systems and storage sites. The captured CO_2 emissions from iron and steel production can be permanently stored underground (depending on geology).

Table 9: Decarbonization Technologies for the Iron and Steel Industry

Decarbonization pillar	Key technologies
Energy efficiency (see Hasanbeigi and Price, 2013, Worrell et al., 2010 for a detailed list of energy efficiency technologies for each process)	Improved sintering efficiency • Heat recovery from sinter cooler • Reduction of air leakage (e.g., through monitoring technologies) • Use of waste fuel in sinter plant Improved coke making • Coke dry quenching • Coal moisture control • Variable speed drive on coke oven gas compressors Improved blast furnace ironmaking • Injection of natural gas • Injection of coke oven gas • Recovery of blast furnace gas Improved BOF steelmaking • Recovery of BOF gas and sensible heat • Variable speed drive on ventilation fans • Control system for oxygen supply to BOF process Improved EAF steelmaking • Converting the furnace operation to ultra-high power

Decarbonization pillar	Key technologies
	• Oxy-fuel burners/lancing • Scrap preheating Improved casting, refining, shaping, and hot/cold rolling • Integrated casting and rolling (strip casting) • Efficient ladle preheating • Recuperative or regenerative burners for hot rolling Smart energy monitoring and management systems Smelting reduction for ironmaking (HIsarna)
Material efficiency	• Scrap use in EAF • Scrap pre-melting for BF-BOF • Improving scrap sorting and classification • Improved steel product design and lifetime • Improving manufacturing yields
Electrification	• Direct electrolysis of iron ("Siderwin," ArcelorMittal) • Molten oxide electrolysis (Boston Metal) • Increased use of EAF • Electrification of reheating furnace
LCFFES	• Using lower-carbon electricity for EAFs and other steelmaking processes (e.g., rolling and finishing) • Green hydrogen for direct reduced iron production (H_2-DRI) • Partial replacement of natural gas with hydrogen in DRI-EAF • Using sustainable biomass in blast furnaces • Sustainable biomass to replace coal-based DRI • Injection of lower-carbon fuels or waste gases into blast furnaces (e.g., natural gas, hydrogen, etc.) (COURSE50, H2Stahl, Xingtai Steel)
CCUS	• Use of readily available low-temperature heat to separate CO_2 from blast furnace off-gas ("top-gas CCS"; "3D", ArcelorMittal; Al Reyadah) • DRI with CCUS retrofit for post-combustion capture • CCUS with traditional blast furnace • Using carbon-rich steelmaking waste gas to produce basic chemicals ("Carbalyst"/"Steelanol," ArcelorMittal; Thyssenkrupp) and combine them with hydrogen to form methanol as a clean and exportable fuel

Note: The hydrogen production route is a major determinant of CO_2 emissions. For example, "blue" hydrogen from natural gas with steam methane reforming plus CCS has a higher carbon footprint than "green" hydrogen produced from renewable electricity and water electrolysis.
Source: Authors' elaboration.

4.3. Decarbonization Technologies for the Cement Industry

Energy efficiency: A number of studies have found energy efficiency improvement opportunities in the cement industry around the world through the implementation of commercially available technologies and measures. However, their overall decarbonization impact is limited because process-related emissions from calcination account for around 60 percent of total CO_2 emissions from the cement industry and are not associated with energy use. Among various energy efficiency technologies and measures, one important technology worth highlighting is waste heat recovery (WHR) power generation technology for cement plants. This technology uses a portion of the medium temperature (200-400˚C) waste heat of kiln flue gases to generate electricity.

Although it does not reduce the amount of electricity used at a cement plant, it uses the excess heat that would otherwise be wasted to generate electricity for on-site use or export to the grid. Typically, electricity generation by WHR power generation technology is around 10-25 kWh/t of clinker produced. The electricity output depends on various factors such as kiln configuration, the moisture content of the raw materials, preheater configuration, and others.

Material efficiency: For cement production, material efficiency can be a significant decarbonization lever. Material efficiency in the cement sector is enhanced through optimized concrete recipes and the recycling of cement and concrete. By creating better designs that reduce cement and concrete demand, and through innovations in cement recipes, substantial reductions in material use and associated emissions can be achieved. Such optimization aims to reduce the demand for raw materials and energy in the cement manufacturing process, thereby contributing to overall decarbonization efforts in the sector.

Electrification: Electrification is a longer-term decarbonization pillar for cement decarbonization. Process electrification is in the early stages of development and still faces challenges in meeting the high temperatures and heat transfer required in cement production. Indirect heating can be performed in many ways, and many suggestions for indirect heating have been made, including using heating oils, indirect firing, electric induction coils, and even concentrating solar power. Indirect calcination would be relatively easy to design and incorporate in new cement plants and may be retrofittable (with a loss of thermal efficiency) in existing precalciner kiln systems. Though electric furnace technology for temperatures up to 1,000°C is in the early stages of commercialization for industrial-scale applications, much more RD&D is needed for higher temperatures. Given the aforementioned technological challenges, more basic RD&D is needed for the electrification of the full kiln via plasma arc or other technologies. The use of electric heating for indirect calcination could also be studied in combination with CCUS, given the concentrated process CO_2 emissions associated with this route. Other electrification options also exist. Initial lab tests have shown that sintering of cement can occur at a lower temperature in a microwave environment, and studies have investigated a hybrid method combining conventional kilns and an electric furnace that indicated lower energy use than the fully conventional route. One potential technology is plasma heating, which may replace more carbon-intensive processes if paired with low-carbon electricity.

LCFFES: All the fuel used and around 60 percent of the electricity used in a cement plant are consumed for clinker production (for raw material grinding, fuel preparation, and cement kilns). A higher clinker-to-cement ratio results in higher electricity and fuel intensity per ton of cement produced. Therefore, replacing clinker with supplementary cementitious materials such as fly ash, blast furnace slag, natural pozzolans, ground limestone, and calcined clay is a key element of the LCFFES decarbonization pillar and can help significantly reduce energy intensity per ton of cement produced. Fuel switching also has great potential for decarbonization of cement production. A shift away from coal and petroleum coke to less carbon-intensive fuels such as natural gas and sustainable biomass can significantly reduce emissions from the cement industry. Finally, the LCFFES technology that can address process emissions is alternative binding materials that use different raw materials than Portland cement.

CCUS: CCUS technologies are emerging for the cement industry that capture and compress CO_2 emissions and permanently store them. Because the majority of CO_2 emissions from cement production originate from limestone calcination (and not fuel combustion), pre-combustion technologies do not significantly decrease the CO_2 emissions of cement plants; therefore, pre-combustion CO_2 capture technology is not suitable for the cement industry. It is more appropriate to consider post-combustion CO_2 capture technologies in the context of the cement production process. Oxy-fuel technology uses oxygen instead of air in cement kilns, resulting in a pure CO_2 exhaust stream, which is easier to capture. Post-combustion technologies are end-of-pipe mechanisms that do not need to be fundamentally altered for the clinker-burning process, so these technologies are appropriate for new kilns as well as retrofits. In addition, cement plants have abundant amounts of low- and medium-temperature waste heat, which can be used in the post-combustion carbon capture process. Captured CO_2 can be geologically stored either permanently or over geological time scales, and either directly or after a commercial application. For instance, CO_2 can be used in the concrete curing process, the production of aggregate and construction materials, to cultivate algae biomass, for production of chemicals and fuels by reacting it with hydrogen, and other applications.

Table 10: Decarbonization Technologies for the Cement Industry

Decarbonization pillar	Key technologies
Energy efficiency	• Switching to rotary dry-process kilns with multi-stage preheaters/precalciners • Improved raw materials grinding and finish grinding (roller mills, pre-grinding, classifiers) • Improved waste heat recovery or WHR for power generation • High efficiency clinker cooler • Overall efficiency improvements in insulation, motor, fan, and lighting efficiency, etc.
Material efficiency	• Optimized concrete recipes (e.g., databases for lower-carbon formulas) • Cement and concrete recycling (e.g., the SmartCrusher technology for recovering fine materials) • Better designs to reduce cement/concrete demand (e.g., studies of alternative materials like cross-laminated timber)
Electrification	• Plasma heating
LCFFES	• Substitution of clinkers with SCMs (blast furnace slag, fly ash, calcined clays, natural pozzolans, and limestone) • Alternative raw/binding materials (belite clinker, calcium silicates, alkali-activated binders/geopolymers, carbide slag, etc.) • Alternative fuels (biomass, waste, natural gas, hydrogen, etc.) • Use of lower-carbon electricity
CCUS	• Post-combustion CCUS (e.g., chemical absorption, membranes, calcium looping) • Oxygen enrichment and oxy-fuel technology (e.g., CalPortland's Mojave Plant) • Carbonation and carbon curing for concrete • Recycling cement process CO_2 emissions into algal biomass

Source: Authors' elaboration.

5. Conceptual Framework for Industrial Roadmap Development

This section introduces a conceptual framework designed to guide industrial decarbonization efforts in the LAC region. Rooted in comprehensive research, the framework integrates various technologies and strategies based on the five pillars of industrial decarbonization.

The framework possesses a modular design, which enables it to be tailored to specific needs, particularly for the three subsectors identified within the LAC region. A key component of the framework is its emphasis on evaluating the science, technology, and innovation (STI) landscape of each subsector or country, allowing for an assessment of technology adoption readiness. It is difficult to engage in any of these steps (1 through 5) without the necessary detailed data. In addition, embedded in each step is the need for more information in LAC. For example, in Step 2 it is necessary to gather data about which technologies are commercially available vs. emerging in each LAC country and sub-sector, which is a massive undertaking. Also, these steps are not the only recipe for beginning the process of industrial decarbonization in sectors in LAC. Gischler et al. (2023) offer additional recommendations of actions and public policies that governments (actors across the public sector) can consider developing to facilitate industrial decarbonization in their countries.

Step 1. Situational analysis: This type of analysis provides a holistic view of a subsector's economic, production, trade, energy, and CO_2 emissions profile within the country of interest. Other relevant indicators include the subsector's climate vulnerability and level of technological development and innovation. This analysis dives deeper into the subsector, evaluating economic indicators like output and trade and delving into the production profile to understand the fuel mix and production routes employed by plants. Assessment of data availability and quality is also a key part of this first step, given the variability across LAC countries. So far in LAC countries, emissions data are only available at the sub-sector level, which is not sufficiently detailed to be able to conduct the kinds of roadmaps referred to in the previous section. In other LAC countries, emissions data are not available (or disclosed) even at the sub-sectoral level. Lack of data at the subsector level may require proxying with country-level data, for example, and data availability and quality should be considered throughout the rest of the steps for the framework.

Step 2. Technology options: These involve identifying potential technologies for decarbonization, rooted in five foundational pillars. They are then classified based on their TRL, anticipated costs, and the potential energy and emissions savings they offer. It is important to understand which technologies are commercially available vs. emerging in each LAC country, as well as to assess RD&D needs for potentially shifting the landscape of technology availability over time. They also involve knowing how widely diffused existing technologies are in each LAC country and, if not widely diffused, the potential for broader technology diffusion.

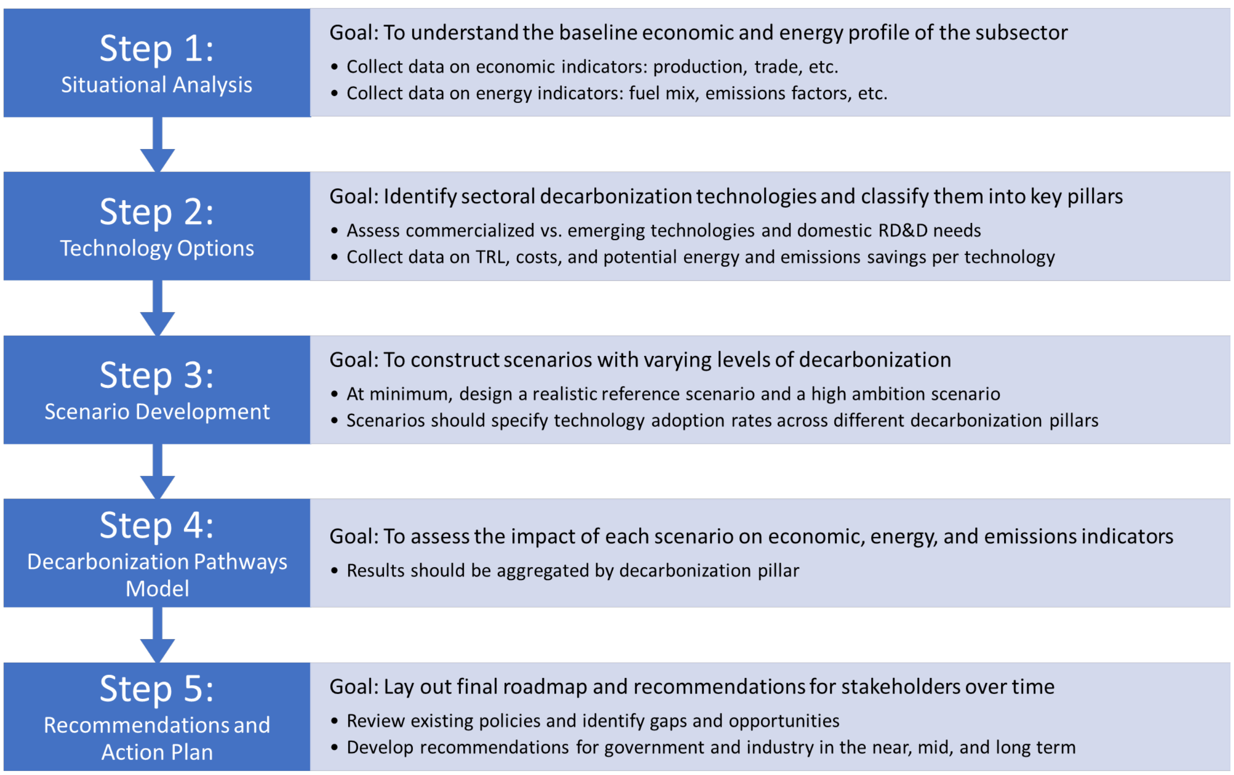
Step 3. Scenario development: Its purpose is to construct well-defined, varied scenarios that mirror the features, ambitions, and realities of the given sector in a specific country. These scenarios should encompass different degrees of ambition, from maintaining the status quo to achieving net zero emissions, ensuring the consideration of plausible intermediate stages of decarbonization and energy efficiency improvement. It is imperative to develop a realistic reference scenario to understand the baseline projections regarding production, decarbonization, and energy efficiency, absent additional interventions or policy changes.

Step 4. Decarbonization pathways model: Based on the scenario design described above, this model should assess the impact of each decarbonization pillar based on selected technologies. This entails forecasting the total final energy use and CO_2 emissions of the industrial subsector over the desired timeline under the different scenarios by applying varying levels of the decarbonization pillars.

Step 5. Recommendations and action plan: This phase calls for reviewing existing policies and regulations to discern gaps and potential opportunities. Synthesizing the insights from all preceding steps, a final, cohesive roadmap for decarbonization is crafted for the country's subsector, and recommendations are developed for government and industry in the near, medium, and long term.

This framework provides a systematic, multi-step approach, ensuring that the roadmap is rooted in both data and the specific context of the LAC country in question. The following infographic (Figure 7) lays out the framework's components and its adaptability mechanisms to support decarbonization across the three key subsectors in this study.

Figure 7: Schematic of Conceptual Framework for Developing Sector-Specific Industrial Decarbonization Roadmaps



Source: Authors' elaboration.

The general steps of the conceptual framework are applied to each subsector in the following subsections to describe in detail the development of a roadmap for each.

5.1. Conceptual Framework for Food and Beverage Decarbonization Roadmap Development

Step 1: Situational analysis

The situational analysis to develop a country's food and beverage decarbonization roadmap should entail an assessment of the country's food and beverage production and trade situation. Given the typical diversity of food and beverage products, it may be important to focus data collection on the most volume- and energy-intense types of food and beverage products. Overall, there should also be a baseline assessment of the technological and innovative capabilities in the country's food and beverage subsector.

Based on the above-described metrics and the availability of data in the country, energy and emissions can be estimated or summarized. When available, detailed energy use data should be summarized, namely, the breakdown of energy inputs for different food and beverage product manufacturing and the share of different fuels in end-use energy consumption. Credible projections of future domestic demand and rates of grid decarbonization and energy efficiency improvement are also important. Given the importance of electrification for food and beverage production, data on the penetration rates of different electrification technologies and the current amount of electricity used for food and beverage production are important. These data and estimates are necessary for constructing a baseline against which to measure different decarbonization options.

It is also important to consider the climate vulnerability of the country's food and beverage manufacturing facilities. Depending on the energy sources used and the location of each facility, future climate-related events may disrupt energy supply chains, affect energy costs, and overall play a key role in the viability of different decarbonization pathways.

Step 2: Technology options

Commercialized technologies

In the domain of food and beverage manufacturing, there are a large number of commercialized technologies for energy efficiency and material efficiency to reduce emissions. Energy-efficient technologies, already in extensive use, are continually optimizing manufacturing processes, such as advanced oven burners and enhancements in steam production, to mitigate energy consumption. Moreover, the sector is leveraging technologies to extend product shelf life and minimize degradation, thereby reducing waste and conserving the resources, energy, and emissions otherwise required. Innovations in packaging are possible, targeting the reduction of energy-intensive practices and volume of waste, while promoting recycling wherever feasible. Electrification is also a key decarbonization pillar for the food and beverage industry, particularly through electric and hybrid boilers, the adoption of industrial heat pumps, and the modularization of process heating, given the sector's prevalent low-temperature process-heating demands. Electrification can be paired with the use of low-carbon electricity for maximum emissions reductions.

Emerging technologies

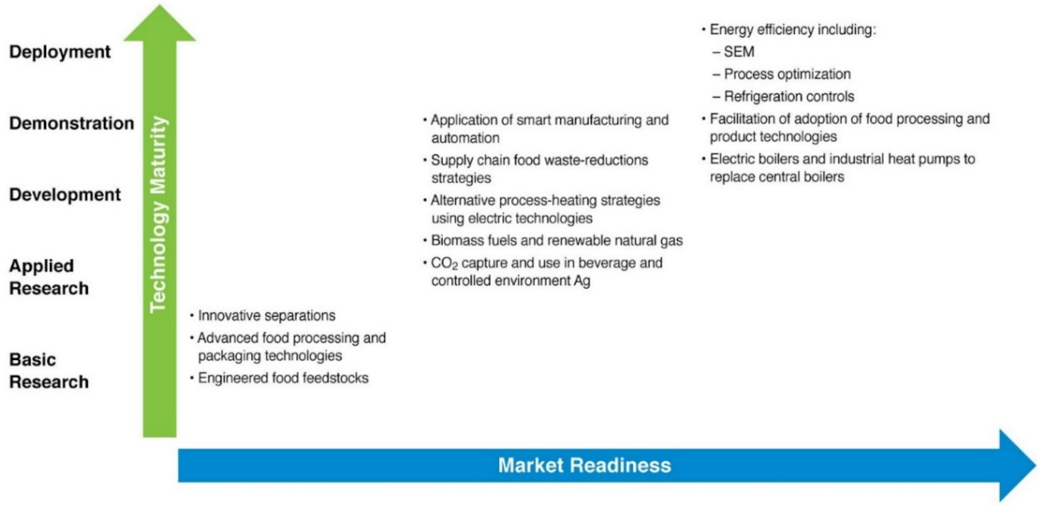
Exploring emerging technologies, smart manufacturing stands out as a promising paradigm, offering substantial efficiency improvements by refining processes and integrating thermal systems, thus refining refrigeration and optimizing supply chains. Innovations like solar drying are emerging as sustainable alternatives to conventional methods, emphasizing adoption of low-carbon fuel. Other LCFFES practices include a shift towards by-products and sustainable biomass to reduce reliance on high-carbon fuels. Although CCUS doesn't prominently feature as a major pillar due to the sector's diverse manufacturing needs and varying CO_2 sources, processing CO_2 for reuse is being explored to overcome associated challenges. In order to support later steps in roadmap development, it is important to gather information on both commercialized and emerging technologies, including TRL and anticipated costs (CAPEX and OPEX) in the context of the country of interest.

RD&D needs and the role of science, technology, and innovation

In the realm of food and beverage decarbonization, RD&D can help maximize the potential emissions reductions of different decarbonization pillars. For energy efficiency and material efficiency, RD&D can help discover and refine practices and technologies aimed at enhancing the shelf life and reducing degradation of products, mitigating energy-intensive packaging, and exploring resource-efficient alternatives that promote recycling. RD&D can also advance methodologies that reduce waste through the optimal reuse of waste streams and heightened supply chain visibility. Emphasis on exploring advanced and efficient technologies like alternate drying, advanced separations, and cryogenic separation, and the strategic investment in the development of smart manufacturing and automation, particularly in electrification, are vital for realizing accelerated decarbonization. The electrification and LCFFES pillar require intensive research to circumvent challenges related to capital, energy, and operating costs and to assess the impact of energy source modifications on product quality. Lastly, RD&D in the CCUS pillar could help reduce emissions from this pillar, focusing on the viability, safety, and quality implications of CCUS applications in the sector, especially with regard to carbon utilization.

One helpful schematic may be to map the commercialization stage of selected technologies against the market readiness in the given country. An example is given below of food and beverage decarbonization technologies in the United States (Figure 8).

Figure 8: Schematic for Assessing RD&D Needs and STI Preparedness of Food and Beverage Decarbonization Technologies



Source: U.S. DOE (2022).

Step 3: Scenario development

Scenarios should be developed based on the country's domestic food and beverage subsector characteristics. The information provided above should assist in developing scenarios that select the most appropriate or promising decarbonization pillars for the country's food and beverage subsector.

First, the importance of developing a realistic reference scenario should not be underestimated. The reference scenario should include credible projections about production over time and expected rates of decarbonization and energy efficiency improvement without additional policy intervention. Sometimes, reference scenarios are developed based on stated or announced policies.

At minimum, scenarios should include a reference scenario and a maximum ambition scenario (e.g., net zero). Ideally, a comprehensive roadmap would include a reference scenario, a net zero scenario, and one to two scenarios with moderate levels of decarbonization technology adoption. Table 11 below shows hypothetical scenarios for a food and beverage decarbonization roadmap. The scenarios should specify technology adoption timelines. This will allow comparison across scenarios in terms of total final energy use, CO_2 emissions, and costs, depending on available data.

Table 11: Hypothetical Scenario Development for a Food and Beverage Decarbonization Roadmap

Scenario	Description
Reference scenario	A slow improvement in energy efficiency and decarbonization of electricity, which is likely to happen with current business practices and current policies and regulations
Moderate scenario	Higher energy efficiency improvement with commercially available technologies, a higher rate of the shift to electrified technologies
Net zero scenario	Aggressive energy efficiency improvement using commercially available and emerging technologies, more aggressive fuel switching to lower carbon fuels and electricity, and the highest rate of electrification

Source: Authors' elaboration.

Step 4: Decarbonization pathways model

Based on the above-described scenario design, the next step is to assess the impact of each decarbonization pillar based on selected technologies. This entails forecasting the total final energy use and CO_2 emissions of the food and beverage subsector over the desired timeline under the different scenarios by applying varying levels of the decarbonization pillars. Below, the report summarizes expected impacts from each decarbonization pillar, though exact numbers will vary by the underlying data and selected scenarios.

Energy efficiency can significantly reduce CO_2 emissions from the food and beverage sector and is one of the key expected decarbonization pillars. By refining operational procedures, optimizing supply chains, and implementing advanced technologies, industries can minimize energy use, thereby reducing emissions while simultaneously enhancing productivity.

Material efficiency strategies have demonstrated substantial potential for material savings and emissions mitigation, also reducing product degradation, spoilage, and packaging waste. Improved handling, processing, and packaging can substantially decrease product waste and the consequent emissions, energy, and resources expended on unconsumed products. Progress in this pillar would necessitate comprehensive research and innovations in packaging technologies and product preservation methods.

Electrification is the other major pillar for food and beverage decarbonization. The incorporation of electric boilers, heat pumps, and the modularization of process heating can offer substantial advancements in decarbonizing heat processes. The adaptation and intensification of electrification in lower to medium-temperature applications are anticipated to result in significant emissions reductions, especially when combined with the proliferation of clean electricity.

LCFFES can offer some emissions reductions through the utilization of low-carbon fuels and by-products or sustainable biomass. The potential of CCUS is somewhat limited in the food and beverage industry due to the prevalence of small-scale, dispersed production plants and the lower concentration of point-source CO_2 emissions.

Step 5: Recommendations and action plan

The findings of the scenario analysis should inform final recommendations. Decarbonization of the food and beverage industry is capital intensive, and a clear action plan can overcome potential misallocation of investments. In addition to reporting results from all of the previous steps, the action plan should include recommendations for governments and manufacturers, categorized by near-, medium-, and long-term actions.

While the policy mix to support the transition toward net-zero carbon emissions in the food and beverage industry may vary across countries, the transition is unlikely to happen at the speed required without government intervention. Therefore, government recommendations are an important part of the roadmap. Below are examples of government-oriented recommendations for food and beverage decarbonization in the near and medium to long term.

Near term:

- Promote the development and adoption of electric processes such as ovens, fryers, electric boilers, and heat pumps.
- Provide tax incentives and other financial incentives for manufacturers to adopt specific decarbonization technologies.
- Allocate funds for strategies focusing on system optimization, integration of thermal systems, and refrigeration optimization.
- Focus on capacity building, especially for an installation and maintenance workforce for new electrified technologies, considering raising awareness of the various benefits of decarbonization, including climate resilience.

Medium to long term:

- Increase RD&D on waste heat recovery, automation, and potentially transformative efficiency technologies.
- Pursue material efficiency measures such as scaled-up recycling, alternative packaging, and packaging waste reduction.
- Engage government agencies and power system operators to facilitate improvements in transmission planning and funding to meet increased electricity needs and transmission infrastructure from electrification, considering climate resilience for the electricity sector as a key factor in promoting industrial decarbonization.

- Work with industry and utilities to explore new electricity rate structures for industrial users in order to lower the overall barrier of electricity cost to decarbonization efforts (e.g., time of use pricing).

5.2. Development of a Conceptual Framework for an Iron and Steel Decarbonization Roadmap

Step 1: Situational analysis

Situational analysis to develop a country's iron and steel decarbonization roadmap should entail an assessment of the country's steel production and trade situation (namely import and export levels for various steel products). It is important to characterize trade dynamics for countries that import a significant amount of steel for domestic consumption, as decarbonization policies that target traded products may be necessary (e.g., a carbon border adjustment mechanism). Domestically, it is critical to characterize the share of steel production from different production routes, such as BF-BOF vs. EAF. Steel production may be broken down by subnational jurisdictions, such as states or provinces. Overall, there should also be a baseline assessment of the technological and innovative capabilities in the country's iron and steel subsector.

It is also important to consider the vulnerability of the country's iron and steel facilities to climate change. Depending on the energy sources used and the location of each facility, future climate-related events may disrupt energy supply chains, affect energy costs, and overall play a key role in the viability of different decarbonization pathways.

Step 2: Technology options

Commercialized technologies

In developing a roadmap for the decarbonization of the iron and steel sector, a multifaceted approach that includes both commercialized and emerging technologies is necessary. As described earlier in this report, energy efficiency technologies like waste heat recovery and coke dry quenching (CDQ) are commercially ready and offer multiple benefits, including reduced energy costs and improved productivity. Integrating smart manufacturing and predictive maintenance can further enhance energy management in production processes. Material efficiency is also important and can be implemented in the near term, with strategies encompassing optimized design for reduced material use and enhanced recycling and promoting the usage of scrap-based EAF production. In general, a key technology for decarbonization of the iron and steel sector for any country is electrification, namely increasing the share of EAF production over the BF-BOF route, especially in tandem with low-carbon electricity.

Emerging technologies

Another key technology is green hydrogen-based DRI. Many countries are piloting this technology, including China. Currently, most direct reduction processes utilize H_2-rich gas from natural gas as the reducing agent, which emits significant amounts of CO_2. However, when DRI is paired with EAF to produce steel, it emits less CO_2 than the traditional BF-BOF route. The integration of green hydrogen, produced via renewable energy sources, into DRI production is an alternative pathway, allowing for even further reductions in CO_2 emissions under the LCFFES pillar.

The fifth decarbonization pillar, CCUS, is essential for various steel production routes. However, most technologies are currently at the pilot stage, facing challenges in cost reduction and operational efficiencies. Overcoming these challenges would enable the utilization of captured CO_2 for multiple applications or its permanent storage underground. Prioritizing these technological domains while addressing their respective challenges and potential will provide a comprehensive pathway to decarbonize the iron and steel industry effectively.

To support later steps in roadmap development, information should be gathered on both commercialized and emerging technologies, including TRL and anticipated costs (CAPEX and OPEX) in the context of the country of interest. For the iron and steel sector, it is essential to know the availability and cost of scrap for domestic production and the potential for hydrogen acquisition in the country, given the importance of these technologies for iron and steel decarbonization overall.

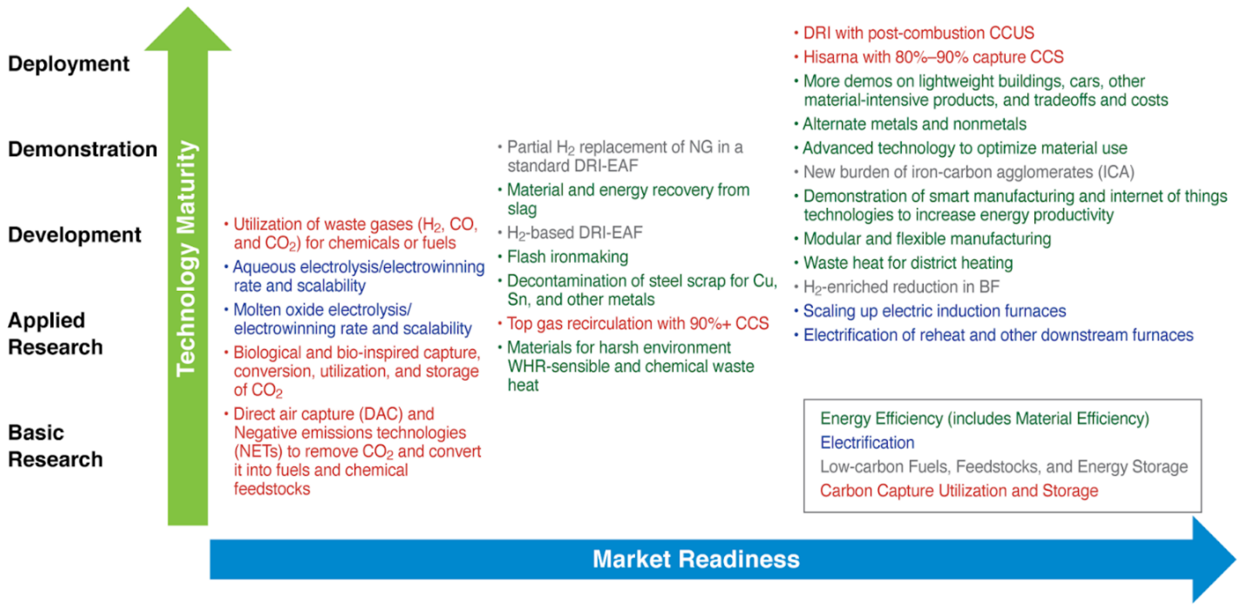
RD&D needs and the role of science, technology, and innovation

Given the importance of emerging technologies for the decarbonization of the iron and steel subsector, RD&D is also an important part of a decarbonization roadmap. RD&D can facilitate the adoption of lower-carbon fuels like natural gas, biomass, and ultimately, hydrogen, by charting feasible timelines and exploring their incorporation in existing facilities in a way that is tailored to the local context. Furthermore, it can navigate through the challenges and potential in the electrification of production processes, such as corrosion issues, high-temperature requirements, and feasibility of technology scaling in various steel production environments. This includes refining furnace designs, optimizing resistance heating, and identifying solutions to meet higher demands for electricity. Moreover, it can assist in examining the viability, availability, and lifecycle impacts of localized biomass resources and help optimize agricultural waste preparation for use in blast furnaces.

For nascent technologies like the electrolysis of iron ore, RD&D can address fundamental questions related to energy footprints, commercial scalability, and the development of cost-effective, no-carbon inert anodes resilient to high-temperature conditions. Additionally, RD&D can explore economic dimensions, focusing on the technology costs and benefits of byproducts from processes like electrolysis. Furthermore, for CCUS technologies, RD&D can assist in overcoming challenges related to cost reduction, operational efficiency improvement, infrastructure development, and exploring technologies with substantial techno-economic potential. By addressing these multifaceted aspects, RD&D can substantially contribute to the successful implementation of decarbonization strategies in the iron and steel sector.

One helpful schematic may be to map the commercialization stage of selected technologies against the market readiness in the given country. Figure 9 describes iron and steel decarbonization technologies in the United States.

Figure 9: Schematic for Assessing RD&D Needs and STI Preparedness of Iron and Steel Decarbonization Technologies



Source: U.S. DOE (2022).

Step 3: Scenario development

Scenarios should be developed based on the characteristics of a country's domestic iron and steel industry. This information should assist in developing scenarios that select the most appropriate or promising decarbonization pillars for the country's iron and steel industry.

First, the importance of developing a realistic reference scenario should not be underestimated. The reference scenario should include credible projections about production over time and expected rates of decarbonization and energy efficiency improvement without additional policy intervention. Sometimes, reference scenarios are developed based on stated or announced policies.

At minimum, scenarios should include a reference scenario and a maximum ambition scenario (e.g., net zero). Ideally, a comprehensive roadmap would include a reference scenario, a net zero scenario, and one to two scenarios with moderate levels of decarbonization technology adoption. Table 12 shows hypothetical scenarios for an iron and steel decarbonization roadmap. The scenarios should clearly specify technology adoption timelines. This will allow comparison across scenarios in terms of total final energy use, CO_2 emissions, and costs, depending on available data.

Table 12: Hypothetical Scenario Development for an Iron and Steel Decarbonization Roadmap

Scenario	Description
Reference scenario	A slow improvement in energy efficiency and fuel switching and slow adoption of CCUS technologies, which is likely to happen with current business practices and current policies and regulations
Moderate scenario	Higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower carbon fuels and switching to scrap-based EAF steelmaking, and a small adoption of transformative technologies such as H_2 DRI-EAF and CCUS.
Net zero scenario	Aggressive energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower carbon fuels, and the highest rate of the shift to scrap-based EAF steelmaking and a moderate adoption of H_2 DRI-EAF steelmaking and CCUS.

Source: Authors' elaboration.

Step 4: Decarbonization pathways model

Based on the scenario design laid out in Table 12, the next step is to assess the impact of each decarbonization pillar based on selected technologies. This entails forecasting the total final energy use and CO_2 emissions of the steel industry over the desired timeline under the different scenarios by applying varying levels of the decarbonization pillars. Below, the report summarizes expected impacts from each decarbonization pillar, though exact numbers will vary by the underlying data and selected scenarios.

Investments in energy-efficient technologies can significantly reduce energy consumption and related emissions in the iron and steel industry. Implementation of commercialized energy efficiency measures, despite varying capital requirements, can lead to cost savings, improved productivity, enhanced product quality, and ensured environmental compliance, thereby contributing to overall emission reductions.

Material efficiency strategies have demonstrated substantial potential for material savings and emissions mitigation, notably in steel utilized for buildings and vehicles. The implementation of such strategies can significantly curtail steel demand, thereby reducing the energy consumption and emissions associated with steel production. Material efficiency impacts will also be closely tied to projected steel demand in the given country.

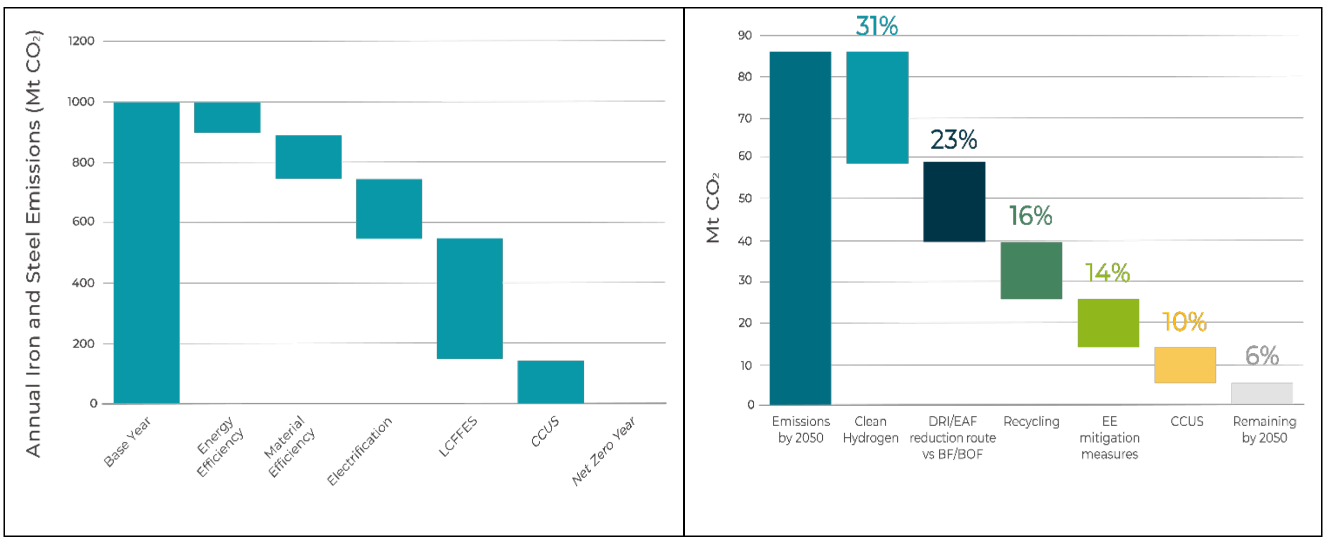
Shifting to lower carbon fuels like electricity, sustainable biomass, and hydrogen can substantially decrease coal and coke consumption in the steel industry, leading to lower CO_2 emissions. This shift becomes crucial as EAF steel production increases. The power sector's CO_2 emissions intensity becomes pivotal in the steel industry's overall CO_2

intensity, emphasizing the need for a parallel decarbonization of the power sector. Scenarios should take projected grid decarbonization into account. Green hydrogen for DRI is also an important part of the LCFFES and electrification pillars. Increased adoption of hydrogen as a reducing agent and fuel can significantly reduce the sector's carbon footprint.

Finally, CCUS technologies can reduce emissions in steelmaking processes by capturing up to 95 percent of CO_2 emissions. However, practical implementation in steel plants faces challenges due to varied emission sources, plant structures, and leakages during capture. Scenarios should consider different potential CCUS pathways to assess the potential of CCUS technologies in reducing emissions in the iron and steel sector.

An illustrative example of how to present results compared with the reference scenario for each decarbonization pillar is presented in Figure 10 below. Note that the numbers are purely hypothetical.

Figure 10: Waterfall Schematic for Presenting Emissions Impacts of Each Decarbonization Pillar



Note: For the left panel, values are just for illustrative purposes.

Source: Left panel: authors' elaboration, and right panel: Gischler et al. (2023)

Step 5: Recommendations and action plan

The findings of the scenario analysis should inform the final recommendations. Decarbonization of the iron and steel industry is capital intensive, and a clear action plan can overcome potential misallocation of investments. In addition to reporting results from all the previous steps, the action plan should include recommendations for governments and steel manufacturers, categorized by near-, medium-, and long-term actions (e.g., 2030, 2040, and 2050, respectively).

While the policy mix to support the transition towards net-zero carbon emissions in the steel industry may vary across countries, the transition is unlikely to happen at the speed required without government intervention. Therefore, government recommendations are an important part of the roadmap. Below are examples of government-oriented recommendations for iron and steel decarbonization in the near- and medium- to long-term.

Near term:

- Discourage installation of new blast furnaces and seek domestic steel scrap resources that could replace the need for construction of new BFs
- Discourage the relining of BFs as much as possible and encourage installation of H_2-DRI or H_2-ready DRI plants to produce iron from iron ore
- Develop policies to promote near-term investment in energy efficiency and ultra-low emissions retrofits, such as incentives for energy efficiency investment, requirements for retrofit ready built, and sunset clauses to strengthen energy efficiency in the steel industry
- Encourage and support the development of steel recycling through dissemination of recycling technology, developing scrap recycling standards, and providing tax benefits and incentives for scrap collection and sorting to recycling facilities
- Develop a hydrogen metallurgical action plan that considers potential future climate-induced impacts and plans for climate resilience
- Establish CO_2 or GHG emission standards for key steel products, such as carbon intensity thresholds per unit of steel product
- Enhance technological development by subsidizing low-carbon steel production
- Expand or establish carbon pricing schemes such as emissions trading systems, supported by the implementation of emission accounting, reporting, and verification systems
- Build capacity for low-carbon iron and steelmaking technologies development and deployment, including supporting RD&D

Medium to long term:

- Provide incentives and financing support to relocate integrated steel mills to regions with rich renewable resources, considering climate resilience in new locations
- Provide policy support to phase out blast furnaces, including job training and replacement support, and incentives to local governments
- Create a market for low-emissions steel using mandates, regulations on carbon content, and programs like certification and product stewardship
- Develop and disseminate guidebooks and best-practice technologies

- Provide financial support for the building of pilot plants and demonstration of the implementation of innovative decarbonization technologies
- Piloting, testing, and validating industry-scale CCUS projects
- Establish and/or facilitate partnerships between government, industry, research institutes, and academia to foster research on low-carbon steel production technologies

5.3. Conceptual Framework for Cement Decarbonization Roadmap Development

Step 1: Situational analysis

Situational analysis to develop a country's cement decarbonization roadmap should entail an assessment of the country's cement production and trade situation. Trade data are generally less critical for the cement sector because most domestically produced cement is also consumed domestically due to the heavy weight of cement and concrete products impeding international trade relative to iron and steel. Production data should entail the volume of cement produced in the base year of the analysis, specifying the type of cement if known (e.g., Portland cement, blended cement, masonry cement). It may also be helpful to characterize end uses of cement and the use of cement by different kinds of concrete manufacturers in the country. Production data should also disaggregate clinker and cement so that the clinker-to-cement ratio, an important proxy for overall energy and carbon intensity, can be assessed. Overall, there should also be a baseline assessment of the technological and innovative capabilities in the country's cement subsector.

It is important to collect data on the types of energy and fuel used for cement production in the country as well as to know the basic production routes for cement in each country—for example wet or dry process, and whether cement plants use the best available technologies or not. In general, process emissions account for about 60 percent of total CO_2 emissions in the cement industry, but if more granular emissions data are available, then the share of process versus energy-related CO_2 emissions should be considered.

Based on these metrics and the availability of data in the country, energy and emissions can be estimated or summarized. A key metric is the CO_2 intensity of cement production in the country, which can be used to estimate overall CO_2 emissions from cement production in that country. Credible projections of future domestic demand, rates of grid decarbonization, changes in fuel mix, and energy efficiency improvement are also important. The data and estimates presented above are necessary for constructing a baseline against which to measure different decarbonization options.

It is also important to consider the climate vulnerability of the country's cement plants. Depending on the energy sources used and the location of each facility, future climate-related events may disrupt energy supply chains, affect energy costs, and overall play a key role in the viability of different decarbonization pathways.

Step 2: Technology options

Commercialized technologies

In developing a roadmap for the decarbonization of the cement sector, a multifaceted approach including both commercialized and emerging technologies is necessary. Decarbonizing the cement sector necessitates leveraging advanced, commercially available technologies to mitigate emissions from energy-intensive production processes. Waste heat recovery (WHR) power generation technology is prominent among such innovations, capitalizing on otherwise lost medium-temperature waste heat from kiln flue gases to generate electricity. Although this does not reduce the cement plant's electricity consumption, it optimally utilizes excess heat for on-site electricity generation or grid export. Additionally, a concerted shift from clinker to supplementary cementitious materials such as blast furnace slag and fly ash is paramount. This shift, coupled with transitioning to lower carbon-intensive fuels like natural gas and sustainable biomass, can substantially reduce the energy intensity and corresponding emissions per tonne of cement produced. These approaches are critical, especially considering that around 60 percent of the CO_2 emissions from the cement industry are attributed to process-related emissions from calcination, disconnected from energy use.

Emerging technologies

Emerging technologies focus primarily on addressing the substantial emissions originating from limestone calcination, a process intrinsic to cement production. CCUS technologies are critical for cement decarbonization. Oxy-fuel technology, which replaces air with oxygen in cement kilns, is one potential CCUS technology, resulting in a purer CO_2 exhaust stream, making capture more straightforward. This technology, along with other post-combustion mechanisms, is appropriate for both new kilns and retrofit applications, and it capitalizes on the abundant low and medium-temperature waste heat available in cement plants. Captured CO_2 has diverse applications, including use in concrete curing processes, production of construction materials, cultivation of algae biomass, and synthesis of chemicals and fuels. These innovative technologies, though still in their infancy, hold the promise of substantially decreasing the carbon footprint of the cement industry by addressing process emissions.

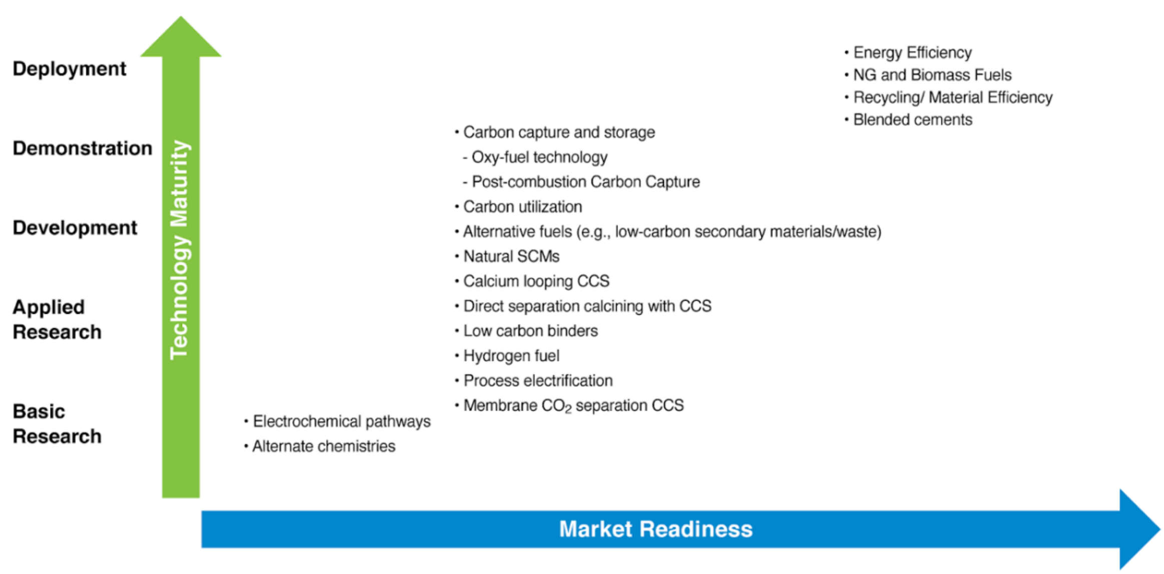
To support later steps in roadmap development, it is important to gather information on both commercialized and emerging technologies, including TRL and anticipated costs (CAPEX and OPEX) in the context of the country of interest. For the cement sector, it is particularly key to understand the geologic aspects of carbon capture and storage, given the importance of this pillar to cement decarbonization.

RD&D needs and the role of science, technology, and innovation

RD&D needs for cement decarbonization span a broad range of technological, economic, and regulatory avenues. Advanced grinding systems and energy efficiency technologies are in the research phase, necessitating further investigation into optimizing processes like preheating and clinker cooling. Innovative heat exchange concepts and simulation models can aid in optimizing preheater designs and management. Economic challenges can be addressed by demonstrating the economic benefits of energy efficiency investments and cataloging best practices in energy management systems for cement operations. RD&D is critical to explore the use of supplementary cementitious materials (SCMs) and alternative binding materials, focusing on their safety, technical performance, and economic feasibility under varied conditions. For the cement sector, it is particularly key to understand the availability and cost of SCMs in the domestic market, given the importance of clinker substitution for cement decarbonization overall. To address infrastructural challenges, RD&D could map natural gas and other alternative fuels' distribution and optimize kiln operations for fuel switching. Studies on the economical scale-up of emerging technologies like certain alternative fuels, electric furnace technology, hydrogen utilization, and CCUS technology are crucial.

One helpful schematic may be to map the commercialization stage of selected technologies against the market readiness in the given country. An example is given below of cement decarbonization technologies in the United States (Figure 11).

Figure 11: Schematic for Assessing STI Preparedness of Cement-Specific Decarbonization Technologies



Source: U.S. DOE (2022).

Step 3: Scenario development

Scenarios should be developed based on the country's domestic cement industry characteristics. The above information should assist in developing scenarios that select the most appropriate or promising decarbonization pillars for the country's cement industry.

First, the importance of developing a realistic reference scenario should not be underestimated. The reference scenario should include credible projections about production over time and expected rates of decarbonization and energy efficiency improvement without additional policy intervention. Sometimes, reference scenarios are developed based on stated or announced policies.

At minimum, scenarios should include a reference scenario and a maximum ambition scenario (e.g., net zero). Ideally, a comprehensive roadmap would include a reference scenario, a net zero scenario, and one to two scenarios with moderate levels of decarbonization technology adoption. Table 13 shows hypothetical scenarios for a cement decarbonization roadmap. The scenarios should clearly specify technology adoption timelines. This will allow comparison across scenarios in terms of total final energy use, CO_2 emissions, and costs, depending on available data.

Table 13: Hypothetical Scenarios for a Cement Decarbonization Roadmap

Scenario	Description
Reference scenario	Slow improvement in energy efficiency and slow adoption of commercially available CCUS technologies, which is likely to happen with current business practices and current policies and regulations
Moderate scenario	Higher energy efficiency improvement, more fuel switching to lower carbon fuels, and a higher rate of clinker substitution compared to the Reference Scenario; low adoption of commercially available CCUS technologies.
Net-zero scenario	Significantly higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower carbon fuels, and a higher rate of clinker substitution similar to today's world best practices; high adoption of CCUS technologies

Source: Authors' elaboration.

Step 4: Decarbonization Pathways Model

Based on the above scenario design, the next step is to assess the impact of each decarbonization pillar based on selected technologies. Analysis will entail projection for cement and clinker production in the country over the desired timeframe, based on assumptions from Step 1. The clinker-to-cement ratio—a key assumption—may be held constant in some scenarios, or it may decrease in more aggressive decarbonization scenarios. Analysis also entails forecasting the total final energy use and CO_2 emissions of the cement industry over the desired timeline under the different scenarios by applying varying levels of the decarbonization pillars. Below, the report summarizes expected impacts from each decarbonization pillar, though exact numbers will vary by the underlying data and selected scenarios.

Given the large share of process emissions in overall emissions from cement production, energy efficiency may play a relatively minor role in cement decarbonization. There are many commercially available energy efficiency technologies for the cement industry. There are also a number of commercially available measures for improving material efficiency through improved design and utilization of concrete.

Clinker production is intensive in both fuel and electricity consumption. Thus, substituting clinker with alternative materials like fly ash and blast furnace slag can greatly reduce energy intensity and emissions per tonne of cement produced. In the long run, enhancing the clinker-to-cement ratio and utilizing supplementary cementitious materials can significantly mitigate emissions, presenting a key lever for LCFFES decarbonization in addition to fuel switching. Different raw materials and binding agents can also offer new avenues for emission reduction, fostering innovation in cement production methodologies.

Finally, CCUS technologies can result in substantial emissions reduction for the cement sector. With a wide range of potential technologies, the CCUS pillar is particularly important for the cement sector given its emissions profile.

Step 5: Recommendations and action plan

The findings of the scenario analysis should inform final recommendations. Decarbonization of the cement is capital intensive, and a clear action plan can overcome potential misallocation of investments. The action plan should include recommendations for governments and cement and concrete manufacturers, categorized by near-, medium-, and long-term actions.

While the policy mix to support the transition to net-zero carbon emissions in the steel industry may vary across countries, the transition is unlikely to happen at the speed required without government intervention. Therefore, government recommendations are an important part of the roadmap. Below are examples of government-oriented recommendations for cement decarbonization in the near- and medium- to long-term.

Near term:

- Set minimum energy performance standards equal to best available technology energy intensity for any new cement plants
- For existing cement plants, set targets for electricity intensity and fuel intensity reduction
- Use financial incentives to stimulate investment in energy efficiency technologies
- Develop new standards and codes for increased use of blended cement and SCMs in cement and concrete

- Work with industry, universities and other third-party organizations to fund R&D projects for the use of blended cement in a wide range of applications

Medium to long term:

- Implement or enhance carbon pricing schemes to encourage the use of lower carbon fuel.
- Work with the cement and concrete industry to increase R&D investment for pilot and demonstration of CCUS technologies in the cement and concrete industries.
- Set new standards and codes for the use of products produced by carbon utilization technologies, considering how the need to adapt to climate change may affect building and construction planning.

6. Discussion of Industrial Decarbonization Policies in Latin America and the Caribbean

LAC countries have taken various policy approaches to industrial decarbonization. In Table 14, the report reviews key industrial decarbonization policies for nine LAC countries. The countries are ordered in the table by level of industrial energy use. There are observable disparities in the approach, focus, and comprehensiveness of the implemented policies across nine LAC countries. This analysis identifies current policies relating to the five pillars of industrial decarbonization.

While the review is not comprehensive, there are some general takeaways that can be gleaned, especially when paired with the information in the rest of this report. The most evident takeaway is that the current industrial decarbonization policies in LAC countries are limited in their sectoral focus. Most initiatives focus predominantly on economy-wide initiatives and, when they have a sector focus, it tends to be on the power sector or the general energy sector. When countries do have a policy directed toward industry, it seems to be aimed at all industry, not tailored to specific sectors within industry.

In addition, the policies addressed mainly cover energy efficiency and LCFFES, with other pillars like electrification, material efficiency, and CCUS lacking specific relevant policies, indicating a lack of comprehensive strategies across the industrial decarbonization spectrum. Most LAC countries lack integrated and harmonized policies across sectors and pillars, resulting in a lack of synergy in decarbonization initiatives. Additionally, there is a notable absence of adequate incentive structures to stimulate widespread and comprehensive industrial decarbonization across all pillars and sectors. The untapped potential of emerging technologies such as green hydrogen and carbon capture is evident, with minimal policies fostering innovation, planning, and development in these areas.

It is crucial to develop comprehensive and coordinated industrial decarbonization strategies encompassing all five pillars and harmonizing policies across different sectors to ensure the cohesive development of initiatives. A sectoral expansion of policies is required, with specific initiatives targeting overlooked sectors and promoting the integration of industrial decarbonization measures.

For more commercialized industrial decarbonization technologies, countries should formulate conducive policies, regulatory frameworks, and incentives to promote investment and adoption. To realize the potential of emerging technologies, fostering innovation through the establishment of innovation hubs, public-private partnerships, and international collaborations for technology transfer is essential.

In terms of broad support for industrial decarbonization policies, countries will need to establish stringent monitoring and compliance frameworks for effective implementation. Finally, elevating public awareness and knowledge regarding industrial decarbonization through campaigns, educational programs, and training is pivotal for cultivating the requisite skills and knowledge for transitioning to decarbonized industries. A holistic approach encompassing comprehensive strategies, expanded focus, enhanced policies, incentivization, innovation, robust compliance, and public awareness is essential to fill the observed gaps and achieve substantial industrial decarbonization in LAC countries.

Table 14: Summary of Key Industrial Decarbonization Policies in Selected Latin American and Caribbean Countries

Country	Policy name	Policy description	Target sectors	Relevant decarbonization pillars
Brazil	Nationally Determined Contribution (2022)	Net zero by 2050	Economy-wide	All
	P+B Industrial Development Plan (2016)	Focuses on enhancing productivity of industrial SMEs with an emphasis on energy efficiency, digitalization, and connectivity; allocated budgets for pilot programs and full-scale implementation	Industrial Small and Medium Enterprises (SMEs)	Energy efficiency
	Energy Efficiency Act (2001)	Mandates minimum energy performance standards (MEPS) for various energy-consuming machines and equipment	Industry	Energy efficiency, electrification
	PROCEL Industry (1985, with multiple updates)	A program aimed at promoting the adoption of efficient best practices in the industrial sector and SMEs by optimizing production systems and drives; includes capacity building for industry technicians, implementation of energy efficiency pilot projects, creation of energy efficiency indicators, and development of computational tools and databases	Industrial Small and Medium Enterprises (SMEs)	Energy efficiency
Mexico	Nationally Determined Contribution (2022)	Reduce emissions by 40% (conditional) by 2030 and 50% by 2050 relative to 2000 levels	Economy-wide	All
	General Law of Climate Change (2012, amended in 2020 and 2022)	Defines several targets for GHG mitigation and renewable energy development, including generating at least 35% of power with clean technologies by 2024; creates a fund to channel financial resources to energy efficiency projects and renewable energy development; revised to support implementation of the Mexican Emission Trading System	Economy-wide	LCFFES, energy efficiency

Country	Policy name	Policy description	Target sectors	Relevant decarbonization pillars
Argentina	Nationally Determined Contribution (2022)	Net zero by 2050	Economy-wide	All
	Argentina Efficient Award (2018)	Recognizes companies and organizations in Argentina that have implemented and certified an Energy Management System	Industry, commercial, service sectors	Energy efficiency
	Law 27.191 Program to Promote the Use of Renewable Energy (2015)	Provides regulatory and financial framework to foster the production of renewable energy; creates a trust fund for renewables and other fiscal incentives	Power sector	LCFFES
	National Program for Rational and Efficient Use of Energy (2007)	Seeks to support the efficient use of energy in various stages including production, transportation, distribution, storage, and consumption; aimed to decrease electricity consumption by 6% and achieve energy savings of 1500 MW by 2016	Industrial, commercial, buildings sectors	Energy efficiency
Colombia	Nationally Determined Contribution (2022)	Net zero by 2050	Economy-wide	All
	Law 1715 (2014)	Provides financial incentives like VAT exemption and tax reductions to energy efficiency and non-conventional energy projects.	Industry, transport	Energy efficiency, LCFFES
	Ten milestones in 2021 - Hydrogen roadmap	Aims for sustainable reactivation of Colombia through 1) Energy Transition, 2) Energy security, and 3) Mining diversification and formalization. Includes the development of a hydrogen roadmap.	Economy-wide	LCFFES
	Energy Plan 2050 (2016)	Targets the diversification of the energy mix and the inclusion of renewable energy sources like wind power plants, solar, geothermal, and biomass to ensure a reliable energy supply by 2028.	Energy sector	LCFFES

Country	Policy name	Policy description	Target sectors	Relevant decarbonization pillars
	PROURE 2017-2022	Adopts an action plan for 2017-2022 to increase energy efficiency and rational energy use; establishes renewable energy targets, energy efficiency indicative goals and objectives, and base sector actions and strategies to the industry and transport sectors	Industry, transport	Energy efficiency, LCFFES
Chile	Nationally Determined Contribution (2022)	Net zero by 2050	Economy-wide	All
	Green Hydrogen Incubator (2021)	Supports early, competitive projects for end-use hydrogen technologies including transport, industry, power generation, and logistics; offers support in pilot design and co-financing	Transport, industry, power generation, logistics	LCFFES
	Decarbonization Plan for the Electrical System (2019)	Details the phase-out plan for coal from the electrical system by 2040	Power sector	LCFFES
	Energy Management Systems Programme for Industry (2015)	Supports the implementation and certification of energy management systems in industrial installations	Industry	Energy efficiency
Peru	Nationally Determined Contribution (2022)	Net zero by 2050	Economy-wide	All
	Measures for the Efficient Use of Energy (2017)	Requires public entities/companies to replace or purchase the most efficient energy equipment available on the market; applies to a range of equipment including electric heaters, boilers, refrigeration appliances, motors, etc.	Industry	Energy efficiency, electrification
	National Energy Plan for 2010-2040 (2010)	Establishes a national legal framework focusing on the protection of private investment, promotion of energy markets, energy efficiency, and development of renewable energies; seeks to	Energy sector	LCFFES, energy efficiency

Country	Policy name	Policy description	Target sectors	Relevant decarbonization pillars
		promote the use of clean energies and technologies with low emissions		
Dominican Republic	Nationally Determined Contribution (2022)	Net zero by 2050	Economy-wide	All
	Law 57-07 on Incentives for Development of Renewable Energy Sources and its Special Regimes (2007)	Aims to diversify energy sources, reduce fossil fuel dependence, stimulate private investment in renewable energy, and contribute to national energy goals; offers various incentives like tax exemptions, tax reductions, and favorable financing to renewable energy projects	Power sector	LCFFES
Costa Rica	Nationally Determined Contribution (2022)	Net zero by 2050	Economy-wide	All
	National Decarbonization Plan (2019)	Sets out ten sectoral focus areas with policy packages for decarbonization up to 2050; aims to transition to a completely renewable energy system, which will also support the transformation of the industrial sector; also aims to maximize efficiency of waste management	Economy-wide	LCFFES, material efficiency
Uruguay	Nationally Determined Contribution (2022)	Net carbon negative by 2030	Economy-wide	All
	Energy Efficiency Obligation (1998, updated in 2016)	Aims for incremental energy savings of 0.94% per year compared to total fuel consumption; covers electricity, natural gas, and all other "burnable fuels" across all sectors, with obligated parties being energy utility companies	Power sector	Energy efficiency

Sources: IEA Policies Database, Climate Action Tracker; ClimateWatchData, IDB (2020).

7. Conclusions

Industrial decarbonization is indispensable for the LAC region due to its vulnerability to climate change impacts, despite its minimal contribution to global emissions. In addition, industrial decarbonization can drive innovation, with the potential to encourage industrial modernization, boost productivity, and enhance competitiveness. This report has synthesized comprehensive insights and conceptual frameworks that can drive industrial decarbonization strategies across the key sectors of iron and steel, cement, and food and beverages.

Based on a country-level analysis of key energy-consuming and emitting industrial subsectors in the LAC region, this report identified the iron and steel sector, the cement sector, and the food and beverage sector as critical industrial subsectors in the LAC region both economically and in terms of energy use and emissions. It then reviewed existing decarbonization roadmaps from around the world for the iron and steel, cement, and food and beverage industries. The review identified a comprehensive collection of decarbonization technologies for each subsector, with the technologies organized into five decarbonization pillars.

The key contribution of the report is the development of a conceptual framework for industrial decarbonization roadmaps that can be applied at the sector level. The conceptual framework, grounded in extensive research and a literature review, offers a modular and universally applicable approach, enabling LAC countries to develop tailored, structured, and effective decarbonization roadmaps. These are particularly crucial for the identified sectors, which are the linchpins for industrial decarbonization in the region. In addition, the framework must be flexible in recognition of varying data availability and quality across the LAC region, given that data underpins the roadmap framework.

The identified technologies within the five pillars of industrial decarbonization are integral to not only reducing CO_2 emissions but also augmenting climate resilience. The conceptual framework entails situational analysis and technology options assessment that consider the climate vulnerability of the given subsector and country and how decarbonization approaches would intersect with future climate impacts. The practical and adaptable nature of the conceptual framework ensures that the strategies and recommendations developed are aligned with the specific socio-economic and environmental contexts of countries in the LAC region.

Finally, the report underscores the significant disparities in existing policies across the LAC countries studied and offers recommendations, aiming to fill the policy gaps and promote a more integrated and comprehensive approach to industrial decarbonization. This integrative approach is paramount for the LAC region to foster sustainable development, enhance global competitiveness, and protect its diverse ecosystems and communities from the adverse impacts of climate change.

References

Agora Industry, and Wuppertal Institute. 2023. 15 Insights on the Global Steel Transformation.

ArcelorMittal. 2021. Climate Action Report 2.

Bhadbhade, N., and M. K. Patel. 2020. Analysis of Energy Efficiency Improvement and Carbon Dioxide Abatement Potentials for Swiss Food and Beverage Sector. *Resources, Conservation and Recycling 161* (October): 104967.

Brush, A., E. Masanet, and E. Worrell. 2011. Energy Efficiency Improvement and Cost Saving Opportunities for the Dairy Processing Industry: An ENERGY STAR? Guide for Energy and Plant Managers. LBNL--6261E, 1171534.

Cameron, I., A. Lopez, and A. Yule. 2021. Decarbonisation Road Map for the European Food and Drink Manufacturing Sector. *FoodDrink Europe*.

European Investment Bank. 2023. Climate risks for Latin America and the Caribbean: are banks ready for the green transition? ISBN: 978-92-861-5571-0

Fan, Z., and S. J. Friedmann. 2021. Low-Carbon Production of Iron and Steel: Technology Options, Economic Assessment, and Policy. *Joule* 5 (4): 829–62.

Galitsky, C., N. Martin, E. Worrell, and B. Lehman. 2003a. Cost Saving Opportunities for Breweries.

Galitsky, C., E. Worrell, and M. Ruth. 2003b. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry: An ENERGY STAR Guide for Energy and Plant Managers. LBNL--52307, 816536.

Gischler, C., et al. 2023. Acelerando la descarbonización de la industria pesada en América Latina y el Caribe

Hall, W., S. Kumar, S. Kashyap, and S. Dayal. 2022. Achieving Green Steel: Roadmap to a Net Zero Steel Sector in India. The Energy and Resources Institute (TERI).

Hasanbeigi, A., L. A. Kirshbaum, and B. Collison. 2023. Industrial Electrification in U.S. States. Global Efficiency Intelligence.

Hasanbeigi, Ali, Hongyou Lu, and Nan Zhou. 2023. "Net-Zero Roadmap for China's Steel Industry." Global Efficiency Intelligence.

Hasanbeigi, A., L. Price, M. Arens, and F. Inst. for Systems and Innovation Research (ISI), Karlsruhe (Germany). 2013. Emerging Energy-Efficiency and Carbon Dioxide Emissions-Reduction Technologies for the Iron and Steel Industry. LBNL--6106E, 1172118.

Hasanbeigi, A., and C. Springer. 2019. Deep Decarbonization Roadmap For The Cement And Concrete Industries In California. *Global Efficiency Intelligence*.

IDB (Inter-American Development Bank). 2020. Costa Rica Advances with Its National Decarbonization Plan with IDB Support. Washington, DC: IDB.

IDB. 2023. Unlocking Green and Just Hydrogen in Latin America and the Caribbean. Washington, DC: IDB.

IEA (International Energy Agency). 2022. World Energy Statistics. Paris: IEA.

IEA. 2018. Technology Roadmap - Low-Carbon Transition in the Cement Industry. Paris: IEA.

IEA. 2020. Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking. Paris: IEA.

IEA. 2010. The Energy Technology Systems Analysis Program (ETSAP)- Technology Brief: Iron and Steel. Paris: IEA.

IEA/ World Business Council for Sustainable Development. 2018. Technology Roadmap Low-Carbon Transition in the Cement Industry.

IEA. 2010. The Energy Technology Systems Analysis Program (ETSAP)- Technology Brief: Iron and Steel. Paris: IEA.

Jamison, K., C. Kramer, S. Brueske, and A. Fisher. 2015. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing. Washington, DC: U.S. Department of Energy.

Karlsson, I, A. Toktarova, J. Rootzén, and M. Odenberger. 2020. Technical Roadmap: Cement Industry. Mistra Carbon Exit.

Kermeli, K., and E. Worrell. 2018. Energy Efficiency and Cost Saving Opportunities for Breakfast Cereal Production. Washington, DC: U.S. Environmental Protection Agency.

Masanet, E., E. Masanet, E. Worrell, W. Graus, and C. Galitsky. 2008. Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry. An ENERGY STAR Guide for Energy and Plant Managers. LBNL-59289-Revision, 927884.

McKinsey and Company. 2020. Decarbonization Challenge for Steel.

Mission Possible Partnership. 2022. Making Net-Zero Steel Possible: An Industry-Backed, 1.5C-Aligned Transition Strategy. Energy Transitions Commission.

Rocky Mountain Institute, and China Cement Association. 2022. Toward Net Zero: Decarbonization Roadmap for China's Cement Industry.

Sovacool, B. K., M. Bazilian, S. Griffiths, J. Kim, A. Foley, and D. Rooney. 2021. Decarbonizing the Food and Beverages Industry: A Critical and Systematic Review of Developments, Sociotechnical Systems and Policy Options. *Renewable and Sustainable Energy Reviews* 143 (June): 110856.

Toktarova, A., I. Karlsson, J. Rootzén, and M. Odenberger. 2020. Technical Roadmap: Steel Industry. Mistra Carbon Exit.

UK Concrete. 2020. UK Concrete and Cement Industry Roadmap to Beyond Net Zero. Mineral Products Association.

U.S. Department of Energy. 2022. Industrial Decarbonization Roadmap. Washington, DC: Department of Energy.

U.S. Department of Energy. 2023. Pathways to Commercial Liftoff: Low-Carbon Cement. Washington, DC: Department of Energy.

Worrell, E., P. Blinde, M. Neelis, and E. Blomen. 2010. Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry - An ENERGY STAR® Guide for Energy and Plant Managers. Washington, DC: U.S. Environmental Protection Agency.

Yadav, D., A. Guhan, and T. Biswas. 2021. Greening Steel: Moving to Clean Steelmaking Using Hydrogen and Renewable Energy. Council on Energy, Environment, and Water.

Yuan, C., and D. Riley. 2023. Playbook for Decarbonizing Process Heat in the Food and Beverage Sector: Heat Pumps and Electric Boilers as Enabling Technologies. Renewable Thermal Collaborative.