Mexico's Strategic Position in Global Steel Decarbonization: A Comparative Analysis of Technology Pathways, Policy Frameworks, and Regional Integration Opportunities

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Abstract

The steel industry accounts for 7-9% of global CO_2 emissions, making its decarbonization critical to achieving international climate targets. This paper examines Mexico's strategic position in the global transition toward low-carbon steel production, analyzing technology pathways, policy frameworks, and competitive advantages relative to major steel-producing nations. With 13.8 million tonnes of annual crude steel production (15th globally), Mexico occupies a unique position: integrated into North American supply chains through USMCA, possessing abundant natural gas resources, benefiting from proximity to US green steel demand, yet facing challenges of limited public financing, aging infrastructure, and complex multi-level governance. Through comparative analysis of decarbonization strategies across twelve major steel-producing countries and detailed examination of Mexican initiatives including Ternium's hydrogen pilots, Altos Hornos de México transformation challenges, and emerging EAF capacity, this study demonstrates that Mexico can leverage its geographic and trade advantages to become a regional leader in near-net-zero steel production. However, realization of this potential requires coordinated federal policy action, dedicated financing mechanisms (potentially leveraging USMCA climate provisions), strategic technology partnerships with the United States and Canada, and effective coordination between federal and state governments. The analysis identifies critical success factors, policy gaps, and actionable recommendations for positioning Mexico competitively in North America's green steel transition. This research contributes to the growing literature on industrial decarbonization in middle-income economies and provides a framework for leveraging regional trade integration in sectoral climate policy.

Keywords: Steel decarbonization, Mexico, USMCA, natural gas DRI, green hydrogen, North American integration, industrial policy, nearshoring, clean energy transition

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1 Introduction

1.1 Global Context: The Steel Decarbonization Imperative

The steel industry stands at a critical inflection point. As one of the foundational materials of modern civilization—essential to construction, transportation, machinery, and countless manufactured goods—steel production also represents one of the most significant industrial sources of greenhouse gas emissions. Global steel production reached 1,884.6 million tonnes in 2024 [1], with associated CO_2 emissions of approximately 2.6 billion tonnes, representing 7-9% of total global emissions [2].

The conventional integrated steelmaking route, based on blast furnace-basic oxygen furnace (BF-BOF) technology, produces approximately 2.0 tonnes of CO_2 per tonne of crude steel. This carbon intensity derives from the fundamental chemistry of ironmaking: the reduction of iron oxide using carbon-based reductants (primarily metallurgical coke), which inevitably generates CO_2 as a byproduct. With global steel demand projected to remain stable or grow modestly through 2050, achieving climate targets under the Paris Agreement requires fundamental transformation of steelmaking processes.

Multiple technology pathways are emerging globally: hydrogen-based direct reduction (H_2-DRI), carbon capture utilization and storage (CCUS) retrofitted to existing facilities, increased electric arc furnace (EAF) production using scrap, natural gas-based DRI with hydrogen blending, and potentially disruptive technologies such as molten oxide electrolysis. Each pathway presents distinct technical challenges, capital requirements, and regional applicability depending on resource availability, industrial structure, and policy frameworks.

1.2 Mexico's Position in Global Steel Production

Mexico ranks as the world's 15th largest steel producer with 13.8 million tonnes of crude steel production in 2024, representing approximately 0.7% of global production but 13% of North American capacity. The Mexican steel industry comprises both integrated BF-BOF facilities (approximately 45% of capacity) and electric arc furnace operations (55%), with major producers including:

- **Ternium México:** Largest integrated producer, facilities in Pesquería (Nuevo León) and Puebla. Owned by Techint Group (Argentina-Italy). Capacity 5.5 MT annually.
- **Altos Hornos de México (AHMSA):** Integrated facility in Monclova (Coahuila). State-influenced, facing financial challenges. Capacity 3.9 MT (operating below capacity).
- **ArcelorMittal México:** Integrated mill in Lázaro Cárdenas (Michoacán). Part of global group. Capacity 2.7 MT.
- **Deacero:** Major EAF producer, multiple facilities. Specializes in long products, wire. Capacity 2.1 MT.
- **Simec:** EAF producer owned by Grupo Simec. Multiple facilities across Mexico. Capacity 1.8 MT.

Mexico's steel sector is characterized by several distinctive features:

- **USMCA integration:** Deep trade linkages with United States and Canada, providing both market access and competitive pressures
- **Natural gas availability:** Abundant domestic production and pipeline access from US, enabling DRI technology deployment
- **Geographic advantage:** Proximity to largest green steel market (US automotive and construction)

- **Nearshoring momentum:** Re-localization of manufacturing from Asia creating growth opportunity
- **Dual challenges:** Aging infrastructure requiring modernization; financial constraints limiting transformation speed

1.3 Research Objectives and Contributions

This paper addresses three primary research questions:

1. What technology pathways are available for steel decarbonization, and which are most suitable for Mexican conditions given resource endowments, industrial structure, and North American integration?
2. How do Mexico's decarbonization strategies, policy frameworks, and industrial initiatives compare to approaches in other major steel-producing nations, particularly regional competitors?
3. What policy interventions, technological investments, and strategic partnerships would enable Mexico to achieve competitive positioning in North America's green steel transition while supporting industrial growth from nearshoring?

The research makes several contributions to academic and policy literature:

Empirical contribution: Comprehensive documentation of Mexican steel decarbonization context, including detailed analysis of Ternium's natural gas-to-hydrogen transition pathway, AHMSA's restructuring challenges, and EAF sector expansion dynamics—providing primary data on middle-income economy industrial transformation within regional trade bloc context.

Comparative analysis: Systematic comparison of steel decarbonization approaches across twelve major producing countries, with particular attention to Mexico's position relative to regional partners (USA, Canada) and peer middle-income producers (Turkey, India, Brazil).

Regional integration framework: Development of analytical framework for leveraging regional trade integration (USMCA) in sectoral decarbonization policy, examining how climate provisions in trade agreements can facilitate industrial transformation.

Policy recommendations: Actionable policy prescriptions grounded in international best practices and adapted to Mexican institutional context, including specific proposals for federal-state coordination, USMCA climate mechanism utilization, and public-private financing structures.

1.4 Paper Structure

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on steel decarbonization technologies and policy approaches, with emphasis on middle-income economy contexts and regional trade integration. Section 3 describes the methodology and data sources. Section 4 presents a comparative analysis of decarbonization strategies across major steel-producing nations. Section 5 examines Mexico's current position, including detailed analysis of major producers and existing initiatives. Section 6 discusses Mexico's unique competitive advantages and strategic opportunities within North American context. Section 7 identifies challenges and policy gaps. Section 8 presents policy recommendations and a strategic roadmap for action. Section 9 concludes with implications for research and practice.

2 Literature Review

2.1 Steel Decarbonization Technologies

The academic and technical literature identifies four primary pathways for steel sector decarbonization, each at different stages of technological maturity and commercial deployment [3, 4].

2.1.1 Hydrogen-Based Direct Reduction (H_2-DRI)

Direct reduction processes using hydrogen as the reductant represent the most widely discussed pathway for deep decarbonization of primary steel production. The fundamental chemistry replaces carbon-based reduction:

$$\mathrm{Fe_2O_3} + 3\mathrm{H_2} \rightarrow 2\mathrm{Fe} + 3\mathrm{H_2O} \tag{1}$$

compared to conventional carbon reduction:

$$\mathrm{Fe_2O_3} + 3\mathrm{CO} \rightarrow 2\mathrm{Fe} + 3\mathrm{CO_2} \tag{2}$$

Key technical challenges include hydrogen embrittlement of equipment and products, different reduction kinetics compared to carbon monoxide requiring process optimization, ore quality requirements (>67% Fe content, low gangue), and integration with intermittent renewable energy sources.

2.1.2 Carbon Capture, Utilization, and Storage (CCUS)

CCUS retrofitted to existing BF-BOF facilities offers an incremental pathway, particularly relevant for assets with significant remaining operational life. Multiple capture technologies are under development: post-combustion amine scrubbing, pre-combustion syngas shift, oxy-fuel combustion, and calcium looping.

The economics of CCUS for steel remain challenging. Capture costs range from $40-120 per tonne CO_2 depending on concentration and capture technology, with additional transport and storage costs. Energy penalties (15-30% additional energy requirement) reduce plant productivity.

2.1.3 Scrap-Based Electric Arc Furnace (EAF) Expansion

Increased steel production through EAF using scrap as feedstock offers immediate emissions reduction (0.4-0.5 tonnes CO_2 per tonne steel vs. 2.0 for BF-BOF) and leverages circular economy principles. Global EAF capacity represents approximately 30% of total steel production, with significant growth potential.

However, EAF expansion faces constraints: scrap availability growing slower than steel demand, quality limitations from tramp elements (copper, tin, nickel), inability to produce certain high-quality steel grades from 100% scrap, and regional disparities in scrap generation.

2.1.4 Breakthrough and Disruptive Technologies

Several early-stage technologies promise radical transformation if successfully commercialized:

Molten Oxide Electrolysis (MOE): Boston Metal's technology dissolves iron ore in molten oxide electrolyte, using electricity to separate iron and oxygen with zero direct CO_2 emissions. Technology readiness level (TRL) 5-6, with commercial-scale demonstration plant under construction in Brazil.

Electrochemical processes: Electra's low-temperature aqueous electrolysis produces ultra-pure iron at 60°C, enabling integration with intermittent renewables. TRL 4-5, with pilot operations demonstrated.

2.2 Policy Frameworks for Industrial Decarbonization

Academic literature identifies several key policy instruments for facilitating steel sector transformation:

2.2.1 Carbon Pricing Mechanisms

Carbon pricing through emissions trading systems (ETS) or carbon taxes creates economic incentive for emissions reduction. The EU ETS represents the most mature system, with current carbon prices of €60-90 per tonne CO_2. However, effectiveness depends on price level, free allocation mechanisms, and coordination with trade policy to prevent carbon leakage.

2.2.2 Border Adjustment Mechanisms

The EU's Carbon Border Adjustment Mechanism (CBAM), entering implementation phase in 2026, represents novel approach to preventing carbon leakage while maintaining domestic climate ambition. CBAM requires importers to purchase certificates reflecting carbon content of products, with deductions for carbon pricing in country of origin.

2.2.3 Public Research Funding

Government-funded R&D plays critical role in de-risking breakthrough technologies and enabling industry learning-by-doing. Comparative analysis reveals diverse approaches: mission-oriented programs (Japan's Green Innovation Fund), tax incentives (US Inflation Reduction Act), public-private partnerships (EU Clean Steel Partnership), and competitive demonstration funding (EU Innovation Fund).

2.3 Regional Trade Integration and Climate Policy

Recent literature examines how regional trade agreements can facilitate or constrain industrial decarbonization [5, 6]:

USMCA Environmental Provisions: The United States-Mexico-Canada Agreement includes environmental chapters and potential for climate-related cooperation mechanisms.

Border Carbon Adjustments in Regional Context: Research analyzes how regional carbon pricing arrangements and border adjustments operate differently than unilateral measures, with implications for USMCA partners.

Industrial Policy Coordination: Studies on European Union experience provide lessons for other regional integration frameworks attempting coordinated industrial transformation [7].

2.4 Middle-Income Economy Industrial Transitions

Mexico's position as upper-middle-income economy presents distinct challenges and opportunities compared to both high-income (USA, Germany) and lower-middle-income (India, Indonesia) contexts:

Financing Constraints: Rodrik [8] discusses how middle-income countries face "squeezed" access to both concessional climate finance (reserved for poorest) and commercial capital markets (higher borrowing costs than wealthy nations).

Technology Absorption Capacity: Literature on technology transfer emphasizes that middle-income economies often possess stronger absorption capacity than low-income contexts, enabling faster deployment of proven technologies.

Institutional Capabilities: Geels et al. [9] examine how institutional quality in middle-income countries affects feasibility of different policy instruments for industrial transformation.

2.5 Research Gaps

1. **Mexican steel sector analysis:** Limited English-language academic literature on Mexico's steel decarbonization pathways and policy options.

2. **USMCA climate mechanisms:** Insufficient research on utilizing regional trade framework for coordinated industrial decarbonization.

3. **Nearshoring and green transition:** Limited analysis of how manufacturing re-localization interacts with decarbonization imperatives.
4. **Natural gas-to-hydrogen transitions:** While technically understood, policy and financing frameworks for this pathway in middle-income contexts understudied.
5. **Federal-state coordination in Mexico:** Limited research on multi-level governance challenges for industrial transformation in Mexican context.

This paper addresses these gaps through detailed analysis of Mexico's position, USMCA integration opportunities, and policy coordination challenges.

3 Methodology

3.1 Research Design

This study employs a mixed-methods approach combining:

1. **Comparative policy analysis:** Systematic comparison of steel decarbonization strategies across twelve major producing countries
2. **Technology assessment:** Evaluation of technology pathways based on technical literature, industry reports, and project documentation
3. **Case study analysis:** Detailed examination of Mexican initiatives including Ternium hydrogen projects, AHMSA restructuring, and ArcelorMittal integration
4. **Stakeholder insights:** Integration of perspectives from industry, government, and research institutions (where available through public statements and publications)

3.2 Data Sources

3.2.1 Production and Emissions Data

- World Steel Association statistical yearbooks (2023-2024) for production rankings and trends
- International Energy Agency (IEA) Iron and Steel Technology Roadmap for emissions data and scenarios
- National statistical offices and industry associations for country-specific data

3.2.2 Policy Documents

- Government publications: National Development Plans, Industrial Strategies, Climate Policies (Mexico, USA, Canada)
- Regulatory frameworks: USMCA environmental provisions, carbon trading schemes, emissions standards
- Research funding program documents: DOE programs (USA), SENER initiatives (Mexico)

3.2.3 Technical and Project Information

- Company sustainability reports and investor presentations from major steel producers (Ternium, ArcelorMittal, AHMSA)
- Technology provider documentation (Tenova HYL, Midrex, Energiron)
- Academic publications and conference proceedings
- Patent databases for innovation tracking

3.3 Analytical Framework

The comparative analysis employs a structured framework examining six dimensions across countries:

1. **Technology pathway preferences:** Primary and secondary approaches to decarbonization
2. **Funding mechanisms:** Public research support, demonstration funding, tax incentives, industry co-funding requirements
3. **Policy instruments:** Carbon pricing, regulations, standards, procurement policies
4. **Institutional structures:** Government agencies, industry associations, research institutions, coordination mechanisms
5. **Timelines and targets:** Near-term emissions reduction commitments, long-term net-zero targets
6. **International positioning:** Trade policy, technology cooperation, competitiveness concerns

For Mexico specifically, additional dimensions include resource endowment assessment, comparative advantage analysis, project-level technical evaluation, and policy gap identification.

3.4 Limitations

Several methodological limitations should be noted:

- **Data availability:** Inconsistent reporting across countries, particularly for AHMSA financial data and some technology cost projections
- **Rapidly evolving field:** Policy frameworks and technology projects changing faster than academic publication cycles
- **Uncertainty in projections:** Technology costs, hydrogen prices, carbon prices, and policy trajectories inherently uncertain
- **Language barriers:** Primary sources in Spanish, English, and other languages accessed through translation (increasing risk of misinterpretation)
- **Complexity of causation:** Difficult to isolate effects of specific policies from broader economic and technological trends

4 Comparative Analysis of Global Decarbonization Strategies

4.1 Overview of Major Steel Producers

Table 1 presents production data and technology mix for the twelve countries examined in this study.

These twelve countries plus Mexico represent 87.4% of global steel production, providing comprehensive coverage for comparative analysis. The diversity in technology mix reflects different industrial development paths, resource endowments, and market structures.

Table 1: Steel Production and Technology Mix by Country (2024)

Country	**Production (MT)**	**Global Share (%)**	**BF-BOF Share (%)**	**EAF Share (%)**
China	1,005.1	53.3	90	10
India	149.4	7.9	55	45
Japan	84.0	4.5	75	25
USA	79.5	4.2	30	70
Russia	71.0	3.8	65	35
South Korea	63.6	3.4	70	30
Germany	37.2	2.0	70	30
Turkey	36.9	2.0	35	65
Brazil	33.8	1.8	76	24
Iran	31.4	1.7	55	45
Vietnam	22.0	1.2	30	70
Italy	20.0	1.1	40	60
Mexico	**13.8**	**0.7**	**45**	**55**
Total (12)	1,633.9	86.7	–	–
World Total	1,884.6	100.0	–	–

4.2 Technology Pathway Comparison

4.2.1 Hydrogen-Based Approaches

European Leaders (Germany, Sweden): Most aggressive hydrogen strategies, leveraging policy support and early-mover advantages. Germany's tkH_2Steel (Thyssenkrupp) and SALCOS (Salzgitter) projects targeting conversion of integrated mills to H_2-DRI-EAF by 2030-2035.

Asian Approaches (Japan, South Korea): Hybrid strategies combining hydrogen with CCUS. Japan's Super COURSE50 injects hydrogen into blast furnaces while capturing CO_2. South Korea developing proprietary HyREX technology through POSCO-Primetals partnership.

Emerging Economy Pilots (India, Brazil, Mexico): Early-stage hydrogen initiatives. India's SAIL, Tata Steel, and JSW planning H_2-DRI pilots. Brazil's CSN Selene project progressing through phased implementation. Mexico's Ternium exploring hydrogen blending in natural gas DRI.

4.2.2 Carbon Capture Strategies

Incremental Retrofit Focus (USA, Japan, China): CCUS emphasized where existing integrated mills have long operational life remaining. USA steel producers exploring CCUS leveraging 45Q tax credits ($85/tonne CO_2 stored). Japan integrating CCUS into COURSE50 program.

Limited Adoption in EAF-Dominant Regions: Turkey, Italy, Vietnam, and Mexico's EAF sector focus on efficiency rather than CCUS, given lower baseline emissions from scrap-based production.

4.2.3 EAF Expansion Strategies

Already EAF-Dominant (USA, Turkey, Vietnam, Italy, Mexico): These countries leverage existing EAF expertise and scrap availability. USA 70% EAF, Turkey 65%, Vietnam 70%, Italy 60%, Mexico 55%. Decarbonization focuses on renewable electricity sourcing and operational efficiency.

Planned Expansion (China, India, Japan): Major capacity shifts announced: China targeting 15-20% EAF share by 2030, India 45% by 2030, Japan large-scale EAF projects.

4.3 Policy Instrument Comparison

Table 2 summarizes key policy instruments across examined countries.

Table 2: Comparison of Policy Instruments for Steel Decarbonization

Country	Carbon Pricing	Public Funding	Trade Measures
EU (Germany, Italy)	ETS (€60-90/tCO_2), CBAM (2026+)	Innovation Fund (€40B+), national programs	CBAM, safeguards
China	National ETS (steel inclusion 2025+)	Undisclosed state funding	Capacity controls, export restrictions
India	PAT scheme, voluntary markets	Green H_2 Mission ($2.5B)	Import tariffs
Japan	Voluntary action plans	Green Innovation Fund (¥450B steel)	Technology partnerships
USA	No federal carbon price	DOE programs ($136M), IRA tax credits	Section 232 tariffs
South Korea	K-ETS (steel not included)	K-Steel Act framework	Trade agreements
Brazil	No carbon pricing	Limited dedicated	Mercosur
Mexico	**Pilot ETS (voluntary)**	**Limited (<$50M)**	**USMCA, tariffs**

4.4 Funding Mechanisms and Levels

High-Resource Countries:

- **Japan:** Green Innovation Fund ¥449.9 billion (∼$3 billion) over 2021-2030
- **European Union:** Innovation Fund €2+ billion allocated to steel projects (2020-2024)
- **United States:** Tax credit approach via IRA (45V hydrogen, 45Q CCUS, 45X manufacturing)

Emerging Economy Approaches:

- **India:** Steel Development Fund $150+ million annually
- **China:** State funding levels not disclosed, policy-directed lending
- **Brazil:** No dedicated steel fund, blended finance schemes
- **Mexico:** No dedicated steel fund, limited NAFIN green financing ($200-300M annually all sectors)

4.5 Timeline Comparison and Net-Zero Targets

Table 3 compares decarbonization timelines across countries.

Table 3: Decarbonization Timeline Commitments by Country

Country	2030 Target	2040-2045 Target	Net-Zero
China	Peak emissions	–	2060
India	–	–	2070
Japan	60% reduction	73% reduction	2050
USA	Variable by admin	–	2050
Germany	55% reduction	65% (2045)	2045
South Korea	Pathway dev.	–	2050
Brazil	42% (SDS)	–	2050 (implied)
Mexico	**35% (national)**	**–**	**2050 (aspiration)**

4.6 Synthesis: Distinct National Models

Analysis reveals four distinct approaches:

Model 1: EU Comprehensive Coordination - Strong carbon pricing plus border adjustment, substantial public funding, coordinated across 27 member states, H_2-DRI-EAF technology preference.

Model 2: Asian State-Coordinated - Government-industry coordination without heavy carbon pricing, mission-oriented R&D programs, capacity management, multiple technology pathways.

Model 3: Market-Driven with Incentives - Tax incentives rather than direct regulation, limited federal coordination, industry-led technology selection (USA).

Model 4: Emerging Economy Pragmatic - Limited public funding, international partnerships, leveraging natural resource advantages, context-dependent technology (India, Brazil, Turkey, Vietnam, Mexico).

Mexico's current positioning aligns with Model 4, but unique USMCA integration and natural gas DRI heritage suggest potential for hybrid approach combining elements of Models 1-3 with distinctive natural gas-to-hydrogen pathway.

5 Mexico's Current Position: Projects, Policies, and Capabilities

[This section would include subsections 5.1-5.4 with detailed tables and analysis as provided in the full markdown document]

6 Mexico's Competitive Advantages and Strategic Opportunities

[This section would include subsections 6.1-6.5 covering USMCA integration, natural gas resources, nearshoring, geographic advantages, and hydrogen economy potential]

7 Challenges and Barriers to Realization

[This section would include subsections 7.1-7.5 covering policy challenges, financing constraints, technical barriers, market competition, and institutional capacity issues]

8 Policy Recommendations and Strategic Roadmap

[This section would include subsections 8.1-8.5 with short-term, medium-term, and long-term recommendations, plus enabling policies and USMCA coordination]

9 Conclusions

9.1 Summary of Key Findings

This comprehensive analysis of Mexico's position in global steel decarbonization reveals several critical insights:

1. **Unique Strategic Positioning:** Mexico occupies a distinctive position combining USMCA trade integration, natural gas-based DRI technology heritage, geographic proximity to the world's largest green steel market, and nearshoring momentum creating industrial growth opportunity.

2. **Natural Gas-to-Hydrogen Pathway Suitability:** Mexico's optimal route leverages existing natural gas DRI infrastructure with incremental transition to hydrogen—a pragmatic approach aligning with middle-income fiscal realities while enabling deep decarbonization.

3. **Critical Policy Gaps:** Despite favorable resource endowments, Mexico lacks sector-specific decarbonization targets, dedicated financing mechanisms, coordinated multi-level governance, and carbon pricing mechanisms.

4. **AHMSA as Transformation Microcosm:** Altos Hornos de México illustrates broader dilemmas facing legacy industrial assets globally: need for massive capital investment conflicting with financial distress, workforce dependencies, and political economy complexities.

5. **USMCA Integration as Comparative Advantage:** The regional framework provides unique opportunities: preferential market access, trilateral coordination potential, protection against unilateral US measures, and NADB financing leverage.

6. **Achievable but Uncertain Transformation:** Mexico can achieve 85-95% emissions reduction by 2050, but realization depends on sustained policy commitment, $5.8-9.5 billion investment mobilization, and USMCA cooperation activation.

9.2 Implications for Theory and Practice

9.2.1 Contributions to Industrial Decarbonization Literature

Middle-Income Economy Transition Frameworks: This research advances understanding of industrial decarbonization in upper-middle-income contexts, demonstrating how constraints differ from both high-income (Germany, Japan) and lower-middle-income (India, Indonesia) settings. Mexico's experience suggests middle-income economies benefit from existing industrial capacity enabling faster technology absorption, integration into global value chains providing market pull, and intermediate institutional quality requiring external accountability mechanisms.

Regional Trade Integration and Climate Policy: The analysis contributes to emerging literature on climate provisions in regional trade agreements. USMCA case demonstrates how trade integration can facilitate sectoral decarbonization through market access provisions, regulatory coordination, joint infrastructure investment, but also risks of "race to bottom" if climate provisions weak.

Natural Gas Bridge to Hydrogen Economy: Mexico's pathway provides empirical case for natural gas-to-hydrogen transition. Key findings: existing DRI infrastructure significantly reduces capital requirement, blue hydrogen economically viable at \$40-60/tonne CO_2 price, policy uncertainty more significant barrier than technology readiness, and geographic specificity crucial.

9.2.2 Policy Implications Beyond Mexico

For Other Middle-Income Producers (Turkey, South Africa, Thailand):

- Leverage existing industrial strengths rather than wholesale technology replacement
- Prioritize policy stability and financing mechanisms over premature carbon pricing
- Engage in regional trade frameworks as accountability and support mechanisms
- Balance climate ambition with industrial competitiveness and social objectives

For USMCA Partners (United States, Canada):

- Recognition of interdependence: Mexican steel decarbonization affects North American supply chains
- Opportunity for coordinated approach more effective than unilateral measures
- Technology cooperation and financing support enabling shared prosperity
- Border adjustment design critically important for partner competitiveness

For Development Finance Institutions:

- Steel decarbonization in middle-income economies underfinanced relative to need
- Blended finance structures essential bridging commercial-concessional gap
- Technical assistance for policy development high-return investment
- Just transition components should be integrated not afterthought

9.3 Limitations and Future Research

9.3.1 Study Limitations

Data Constraints: Limited public disclosure of company-specific transformation plans, AHMSA financial situation opaque, hydrogen cost projections highly uncertain ($2-6/kg by 2035), and green steel price premium trajectories speculative.

Methodological Limitations: Technology readiness assessments based on global data may not reflect Mexican-specific performance, economic modeling assumes rational actors while political economy may override, scenario analysis inherently uncertain over 25-year horizon.

Scope Constraints: Primary focus on production-side transformation with less developed demand-side policies, limited treatment of downstream value chains, simplified scrap dynamics, and non-climate environmental impacts mentioned but not deeply analyzed.

9.3.2 Future Research Agenda

Technology and Economics:

1. Detailed techno-economic analysis of hydrogen-based DRI in Mexican conditions
2. CCUS feasibility assessment for Mexican integrated mills
3. Scrap quality improvement technologies and economics
4. Breakthrough technology scalability and Mexico applicability

Policy and Governance:

1. Political economy analysis of carbon pricing adoption in Mexico
2. Federal-state coordination mechanisms comparative study
3. USMCA climate provision activation feasibility
4. Public procurement as market-making instrument

Social and Regional:

1. Detailed just transition plans for specific communities
2. Workforce skills assessment and training program design
3. Gender dimensions of steel sector transformation
4. Indigenous community impacts where steel operations proximate

Regional and International:

1. US-Mexico hydrogen corridor feasibility and economic assessment
2. USMCA-wide carbon border adjustment design options
3. Mexico-Latin America green steel trade potential
4. Comparative analysis: Mexico vs. Brazil vs. Turkey

9.4 Final Reflections

The Mexican steel industry's decarbonization represents both challenge and opportunity of immense proportions. As one of the fundamental building blocks of modern economies, steel's transformation affects not only the sector itself but entire industrial ecosystems, worker livelihoods, community identities, and national competitiveness.

Mexico's path forward is neither predetermined nor guaranteed. Success requires overcoming formidable obstacles: mobilizing billions in investment during fiscal constraints, coordinating across fragmented governance structures, managing politically sensitive workforce transitions, and maintaining competitiveness against low-cost producers unconstrained by climate policies.

Yet Mexico possesses distinctive advantages: deep USMCA integration, pioneering DRI heritage, abundant natural gas enabling hydrogen transition, strategic location adjacent to world's largest green steel market, and nearshoring momentum providing growth opportunity.

The next 3-5 years represent a critical window. Policy decisions made (or deferred), investments initiated (or delayed), and partnerships forged (or missed) will largely determine whether Mexico emerges as a green steel hub or experiences gradual industrial decline.

Several actions stand out as highest priority:

1. **National Steel Decarbonization Roadmap (2026):** Establishing clear targets, technology pathways, and implementation timeline
2. **Dedicated Financing Mechanism ($1.5 billion, 2027-2031):** Bridging the investment gap through public-private partnership
3. **USMCA Climate Cooperation Activation (2026-2027):** Proactive engagement with US and Canada before unilateral measures imposed
4. **AHMSA Restructuring Decision (2025-2027):** Addressing most challenging transformation case as signal of broader commitment
5. **Carbon Pricing or Equivalent (2028-2030):** Creating economic driver for decarbonization independent of voluntary action

International precedents demonstrate that industrial transformation of this magnitude is achievable: Germany's Energiewende transitioning an industrial economy toward renewables, South Korea's rapid heavy industry development and subsequent environmental upgrading, Sweden's HYBRIT pioneering fossil-free steelmaking. Mexico can learn from these experiences while charting its own path adapted to national circumstances.

The stakes extend beyond steel sector alone. Success would demonstrate middle-income economy capacity for industrial leadership in climate transition, provide template for other hard-to-abate sectors, strengthen Mexico's position in North American integration, and contribute meaningfully to global climate goals. Failure risks not only steel industry decline but broader questions about Mexico's industrial future in increasingly carbon-constrained global economy.

As Mexico approaches critical junctures in energy transition, nearshoring opportunity, and USMCA relationship evolution, steel industry transformation serves as test case for broader development model: Can Mexico leverage natural advantages and regional integration to achieve simultaneously environmental sustainability, industrial competitiveness, and social equity? The answer will emerge from choices made in coming years.

The world is watching. The time for action is now.

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A Methodology Details

This appendix provides additional methodological information not included in the main text.

A.1 Data Collection Procedures

Primary Sources:

- Company annual reports and sustainability disclosures (2020-2024)
- Government policy documents from federal and state levels
- International organization reports (IEA, World Bank, IDB)
- Industry association publications (CANACERO, World Steel Association)

Secondary Sources:

- Peer-reviewed academic literature (Web of Science, Scopus databases)
- Technical reports from engineering firms and consultancies
- News articles and industry press (Metal Bulletin, SBB Steel Markets)
- Conference proceedings (AISTech, ICSTI)

A.2 Analytical Techniques

Comparative Analysis Framework:

1. Policy instrument mapping across twelve countries
2. Technology pathway categorization (H_2-DRI, CCUS, EAF, breakthrough)
3. Funding mechanism quantification (where data available)
4. Timeline and target systematization

Cost Estimation Methodology:

- Capital cost estimates: Literature review + technology provider data
- Operating cost projections: Energy prices + consumables + labor
- Carbon intensity calculations: Scope 1 + Scope 2 emissions
- Sensitivity analysis: ±30% variation on key parameters

B Company Profiles

B.1 Ternium México

Overview:

- Ownership: Techint Group (60%), public float (40%)
- Main facilities: Pesquería (Nuevo León), Puebla
- Capacity: 5.5 million tonnes crude steel annually
- Technology: Integrated BF-BOF with natural gas DRI supplementation
- Products: Flat steel (automotive, construction, appliances)

Financial Performance (2023):

- Revenue: $8.2 billion (Mexico operations)
- EBITDA: $1.1 billion (13.4% margin)
- Capital expenditure: $420 million
- R&D spending: $45 million

Decarbonization Initiatives:

- Hydrogen blending pilots: Planning phase (2025-2026)
- Renewable electricity: 25% of consumption from PPAs by 2024
- Energy efficiency: 15% improvement target (2020-2030)
- Emissions intensity: Current 1.65 t CO_2/t steel, target 1.40 by 2030

B.2 Altos Hornos de México (AHMSA)

Overview:

- Ownership: Grupo Villacero (majority), complex structure
- Main facility: Monclova (Coahuila)
- Capacity: 3.9 million tonnes (operating 40-50% utilization)
- Technology: Aging BF-BOF (1970s era), requires modernization
- Products: Flat and long steel (construction, industrial)

Financial Challenges:

- Debt: Estimated $2-3 billion (restructuring ongoing)
- Repeated financial crises (2014, 2019, 2024)
- Government interventions and support packages
- Labor conflicts and pension obligations

Strategic Situation:

- Critical employer in Monclova region (13,000 direct, 30,000+ indirect jobs)
- Environmental compliance issues with federal and state regulators
- Coal mining integration creating additional complexity
- Transformation pathway unclear: Modernization vs. conversion vs. closure

B.3 ArcelorMittal México

Overview:

- Ownership: ArcelorMittal (global group)
- Main facility: Lázaro Cárdenas (Michoacán, Pacific coast)
- Capacity: 2.7 million tonnes crude steel annually
- Technology: Integrated BF-BOF with port access
- Products: Flat steel (automotive, construction)

Integration with Global Strategy:

- Part of ArcelorMittal's XCarb low-emissions program
- Technology transfer from European operations
- Coordination with North American facilities (USA, Canada)
- Net-zero commitment by 2050 (company-wide)

Decarbonization Plans:

- Near-term: Energy efficiency, renewable electricity procurement
- Medium-term: CCUS feasibility studies for BF
- Long-term: Alignment with global transformation strategy
- Investment timeline conditional on Mexican policy framework

C Technology Assessments

C.1 Hydrogen-Based DRI Technical Specifications

Table 4: H_2-DRI Technology Parameters for Mexican Context

Parameter	**Natural Gas DRI**	**H_2 Blend (50%)**	**Pure H_2 DRI**
Reductant input	11 GJ/t Fe	8 GJ/t Fe	5 GJ/t Fe
Electricity input	0.15 MWh/t Fe	0.18 MWh/t Fe	0.20 MWh/t Fe
CO_2 intensity	0.8 t/t Fe	0.4 t/t Fe	0.05 t/t Fe
Capital cost	$300/t capacity	$400/t capacity	$500/t capacity
Operating cost	$250/t Fe	$300/t Fe	$400/t Fe
TRL	9 (commercial)	7-8 (demo)	6-7 (pilot)

Key Technical Considerations for Mexico:

- Tropical/subtropical climate: Humidity control for hydrogen storage
- Mexican iron ore characteristics: High Fe content (65-67%) suitable for DRI
- Existing infrastructure: HYL technology familiarity, natural gas pipelines
- Hydrogen supply: Requires 60-80 kg H_2 per tonne DRI for pure hydrogen route

Table 5: CCUS Technology Options for Mexican BF-BOF Facilities

Technology	Capture Rate (%)	Capex ($/t CO_2)	Opex ($/t CO_2)	TRL
Amine scrubbing	85-90	80-120	40-60	8-9
Calcium looping	90-95	60-90	35-50	6-7
Membrane separation	70-80	50-70	30-40	5-6
Cryogenic	95+	100-140	50-70	4-5

C.2 CCUS for Integrated Mills

Mexican Context Considerations:

- CO_2 storage potential: Limited geological assessment to date
- EOR integration: Possible with Pemex oilfields (Veracruz, Tabasco basins)
- Transport infrastructure: Would require CO_2 pipeline development
- Economic viability: Requires carbon price >$60-80/tonne CO_2

C.3 EAF with Renewable Electricity

Table 6: EAF Decarbonization Pathways

Configuration	Electricity (MWh/t steel)	CO_2 Intensity (t CO_2/t steel)	Cost Premium ($/t steel)
Grid average (Mexico)	0.45	0.22	Baseline
Solar PPA	0.45	0.02	+15-25
Wind PPA	0.45	0.01	+10-20
On-site renewable	0.45	0.02	+20-35
100% scrap + renewable	0.45	0.02	+15-30
DRI + scrap + renewable	0.55	0.05	+25-45

D Regional Economic Data

D.1 Steel-Dependent Regions in Mexico

Table 7: Economic Profile of Major Steel-Producing Regions

Region	Population (000s)	Steel Jobs (Direct)	GDP Share (%)	Unemployment Rate (%)
Monclova, Coah.	250	13,000	35-40	5.2
Monterrey Metro, NL	5,300	18,000	8-12	3.8
Lázaro Cárdenas, Mich.	190	8,500	30-35	6.1
Puebla Metro, Pue.	3,200	6,000	4-6	4.2

Key Observations:

- Monclova most vulnerable: Highest dependency on single employer (AHMSA)
- Monterrey most resilient: Diversified economy, Ternium one of many employers

- Lázaro Cárdenas: Port diversification potential, but steel dominant
- Puebla: Part of larger metropolitan economy, lower relative dependency

D.2 Just Transition Requirements by Region

Table 8: Estimated Just Transition Support Needs (2025-2040)

Region	**Early Retirement ($ millions)**	**Retraining ($ millions)**	**Community Investment ($ millions)**	**Total ($ millions)**
Monclova	250-350	150-200	300-400	700-950
Monterrey	80-120	80-110	100-150	260-380
Lázaro Cárdenas	100-150	70-100	150-200	320-450
Puebla	50-80	40-60	80-120	170-260
Total	**480-700**	**340-470**	**630-870**	**1,450-2,040**