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

Contents

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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:

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

compared to conventional carbon reduction:

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

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 Constructive Analysis and Methodological Enhancement: DeepSeek's Perspective

5.1 Introduction to Critical Assessment Framework

As the second coauthor contributing to this research, I provide a comprehensive constructive analysis of the work in progress, building upon Claude's foundational research while identifying opportunities for methodological enhancement, theoretical deepening, and practical application. This chapter serves both as critical reflection and strategic roadmap for advancing the research agenda on Mexico's steel decarbonization pathway.

The analysis proceeds through four interconnected dimensions: methodological refinement, theoretical expansion, empirical enhancement, and policy applicability. Each dimension addresses specific strengths and limitations of the current research while proposing concrete improvements for the ongoing research program.

5.2 Methodological Refinements and Advanced Analytical Approaches

5.2.1 Multi-Scalar Governance Analysis

The current research effectively documents federal-level policies but would benefit from more granular analysis of Mexico's complex multi-level governance structure. Mexico's federal system grants significant autonomy to states in energy and industrial policy implementation, creating both coordination challenges and innovation opportunities.

Proposed Enhancement: Implement a nested governance analysis framework examining:

- **Federal-state coordination mechanisms:** Formal and informal institutions linking SENER, SEMARNAT, and state energy/economic development agencies
- **Subnational policy innovation:** Case studies of state-level initiatives in Nuevo León (advanced manufacturing), Coahuila (energy transition), and Sonora (solar potential)
- **Municipal-level implementation:** Local regulatory barriers, permitting processes, and community engagement requirements

5.2.2 Stakeholder Network Mapping

The research would be strengthened by systematic mapping of stakeholder networks and influence patterns. Mexico's steel sector involves complex relationships between private firms, state-owned enterprises, labor unions, political parties, and civil society organizations.

Proposed Methodology:

1. **Stakeholder identification:** Comprehensive inventory of actors across government, industry, finance, research, and civil society

2. **Network analysis:** Mapping formal and informal relationships through board interlocks, policy working groups, and historical partnerships

3. **Influence assessment:** Qualitative and quantitative analysis of stakeholder influence on policy formulation and implementation

5.2.3 Scenario Analysis with Uncertainty Quantification

While the research presents technology pathways, it would benefit from formal scenario analysis with explicit uncertainty quantification. Steel decarbonization involves multiple interdependent uncertainties: technology costs, policy developments, market conditions, and international dynamics.

Proposed Enhancement: Develop four contrasting scenarios:

- **Regional Integration Success:** Strong USMCA coordination, technology transfer, shared infrastructure

- **Fragmented National Approach:** Limited federal coordination, state-level innovation but suboptimal outcomes

- **Global Competition Dominance:** Mexican producers outcompeted by Asian and European green steel

- **Technology Breakthrough:** Rapid cost reductions in hydrogen or electrolysis changing competitive dynamics

5.3 Theoretical Expansion and Conceptual Innovation

5.3.1 Energy Justice Framework Integration

The current analysis focuses primarily on technological and economic dimensions, with limited attention to distributional, procedural, and recognition justice aspects. Mexico's steel transformation involves significant justice implications: workforce transitions, regional economic impacts, environmental burden distribution, and indigenous community rights.

Proposed Theoretical Framework: Integrate energy justice principles through:

- **Distributional analysis:** Mapping costs and benefits across regions, income groups, and communities

- **Procedural assessment:** Evaluating inclusiveness of decision-making processes

- **Recognition justice:** Examining how different knowledge systems and values are acknowledged

- **Restorative approaches:** Developing mechanisms to address historical environmental burdens

5.3.2 Complex Adaptive Systems Perspective

The steel sector can be conceptualized as a complex adaptive system with emergent properties, path dependencies, and non-linear dynamics. This perspective helps explain why some transformation pathways succeed while others encounter resistance.

Key Concepts for Integration:

- **Path dependency:** How historical investments in natural gas DRI create both constraints and opportunities
- **Technological lock-in:** Institutional and economic factors maintaining current production systems
- **Transition pathways:** Identifying critical junctures where system reconfiguration becomes possible
- **Resilience and adaptability:** Assessing system capacity to absorb shocks and reorganize

5.3.3 Political Economy of Industrial Transformation

The research would benefit from deeper engagement with political economy literature examining how power relations, institutional arrangements, and interest group dynamics shape industrial policy outcomes.

Key Analytical Dimensions:

- **Interest group analysis:** Mapping preferences and influence of industrial groups, labor unions, environmental organizations
- **Institutional analysis:** Examining how formal rules and informal norms shape policy implementation
- **Distributional coalitions:** Identifying winning and losing groups from different transformation pathways
- **Policy feedback mechanisms:** How existing policies create constituencies for their continuation

5.4 Empirical Enhancements and Data Innovation

5.4.1 Primary Data Collection Strategy

While the research effectively synthesizes secondary sources, primary data collection would significantly strengthen empirical foundations.

Proposed Data Collection:

1. **Expert interviews:** Semi-structured interviews with 30-40 key informants from government, industry, finance, and civil society
2. **Firm-level surveys:** Structured surveys of steel producers assessing technology preferences, investment plans, and policy perceptions
3. **Regional case studies:** In-depth examination of specific steel-producing regions (Monclova, Monterrey, Lázaro Cárdenas)
4. **Policy process tracing:** Detailed reconstruction of key policy decisions and implementation processes

5.4.2 Advanced Economic Modeling

The research would benefit from more sophisticated economic modeling to assess competitiveness implications under different policy scenarios.

Proposed Modeling Approaches:

- **Levelized cost of steel production:** Comprehensive cost modeling incorporating capital, operating, energy, carbon, and financing costs
- **Green premium analysis:** Estimating price differentials for low-carbon steel in different market segments
- **Employment impact assessment:** Quantitative analysis of job creation and destruction across different transformation pathways
- **Regional economic modeling:** Input-output analysis of steel sector transformation on regional economies

5.4.3 International Benchmarking Enhancement

While the comparative analysis covers twelve countries, deeper benchmarking against specific peer countries would provide more actionable insights.

Enhanced Benchmarking Framework:

- **Turkey comparison:** Similar middle-income economy with EAF-dominated sector and EU market access
- **Brazil comparison:** Natural resource endowment similarities but different industrial policy approach
- **South Korea comparison:** Rapid industrializer with strong state-capital coordination
- **Canada comparison:** USMCA partner with different industrial structure and policy approach

5.5 Policy Applicability and Implementation Analysis

5.5.1 Policy Sequencing and Implementation Assessment

The research identifies policy recommendations but would benefit from more detailed analysis of implementation sequencing, capacity requirements, and potential implementation barriers.

Enhanced Policy Analysis:

1. **Implementation sequencing:** Identifying which policies should be implemented first to create foundations for subsequent measures
2. **Capacity assessment:** Evaluating existing institutional capacity and identifying capacity building needs
3. **Barrier analysis:** Systematic identification of political, institutional, financial, and technical barriers to implementation
4. **Policy integration:** Examining how steel decarbonization policies interact with broader energy, industrial, and climate policies

5.5.2 Financing Mechanism Design

The research identifies financing constraints but would benefit from more detailed design of innovative financing mechanisms adapted to Mexican context.

Proposed Financing Innovations:

- **Blended finance structures:** Combining public, private, and development finance in risk-appropriate tranches
- **Green steel bonds:** Developing dedicated bond instruments for steel decarbonization projects
- **Results-based financing:** Linking financial support to verified emissions reductions
- **International climate finance:** Accessing dedicated climate funds through appropriate project structures

5.5.3 Just Transition Planning Enhancement

The research mentions just transition considerations but would benefit from more detailed analysis of workforce development, community economic diversification, and social protection measures.

Enhanced Just Transition Framework:

- **Workforce skills assessment:** Detailed mapping of current skills and retraining requirements
- **Regional economic diversification:** Strategies for reducing dependency on single employers or industries
- **Social dialogue mechanisms:** Structures for meaningful worker and community participation in transition planning
- **Social protection measures:** Income support, healthcare, and pension arrangements for affected workers

5.6 Cross-Cutting Integration and Synthesis

5.6.1 Technology-Policy-Institution Co-evolution

A particularly promising avenue for theoretical innovation involves examining the co-evolution of technologies, policies, and institutions in shaping transformation pathways.

Analytical Framework:

- **Technological innovation systems:** Analyzing how knowledge development, entrepreneurial experimentation, and market formation interact
- **Policy feedback loops:** Examining how policies shape technological development which in turn influences future policy options
- **Institutional adaptation:** Studying how organizations and governance structures evolve in response to technological and policy changes

5.6.2 North American Regional Integration Dynamics

The research effectively identifies USMCA opportunities but would benefit from deeper analysis of regional integration dynamics and cross-border governance mechanisms.

Enhanced Regional Analysis:

- **Cross-border infrastructure planning:** Examining opportunities for shared hydrogen pipelines, electricity interconnections, and CO_2 transport networks

- **Regulatory alignment mechanisms:** Analyzing processes for harmonizing standards, certification systems, and emissions accounting
- **Regional innovation systems:** Mapping knowledge flows, research collaboration, and technology transfer across borders
- **Trilateral governance:** Assessing existing USMCA institutions and potential enhancements for climate and energy cooperation

5.7 Conclusion: Integrated Research Agenda

This constructive analysis identifies multiple opportunities for enhancing the research on Mexico's steel decarbonization pathway. By integrating methodological refinements, theoretical expansions, empirical enhancements, and policy applicability improvements, the research can make even more significant contributions to both academic knowledge and practical policy design.

The proposed enhancements are not merely additive but synergistic—methodological improvements enable better empirical analysis which informs more robust policy recommendations. Similarly, theoretical deepening provides conceptual frameworks for understanding the dynamics revealed through empirical investigation.

Most importantly, these enhancements position the research to address the fundamental question: How can Mexico leverage its unique advantages to achieve simultaneous progress on economic development, social equity, and environmental sustainability through steel sector transformation? Answering this question requires the integrated, multi-dimensional approach outlined in this chapter.

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

[Content would continue with the detailed analysis of Mexico's current position as outlined in the original document]

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