Steel Decarbonization at the Crossroads: Technological Pathways and China's October 2025 Policy Revolution

Fabio Miani University of Udine, Italy and Claude LLM

November 7, 2025

Abstract

The iron and steel sector faces its most dramatic policy transformation to date. This paper synthesizes breakthrough research from *Nature* (Wu et al., 2025) on cost-effective plant-level decarbonization pathways with China's unprecedented October 2025 draft policy that fundamentally restructures capacity replacement mechanisms. The Nature study demonstrates that energy efficiency and scrap recycling offer immediate, cost-negative solutions, while smelt reduction with carbon capture becomes economically viable after 2030 at US$7-15 per tonne CO_2 in China. China's October 2025 Implementation Measures represent a paradigm shift: mandating minimum 1.5:1 capacity replacement ratios nationwide, terminating inter-enterprise capacity trading by 2027, and creating powerful incentives for electric arc furnace and hydrogen metallurgy deployment through equal replacement provisions. These measures, open for public comment until November 23, 2025, signal China's commitment to absolute capacity reduction while accelerating low-carbon technology transition. The convergence of scientific roadmaps and aggressive policy implementation marks a pivotal moment in global industrial decarbonization.

1 Introduction

November 2025 marks a watershed moment for the global steel industry. Within a single year, two developments of profound significance have emerged: rigorous scientific analysis of cost-optimal decarbonization pathways published in *Nature*, and China's revolutionary October 2025 draft policy that fundamentally restructures how the world's largest steel producer manages capacity and promotes low-carbon technology.

The iron and steel sector accounts for 7% of global CO_2 emissions—approximately 2.8 gigatonnes annually—making it the largest industrial emitter. With China responsible for over 50% of global production and emissions, policy decisions in Beijing reverberate throughout global markets, technology development trajectories, and climate mitigation prospects.

The October 2025 Implementation Measures for Capacity Replacement in the Steel Industry, currently open for public comment, represent the most aggressive steel sector policy intervention China has undertaken. Coupled with the scientific framework provided by Wu et al.'s plant-level optimization model, we now possess both the technological roadmap and the policy architecture to achieve deep decarbonization while maintaining industrial competitiveness.

This paper analyzes these parallel developments through the lens of November 2025, examining how China's draft policy aligns with cost-optimal pathways and what implications emerge for global steel decarbonization efforts.

2 Scientific Framework: Cost-Effective Pathways

2.1 The Plant-Level Optimization Approach

Wu et al. (2025) developed the NZP-steel model, integrating two global plant-level datasets covering 1,967 facilities responsible for 98% of global production. The methodology represents a breakthrough in industrial decarbonization analysis by:

1. Accounting for plant-level heterogeneity in costs, technologies, ages, and locations
2. Forecasting dynamic technology costs using component-based learning curves
3. Respecting 20-year retrofitting cycles aligned with capital investment patterns
4. Balancing bottom-up plant optimization with top-down constraints (national targets, demand projections, scrap availability)

The model identifies distinct cost-optimal pathways for different time horizons and plant characteristics, rejecting one-size-fits-all approaches in favor of tailored solutions.

2.2 Short-Term Solutions (Pre-2030): The Low-Hanging Fruit

2.2.1 Energy Efficiency: Negative-Cost Decarbonization

The most remarkable finding is that energy efficiency improvements actually reduce both emissions and production costs. Implementing Best Available Technology (BAT) for blast furnace-basic oxygen furnace (BF-BOF) plants yields:

- Production cost reduction of US$20 per tonne crude steel
- CO_2 abatement cost of -US$8.5 per tonne CO_2
- Cumulative 7.8 gigatonnes CO_2 reduction potential (2020-2050)
- 31% of total abatement in medium deployment scenario

BAT measures include top gas recovery, enhanced heat efficiency, increased scrap utilization, and optimized pulverized coal injection. These improvements are profitable even without carbon pricing, yet many plants have not adopted them due to capital constraints, information barriers, or short-term financial pressures.

2.2.2 Scrap Recycling: Mature Zero-Carbon Technology

Scrap-electric arc furnace (Scrap-EAF) technology represents the only mature, commercially viable zero-emissions steelmaking route. Key characteristics:

- Reduces emissions by approximately 70% versus BF-BOF
- Negative abatement costs in developed regions (-US$46 per tonne CO_2 in EU, -US$73 per tonne CO_2 in Pacific)
- Cumulative potential of 7.2 gigatonnes CO_2 reduction at US$0.3 per tonne CO_2 globally
- Constrained by limited scrap availability, particularly in rapidly industrializing regions

The scrap constraint is critical: only 45 Chinese BF-BOF plants can transition to Scrap-EAF given projected scrap supply, despite favorable economics.

2.3 Long-Term Solutions (Post-2030): Deep Decarbonization

2.3.1 Smelt Reduction with Carbon Capture: The Economic Choice

After 2030, smelt reduction combined with carbon capture and storage (SR-BOF + CCS) emerges as the most economical zero-carbon option for most regions:

- Projected 6.0 gigatonnes cumulative CO_2 reduction
- China: US$7-15 per tonne CO_2 (4-5 times cheaper than Europe/Japan)
- Japan/Korea: US$46-75 per tonne CO_2
- Europe: US$26-52 per tonne CO_2

- Global average declining from US$63 (2030) to US$36 (2050) per tonne CO_2

China's cost advantage stems from lower CCS infrastructure costs, economies of scale, and favorable geology for CO_2 storage.

2.3.2 Green Hydrogen: The Ultimate Zero-Carbon Route

Post-2040, direct reduction with green hydrogen (DRI-BOF + 100% GH_2) becomes competitive in regions with abundant renewable energy:

- Primary deployment in EU, Latin America, Pacific
- 0.3 gigatonnes additional CO_2 abatement
- Costs of US$27-44 per tonne CO_2 in European plants
- Global average declining from US$110 (2030) to US$63 (2050) per tonne CO_2

2.4 Optimal Deployment Scenarios

Wu et al. model three policy scenarios with varying stringency:

Late Deployment: Plants retain current technologies until final retrofit before national carbon neutrality targets. Achieves 13.5 gigatonnes reduction at US$26.0 per tonne CO_2.

Medium Deployment: Plants adopt low-carbon technologies at early retrofits, transitioning to zero-carbon at final retrofit. Achieves 22.4 gigatonnes reduction at US$24.7 per tonne CO_2—the most cost-effective pathway.

Early Deployment: Mandatory zero-carbon technologies from first retrofit. Achieves 52.7 gigatonnes reduction at US$54.0 per tonne CO_2—highest abatement but nearly double the cost per tonne.

The medium deployment scenario emerges as optimal, leveraging mature low-carbon technologies as cost-effective bridges before zero-carbon options reach commercial viability.

3 China's October 2025 Policy Revolution

3.1 Strategic Context and Timing

The October 2025 Implementation Measures for Capacity Replacement in the Steel Industry (Draft for Comments) represents the most significant restructuring of China's steel policy framework since the 2016 capacity reduction campaign. Released by the Ministry of Industry and Information Technology with a public comment deadline of November

23, 2025, the policy signals fundamental shifts in China's approach to industrial decarbonization.

The timing is strategic: following three years of policy experimentation (2024-2025 Energy Conservation and Carbon Reduction Action Plan), China now codifies lessons learned into comprehensive regulatory architecture. The draft policy addresses persistent implementation challenges—overcapacity, weak sub-national enforcement, stalled EAF transition—through binding mechanisms and explicit timelines.

3.2 Paradigm Shift 1: Absolute Capacity Reduction

3.2.1 Mandatory 1.5:1 Replacement Ratio

Article 10 establishes the most aggressive capacity replacement requirement in Chinese steel policy history:

> *"Standard ratio for all provinces: Iron-making and steel-making capacity replacement ratio shall be no less than 1.5:1"*

This means for every 100 tonnes of new capacity built, 150 tonnes of old capacity must be retired—guaranteeing absolute capacity reduction of 33% on each replacement cycle. Compared to previous policies allowing equal (1:1) replacement in most cases, this represents a fundamental commitment to shrinking total capacity.

Limited exceptions:

- 1.25:1 ratio for capacity acquired through mergers & acquisitions after June 1, 2021
- 1:1 ratio only for: on-site major overhauls preserving equipment specifications; high-end special steel EAF projects; projects in Qinghai and Tibet

Implications: If implemented as drafted, this policy ensures China's steel capacity contracts by approximately 25-30% over the next two retrofit cycles (40 years), even as production can be optimized through utilization rate increases.

3.2.2 Termination of Inter-Enterprise Capacity Trading

Article 6 introduces a radical temporal dimension:

> *"Before [Date] 2027 (within 2 years from implementation): Iron-making and steel-making capacity between different enterprises (groups) nationwide may implement capacity replacement."*
>
> *"From [Date] 2027 onwards: Capacity replacement between different enterprises (groups) nationwide shall no longer be implemented."*

This creates a two-year window for capacity trading before the market closes entirely. After 2027, capacity integration can only occur through "comprehensive and substantive mergers and acquisitions"—requiring actual controlling stakes, legal entity changes, and resolution of debts and employee issues (**Article 7**).

Strategic logic: This forces industry consolidation while preventing inefficient capacity from being perpetually recycled through trading mechanisms. Companies must either:

1. Execute capacity trades before 2027
2. Pursue genuine M&A for capacity integration
3. Retire capacity without replacement if unable to meet 1.5:1 requirements

3.3 Paradigm Shift 2: Low-Carbon Technology Incentives

3.3.1 Electric Arc Furnace Equal Replacement

Article 11 creates powerful incentives for EAF deployment through preferential replacement ratios:

> *"Within the same enterprise (group), projects retiring converters to build electric arc furnaces while simultaneously retiring supporting blast furnaces may implement equal replacement of steelmaking capacity, but the retired supporting blast furnace ironmaking capacity shall not be used for replacement."*

This provision is transformative. Enterprises converting from BF-BOF to EAF can:

- Replace steel capacity 1:1 instead of 1.5:1
- Effectively gain a 50% capacity bonus compared to standard replacement
- Simultaneously reduce emissions by approximately 70% per tonne

Example: An enterprise retiring a 3 million tonne/year BF-BOF line to build a 3 million tonne/year EAF line under standard rules would need 4.5 million tonnes of retired capacity (1.5:1 ratio). Under Article 11, only 3 million tonnes retired capacity is required (1:1 ratio), saving 1.5 million tonnes of retired capacity that can be used elsewhere or sold (before 2027).

3.3.2 Hydrogen Metallurgy Incentives

Article 11 extends equal replacement to hydrogen-based iron production:

> *"Projects retiring existing blast furnaces and using low-carbon process technologies such as hydrogen metallurgy to build iron-making projects, where the carbon emission reduction ratio is no less than 60% compared to blast furnace processes, may implement equal replacement of iron-making capacity."*

This creates a clear technology pathway:

- 60% emission reduction threshold ensures meaningful decarbonization
- Equal replacement (1:1) provides economic incentive
- Carbon emission comparison based on previous year's ETS balance value
- Suitable for regions with renewable energy resources

Strategic alignment: This directly supports Wu et al.'s projection that hydrogen metallurgy becomes cost-competitive post-2040, particularly with policy support reducing effective capital costs through favorable replacement ratios.

3.4 Paradigm Shift 3: Regional Controls and Air Quality

3.4.1 Key Region Restrictions

Article 9 imposes stringent geographic constraints on capacity expansion:

Beijing-Tianjin-Hebei and Surrounding Areas: 15 cities including major steel centers (Tangshan, Handan, Xingtai)

Yangtze River Delta: Shanghai, all Jiangsu cities, and major Zhejiang/Anhui cities

Fen-Wei Plain: Shanxi and Shaanxi industrial regions

For these regions:

- *"Strictly prohibit any increase in total steel capacity"*
- *"Strictly prohibit transfer of steel capacity from non-key regions to key regions"*
- *"Strictly prohibit transfer of steel capacity between different key regions"*

Additional constraint: New construction outside compliant industrial parks prohibited in Yangtze River Economic Belt.

Implications: These regions—home to much of China's steel capacity—cannot expand production even with 1.5:1 replacement. They can only optimize existing facilities or transition to cleaner technologies on-site.

3.5 Enforcement Mechanisms and Timelines

3.5.1 24-Month Project Validity Period

Article 19 imposes strict time limits on approved capacity replacement plans:

> *"Capacity replacement plans announced by regions shall specify validity period of 24 months. Within 24 months from announcement date, must complete project filing, energy conservation review and carbon emission evaluation, environmental assessment, and officially commence construction."*

After 24 months, provincial authorities must revoke plans that haven't commenced construction. This prevents capacity hoarding and ensures replacement commitments are executed.

3.5.2 Annual Reporting and Acceptance Procedures

Article 18 establishes systematic monitoring:

- Provincial authorities conduct annual self-inspections
- Submit reports to MIIT by December 31 each year
- MIIT annually announces national capacity replacement status
- Violations result in immediate halt of construction/production, corrections within time limits, and potential joint disciplinary actions

Article 17 requires provincial authorities to organize capacity replacement project acceptance before production:

- Verify construction project matches announced plan (location, equipment, capacity)
- Verify retired equipment demolition status
- Non-compliant projects must be corrected before production
- Announce acceptance status within 10 working days

3.6 Policy Transition and Continuity

3.6.1 Grandfather Provisions

Article 20 provides detailed transition rules to ensure policy stability:

For plans announced before August 23, 2024:

- Implemented according to original capacity replacement measures

- 24-month window from new policy implementation to complete project filing and commence construction
- Split retired capacity not fully implemented within 24 months becomes void

For capacity trading contracts signed before August 23, 2024 with ≥20% payment:

- After providing payment proof, retired capacity verified according to original measures
- Cannot be transferred again
- After implementation to construction projects, new measures apply

This balances policy certainty for existing commitments with aggressive new standards for future projects.

4 Synthesis: Policy-Technology Alignment Analysis

4.1 Alignment with Cost-Optimal Pathways

4.1.1 Short-Term Alignment: Efficiency and Scrap

The October 2025 policy aligns remarkably well with Wu et al.'s short-term recommendations:

Energy Efficiency:

- **Article 21** mandates coordination with energy consumption reduction policies
- Requires projects meet energy efficiency benchmarks
- Wu et al. identify BAT implementation as having -US$8.5 per tonne CO_2 cost
- Policy creates regulatory push for improvements that are already economically rational

Scrap Recycling via EAF:

- **Article 11** EAF equal replacement provision creates powerful economic incentive
- 50% capacity bonus compared to standard replacement
- Wu et al. identify scrap-EAF as having US$0.3 per tonne CO_2 abatement cost globally
- Policy subsidizes transition to mature, low-cost zero-carbon technology

Scrap Supply Challenge: Wu et al. note only 45 Chinese plants can transition to Scrap-EAF given scrap constraints. The policy's EAF incentives may exceed scrap availability, requiring complementary scrap collection infrastructure development.

4.1.2 Long-Term Strategic Positioning: CCS and Hydrogen

Hydrogen Metallurgy:

- **Article 11** hydrogen equal replacement directly incentivizes technology Wu et al. project becomes cost-competitive post-2040
- 60% emission reduction threshold ensures meaningful impact
- Wu et al. project DRI-BOF + 100% GH_2 costs decline to competitive levels by 2050
- Policy accelerates deployment timeline through favorable economics

CCS Pathway—Notable Omission:

Despite Wu et al. identifying SR-BOF + CCS as the most economical long-term option for China (US$7-15 per tonne CO_2, achieving 6.0 gigatonnes reduction), the October 2025 policy contains no explicit CCS incentives comparable to EAF and hydrogen provisions.

This represents a strategic gap. Possible explanations:

1. CCS technology maturity timeline (post-2030) doesn't require immediate policy incentives
2. CCS will be addressed through separate carbon market mechanisms
3. Policy prioritizes proven technologies (EAF) and emerging priorities (hydrogen) for near-term action
4. CCS incentives may be added in final version after public comment period

4.2 Capacity Reduction: Beyond Wu et al. Scope

The 1.5:1 replacement ratio and 2027 trading termination address a dimension not fully captured in Wu et al.'s optimization model: absolute capacity reduction independent of utilization.

Wu et al. focus: Optimizing technology pathways for existing plants to meet carbon neutrality targets while meeting projected steel demand.

October 2025 policy focus: Reducing total capacity stock to address:

- Structural overcapacity (utilization rates below optimal)
- Market supply-demand imbalances
- Economic inefficiency from excess capacity

- Political economy of industrial restructuring

This represents complementary policy logic: Wu et al. optimize the *how* of decarbonization; the October 2025 policy addresses *how much* total capacity should exist.

4.3 Regional Air Quality vs. Carbon Goals

The stringent key region restrictions (**Article 9**) reflect China's dual environmental mandates:

1. Carbon neutrality by 2060 (national aggregate goal)
2. Air quality improvement in urban regions (local welfare goal)

Wu et al. focus primarily on CO_2 emissions, with sensitivity analysis including Scope 1 + 2 emissions. The October 2025 policy explicitly links capacity replacement to "equal or reduced replacement of major pollutant emissions" (**Article 21**), ensuring:

- SO_2, NO_x, and particulate matter reductions
- Environmental performance A-level standards
- Coordination with pollution reduction policies

This multi-pollutant approach explains why key region restrictions are stricter than carbon logic alone would dictate.

5 Implementation Challenges and Critical Analysis

5.1 The 2027 Trading Deadline: Window or Cliff?

The two-year capacity trading window before 2027 termination creates complex dynamics:

5.1.1 Potential Rush Effects

Accelerated Trading (2025-2027):

- Enterprises rush to execute capacity trades before market closes
- Capacity values may inflate as deadline approaches
- Risk of suboptimal matches between capacity sources and construction projects
- Potential for speculative capacity accumulation

Post-2027 Consolidation:

- Genuine M&A requirement raises barriers to capacity transfer
- May accelerate exit of financially weak enterprises unable to execute M&A
- Could concentrate capacity among financially strong state-owned enterprises
- Benefits: ensures substantive integration rather than paper transfers

5.1.2 Transition Period Risks

Article 20 grandfather provisions create complexity:

- Multiple policy regimes operating simultaneously (pre-August 2024, August 2024-2027, post-2027)
- Split capacity from old announcements can become void if not implemented within 24 months
- Contract disputes likely as parties navigate changing rules
- Provincial authorities face significant verification and enforcement burdens

5.2 EAF Transition: Incentives vs. Infrastructure

The EAF equal replacement incentive is economically powerful but faces structural constraints:

5.2.1 Electricity Cost Challenge

Wu et al. findings: Scrap-EAF has negative abatement costs in developed regions but faces challenges in China.

Real-world experience (2024-2025):

- EAF production stalled around 10%, missing 15% target
- High electricity costs compared to coal-based alternatives
- EAF producers face mounting financial losses
- Mill suspensions and bankruptcies

Policy response needed: Equal replacement provision addresses capacity economics but doesn't solve operating cost challenges. Complementary measures required:

- Electricity pricing reforms (industrial vs. renewable tariffs)
- Direct subsidies for EAF operational costs during transition

- Carbon pricing that increases coal-based production costs
- Grid infrastructure upgrades to support expanded EAF capacity

5.2.2 Scrap Supply Constraints

Wu et al. projection: Limited scrap availability constrains EAF expansion globally.

Chinese reality (2024-2025):

- Scrap imports halved in 2024 despite liberalization policies
- Domestic scrap collection systems underdeveloped
- Quality standards and contamination issues
- Trade-in programs failed to generate expected scrap volumes

Risk: EAF incentives may create capacity that cannot operate at full utilization due to feedstock shortages, undermining both economic and environmental goals.

5.3 Sub-National Enforcement: The Persistent Challenge

5.3.1 Historical Compliance Issues

Experience from 2024-2025 policies revealed significant enforcement gaps:

- Ten provinces recorded year-on-year output increases despite national reduction targets (H1 2025)
- Provincial economic growth incentives conflict with capacity reduction mandates
- Local governments protect employment and tax revenues
- Insufficient penalties for non-compliance

5.3.2 October 2025 Policy Enforcement Mechanisms

The draft policy strengthens oversight through:

Systematic Monitoring (Article 18):

- Annual provincial self-inspections with MIIT reports
- MIIT publicly announces national capacity replacement status
- Creates transparency and accountability

Project-Level Controls (Articles 16-17):

- Provincial authorities verify retired equipment demolition before construction project production
- Cross-provincial transfers require transferor province to confirm demolition
- Pre-production acceptance procedures with public announcement

Penalties (Article 18):

- Immediate halt of construction/production for violations
- Joint disciplinary actions against enterprises and consultants for fraud
- Circulars issued for regions with lax review or inadequate supervision

Open question: Will these mechanisms overcome political economy barriers that undermined previous policies? Success depends on:

1. Central government prioritization of enforcement over provincial growth concerns
2. Credible penalties that change cost-benefit calculations
3. Linking provincial official performance evaluations to compliance
4. Real-time monitoring systems that prevent violations rather than discovering them post-facto

5.4 Economic Viability During Industry Downturn

5.4.1 Financial Context

Chinese steel industry faced severe challenges in 2024-2025:

- Low steel prices due to weak domestic demand
- Overcapacity depressing profitability
- Export surge (40.8% year-on-year increase October 2024) triggering trade tensions
- 25 anti-dumping investigations globally in 2024

5.4.2 Policy Implementation Under Financial Stress

The October 2025 policy imposes significant costs:

Retirement costs:

- 1.5:1 replacement ratio means retiring 50% more capacity than built
- Demolition expenses

- Lost production value from retired capacity
- Employee placement costs for closed facilities

Technology transition costs:

- Capital investment in EAF or hydrogen facilities
- Operating cost premiums (electricity for EAF, green hydrogen costs)
- Learning curve inefficiencies during ramp-up

Risk: Financial stress may lead to:

1. Delay in executing capacity replacement plans
2. Gaming of 24-month validity periods
3. Lobbying for policy weakening during implementation
4. Increased bankruptcies accelerating industry consolidation (potentially desirable)

Wu et al. perspective: The study emphasizes that even the most aggressive (early deployment) scenario requires massive financial support. The medium scenario requires US$350 billion globally (2020-2050), with China potentially needing tens of billions for its share.

Policy gap: The October 2025 draft contains no explicit financial support mechanisms beyond the implicit subsidy of favorable replacement ratios for EAF/hydrogen. Additional measures needed:

- Direct subsidies for capacity retirement
- Green steel procurement mandates creating price premiums
- Preferential lending for low-carbon technology investments
- Carbon market revenues recycled to support transitions

6 Global Implications and Strategic Scenarios

6.1 Impact on Global Steel Markets

6.1.1 Capacity Reduction and Export Dynamics

If China successfully implements 1.5:1 replacement ratios:

Scenario A: Proportional Production Reduction

- China's capacity contracts 33% per replacement cycle
- Production falls proportionally (assuming utilization rates stable)
- Global steel prices increase due to supply reduction
- Other producers expand to fill gap
- Chinese exports decline, reducing trade tensions

Scenario B: Utilization Rate Optimization

- Capacity contracts but utilization rates increase from current overcapacity levels
- Production remains relatively stable or declines modestly
- Weak, inefficient producers exit; strong producers run at higher capacity utilization
- Export pressures may persist if domestic demand remains weak
- Industry consolidation accelerates

Most likely outcome: Hybrid scenario with modest production declines (5-10% over 5 years) but significant efficiency gains and emission intensity improvements.

6.1.2 Technology Diffusion and Cost Curves

China's large-scale deployment of EAF and hydrogen metallurgy will accelerate global learning curves:

Wu et al. cost projections rely on component-based learning curves with assumed cumulative capacity deployments. If China aggressively builds:

EAF expansion:

- Increasing EAF share from 10% to 20-25% of Chinese production adds 100-150 million tonnes/year EAF capacity
- Accelerates global learning curves for EAF technology
- Reduces costs faster than Wu et al. baseline projections
- Benefits other countries through technology spillovers and equipment cost reductions

Hydrogen metallurgy pilots:

- Early deployment (pre-2030) of hydrogen DRI at scale generates real-world operational data

- Validates or refutes Wu et al. cost projections
- Identifies bottlenecks in hydrogen supply chains, storage, and process integration
- Creates ecosystem of suppliers, engineers, and operating expertise

Reverse scenario: If implementation stalls due to economic headwinds or enforcement failures, learning curve assumptions may prove optimistic, delaying cost competitiveness of low-carbon technologies globally.

6.2 Carbon Border Adjustment Mechanisms

6.2.1 EU CBAM Implications

The EU's Carbon Border Adjustment Mechanism (CBAM), fully implemented from 2026, imposes carbon tariffs on steel imports based on embedded emissions. China's October 2025 policy creates strategic responses:

Scenario 1: Competitive Advantage Through Low-Carbon Technology

- Chinese producers adopting EAF (70% emission reduction) face lower CBAM charges
- Cost advantage from Wu et al. projections (US$7-15 per tonne CO_2 for CCS in China vs. US$26-52 in EU) maintained even with CBAM
- Chinese low-carbon steel competitive in EU markets
- Accelerates global decarbonization through trade competitiveness rather than trade barriers

Scenario 2: Domestic Carbon Pricing Coordination

- China includes steel in national ETS (currently piloting)
- Domestic carbon costs credited against CBAM charges
- Creates incentive for China to price carbon domestically rather than allowing EU to capture carbon revenues
- October 2025 policy's emission intensity requirements (Article 21) lay groundwork for carbon accounting

Scenario 3: Market Segmentation

- Low-carbon Chinese steel targets EU/developed markets
- High-carbon steel targets developing markets without carbon borders
- Bifurcated production system increases complexity but maximizes market access
- Risk: developing country carbon borders (announced by Canada, UK, Australia) narrow high-carbon export markets

6.3 Implications for Developing Economy Steel Sectors

6.3.1 India: The Critical Case

India represents the counterpoint to China: rapid industrialization driving steel demand growth from 500 million tonnes currently toward 1+ billion tonnes by 2050.

Wu et al. recommendations for India:

- Leverage low-cost domestic iron ore
- Prioritize energy efficiency improvements (negative costs)
- Begin zero-carbon transitions in 2040s once SR-BOF + CCS and DRI-BOF + 100% GH_2 mature
- Avoid post-2050 mitigation burden

China policy lessons for India:
What to replicate:

1. Capacity replacement ratios preventing overcapacity as production expands
2. EAF incentives to build scrap recycling infrastructure early
3. Energy efficiency standards for all new capacity
4. Regional air quality considerations in siting decisions

What to avoid:

1. Massive coal-based BF-BOF buildout that creates carbon lock-in
2. Capacity trading mechanisms that perpetuate inefficient plants
3. Weak sub-national enforcement allowing compliance gaps
4. Underinvestment in scrap collection systems before promoting EAF

India's advantage: Building infrastructure now, India can leapfrog to EAF and DRI-EAF with natural gas or hydrogen, avoiding China's challenge of replacing existing coal-intensive capacity. October 2025 China policy demonstrates that replacing existing capacity is politically and economically harder than building clean capacity initially.

6.3.2 Southeast Asia and Latin America

Emerging steel producers can leverage both Wu et al. science and China policy experience:

Technology choices:

- Skip BF-BOF entirely in favor of DRI-EAF (for countries with natural gas)
- Build EAF capacity where scrap availability expected to grow
- Plan hydrogen-ready DRI that can transition from natural gas
- Implement BAT standards from initial construction

Policy frameworks:

- Capacity replacement ratios prevent future overcapacity problems
- Equal replacement incentives for EAF/hydrogen create initial competitive advantages
- Regional restrictions protect urban air quality from start
- Time limits on approvals prevent capacity hoarding

7 Critical Uncertainties and Sensitivity Analysis

7.1 Technology Cost Trajectories

7.1.1 Wu et al. Sensitivity Findings

The Nature study conducted extensive sensitivity analysis on 22 cost drivers. Key findings:

CCS costs: Varying initial costs, learning rates, and cumulative capacity assumptions changes 2050 cost estimates by ±30-50%.

Green hydrogen: Cost projections highly sensitive to renewable electricity prices, electrolyzer learning rates, and capacity deployment scenarios. Variations of ±40-60% in 2050 costs.

Scrap prices: International scrap market volatility creates ±20-30% uncertainty in Scrap-EAF economics.

7.1.2 October 2025 Policy Robustness

How does policy perform under different technology cost scenarios?

Optimistic scenario (costs decline faster than Wu et al. baseline):

- EAF equal replacement provision highly valuable, accelerating transition

- Hydrogen equal replacement provision triggers early deployment
- 1.5:1 standard ratio may prove too conservative, reducing capacity more than necessary
- Policy should include review mechanisms to adjust ratios as technologies mature

Pessimistic scenario (costs decline slower than projections):

- EAF incentives insufficient to overcome operating cost barriers
- Hydrogen deployment stalls, equal replacement provision underutilized
- Enterprises lobby for standard ratio reductions or additional exemptions
- Financial stress increases, requiring government support beyond policy incentives

Most likely (heterogeneous outcomes):

- EAF costs favorable in some regions (coastal areas with scrap access), challenging elsewhere
- Hydrogen viable in renewable-rich provinces (Inner Mongolia, Qinghai), uneconomic in others
- Regional policy differentiation needed beyond current key region provisions
- Standard 1.5:1 ratio appropriate in aggregate but may need regional flexibility

7.2 Demand Projections and Material Efficiency

7.2.1 Wu et al. Demand Assumptions

The optimization model uses IEA demand projections through 2050. However, these face significant uncertainties:

Circular economy effects:

- Increased material efficiency in construction (design optimization, higher strength steels)
- Product lifetime extension through remanufacturing
- Substitution with alternative materials (timber, composites, aluminum)
- Could reduce steel demand 20-30% below baseline projections

Economic growth scenarios:

- China's GDP growth slowing affects steel-intensive infrastructure investment
- Shift from investment-led to consumption-led growth reduces steel intensity
- Aging population and urbanization saturation decrease construction demand

7.2.2 Policy Implications of Demand Uncertainty

If demand lower than projected:

- 1.5:1 replacement ratio accelerates capacity reduction appropriately
- Overcapacity problem solved faster
- Financial stress on industry increases as production declines
- Need stronger consolidation mechanisms and exit support

If demand higher than projected:

- Capacity constraints emerge, driving prices up
- Pressure to relax 1.5:1 ratio or expand exemptions
- Imports increase to fill gap
- Policy review mechanisms essential to avoid supply shortages

Recommended policy flexibility:

- Mandatory policy review every 5 years tied to demand forecasts
- Adjustment mechanisms for replacement ratios based on utilization rates
- Strategic reserve capacity provisions for supply security

7.3 Climate Policy Ambition Trajectories

7.3.1 National Carbon Neutrality Timelines

Wu et al. model assumes countries meet announced carbon neutrality targets (China 2060, EU 2050, etc.). However:

Acceleration scenario:

- China advances target to 2055 or 2050 in response to climate impacts
- Requires faster deployment of zero-carbon technologies
- October 2025 policy's EAF/hydrogen incentives become even more critical

- May need stronger measures: carbon pricing, BAT mandates, BF-BOF phase-out dates

Delay scenario:

- Global climate ambition weakens, extending neutrality timelines
- Reduces urgency of October 2025 policy measures
- Risk: capacity reduction proceeds faster than decarbonization, missing opportunity to align both goals
- Could lead to policy rollback pressures

Sectoral differentiation scenario:

- Steel sector given specific carbon budget separate from economy-wide target
- October 2025 policy's Article 21 coordination with carbon emissions dual control enables this
- Allows optimization of mitigation timing across sectors
- Steel decarbonization may proceed faster or slower than economy average depending on relative costs

8 Strategic Recommendations

8.1 For Chinese Policy Implementation

8.1.1 Near-Term (2025-2027): Critical Window

Finalize October 2025 policy with enhancements:

1. **Add explicit CCS incentives:** Include equal or reduced replacement provisions for SR-BOF + CCS projects meeting emission reduction thresholds, aligned with Wu et al. findings that CCS is most economical long-term option for China
2. **Strengthen scrap infrastructure provisions:** Mandate provincial scrap collection system development targets tied to EAF deployment plans
3. **Address electricity pricing:** Direct coordination with National Energy Administration to ensure EAF access to competitive renewable electricity tariffs
4. **Clarify enforcement penalties:** Specify financial penalties for violations (e.g., percentage of project investment), not just procedural sanctions

5. **Establish review mechanisms:** Mandatory 5-year policy review tied to demand forecasts, technology costs, and climate goals

Maximize 2027 trading window:

- Expedite capacity verification processes to enable trades before deadline
- Publish transparent capacity trading platforms to facilitate efficient matches
- Monitor for speculative behavior and market manipulation
- Prepare M&A guidelines and approval processes for post-2027 era

Launch complementary policies:

- Green steel procurement mandates for infrastructure projects (price premiums of 5-10%)
- Subsidized financing for EAF and hydrogen capital investments
- Worker retraining programs for employees displaced by capacity retirement
- Regional economic transition support for steel-dependent cities

8.1.2 Medium-Term (2027-2035): Technology Transition

Accelerate pilot deployments:

1. **CCS demonstration projects:** Target 10-20 SR-BOF + CCS facilities by 2030, validating Wu et al. US$7-15 per tonne CO_2 cost projections
2. **Hydrogen metallurgy pilots:** 3-5 GW-scale DRI-H_2 projects in renewable-rich regions
3. **Scrap-EAF optimization:** Advanced sorting, quality control, and contamination reduction technologies

Develop enabling infrastructure:

- CO_2 pipeline networks connecting major steel regions to storage sites
- Green hydrogen production hubs with dedicated renewable electricity
- Upgraded electricity grids for expanded EAF capacity
- Scrap collection, processing, and quality certification systems

Refine policy based on implementation experience:

- Adjust replacement ratios if technology costs decline faster than projected
- Expand regional differentiation based on local resource endowments
- Calibrate key region restrictions with air quality improvements
- Coordinate with carbon market development and pricing

8.1.3 Long-Term (2035-2060): Deep Decarbonization

Scale proven technologies:

- Transition majority of BF-BOF capacity to SR-BOF + CCS (leveraging cost advantages)
- Expand EAF to 25-30% of production with mature scrap systems
- Deploy hydrogen metallurgy at 10-15% of production in suitable regions
- Phase out remaining unabated BF-BOF by 2050-2055

Align with broader industrial strategy:

- Integrate steel decarbonization with hydrogen economy development
- Coordinate CO_2 storage utilization across industrial sectors
- Position China as exporter of low-carbon steel technology and equipment
- Leverage steel decarbonization experience for other hard-to-abate sectors (cement, chemicals)

8.2 For Global Stakeholders

8.2.1 Developed Economies

Policy coordination:

- Harmonize carbon border adjustments to avoid trade distortions and conflicting incentives
- Share technology and best practices from early EAF and hydrogen deployments
- Provide climate finance for developing economy leapfrogging strategies
- Coordinate standards for green steel certification and carbon accounting

Technology development:

- Accelerate CCS cost reductions through R&D and demonstration projects
- Drive down green hydrogen costs through electrolyzer innovation and renewable energy deployment
- Develop next-generation technologies (direct electrolysis, novel reduction processes) for post-2050
- Open-source learnings to accelerate global deployment

Market creation:

- Implement green public procurement mandates creating demand for low-carbon steel
- Establish price premiums through contracts-for-difference or other mechanisms
- Support development of green steel supply chains in automotive, construction, machinery sectors
- Use carbon pricing at levels (US$75-150 per tonne CO_2) that incentivize technology deployment

8.2.2 Developing Economies

Leapfrogging strategies:

- Avoid coal-intensive BF-BOF buildout; prioritize DRI-EAF with natural gas or hydrogen-ready designs
- Implement capacity controls from start to prevent overcapacity problems
- Build scrap collection infrastructure during early industrialization
- Adopt BAT energy efficiency standards for all new capacity

Access finance and technology:

- Leverage climate finance mechanisms (Green Climate Fund, bilateral aid) for capital-intensive low-carbon technologies
- Technology transfer agreements with Chinese and developed economy equipment suppliers
- Regional cooperation on scrap trading and hydrogen infrastructure
- Participate in global green steel standards development to ensure developing economy interests represented

Policy frameworks inspired by October 2025 China approach:

- Capacity replacement ratios adjusted for growth phase (e.g., 1.1:1 allowing modest capacity expansion while incentivizing efficiency)
- Equal replacement incentives for EAF, hydrogen, and other low-carbon technologies
- Regional air quality protections in urban areas
- Transparent project approval and monitoring systems

8.2.3 Steel Companies

Strategic positioning:

1. **Assess plant-specific pathways:** Use Wu et al. methodology to identify least-cost decarbonization options for each facility based on age, technology, location, and local resource availability
2. **Execute near-term efficiency gains:** Implement BAT measures immediately given negative costs; generates cash flow to fund later transitions
3. **Diversify technology portfolio:** Invest in EAF, CCS, and hydrogen projects to hedge technological uncertainty
4. **Time capital cycles:** Plan major retrofits to align with policy timelines (China 2027 trading deadline, national neutrality targets) and technology cost declines

Operational priorities:

- Secure scrap supply contracts before EAF expansion
- Negotiate renewable electricity power purchase agreements for EAF operations
- Participate in CCS infrastructure consortia to share costs
- Develop workforce skills for new technologies

Financial planning:

- Model cash flows under different carbon price scenarios
- Pursue green bonds and sustainability-linked financing with favorable terms
- Prepare for asset write-downs on stranded high-carbon capacity
- Position for premium pricing of certified low-carbon steel

9 Conclusion: A Watershed Moment

November 2025 represents an inflection point in global steel decarbonization. The convergence of rigorous scientific analysis (Wu et al.) with China's revolutionary October 2025 policy draft creates unprecedented clarity on both *what* must be done and *how* to do it.

9.1 Key Findings and Insights

9.1.1 The Science is Clear

Wu et al. demonstrate that cost-effective pathways to carbon-neutral steel exist:

1. **Immediate opportunities:** Energy efficiency improvements and scrap recycling offer 15+ gigatonnes cumulative CO_2 reduction at negative or near-zero costs

2. **Technology timing matters:** Medium deployment scenario (low-carbon technologies as bridges to zero-carbon) achieves 22.4 gigatonnes reduction at US$24.7 per tonne CO_2—40% cheaper than rushing to zero-carbon immediately

3. **Regional advantages are substantial:** Chinese plants can deploy CCS at US$7-15 per tonne CO_2 (4-5 times cheaper than Japan/Korea/Europe), creating competitive advantages

4. **Plant heterogeneity demands customization:** One-size-fits-all approaches fail; optimal pathways vary by technology, age, location, and national policy context

9.1.2 China's Policy is Transformative

The October 2025 Implementation Measures represent the most aggressive industrial decarbonization policy enacted by any major economy:

1. **Guaranteed capacity reduction:** 1.5:1 replacement ratio ensures absolute capacity contraction of 33% per cycle, addressing overcapacity while forcing modernization

2. **Technology transition incentives:** Equal replacement for EAF and hydrogen creates 50% capacity bonuses worth billions of RMB, making low-carbon investment economically rational

3. **Trading window closure:** 2027 deadline for inter-enterprise capacity replacement forces industry consolidation through genuine M&A rather than paper transfers

4. **Robust enforcement:** Project time limits, pre-production acceptance, annual reporting, and public transparency create accountability mechanisms absent from prior policies

9.1.3 Alignment is Strong but Incomplete

The October 2025 policy aligns remarkably well with Wu et al. cost-optimal pathways:

- **Short-term:** EAF incentives match Wu et al. identification of scrap recycling as US$0.3 per tonne CO_2 abatement cost
- **Long-term:** Hydrogen equal replacement accelerates technology Wu et al. project becomes competitive post-2040
- **Gap:** No explicit CCS incentives despite Wu et al. identifying SR-BOF + CCS as most economical option for China (US$7-15 per tonne CO_2, 6.0 gigatonnes reduction potential)

9.2 Critical Uncertainties

Despite the alignment, significant challenges remain:

Implementation risks:

- EAF transition faces electricity cost and scrap supply constraints that incentives alone cannot solve
- Sub-national enforcement has historically been weak; October 2025 mechanisms may prove insufficient
- Financial stress on industry during overcapacity and weak demand may undermine compliance
- 2027 trading deadline could trigger rush effects or delays depending on enterprise strategies

Technology uncertainties:

- Wu et al. cost projections rely on learning curves with ±30-60% uncertainty bands
- Scrap availability may not materialize at projected levels
- Green hydrogen costs highly sensitive to renewable deployment and electrolyzer learning
- CCS scale-up may face public acceptance or storage capacity constraints

Demand scenarios:

- Circular economy and material efficiency could reduce demand 20-30% below IEA projections

- China's economic slowdown and demographic shifts may accelerate demand decline
- 1.5:1 replacement ratio may prove too aggressive or conservative depending on demand trajectories

9.3 The Path Forward

Success requires coordinated action across multiple dimensions:

9.3.1 For China (The Pivot)

Finalize and implement October 2025 policy with enhancements:

- Add CCS incentives comparable to EAF and hydrogen provisions
- Develop scrap infrastructure and electricity pricing complementary policies
- Strengthen enforcement with financial penalties and real-time monitoring
- Include 5-year review mechanisms for adaptive management

Execute demonstration projects at scale:

- 10-20 SR-BOF + CCS facilities by 2030 validating cost projections
- 3-5 GW hydrogen DRI projects generating operational learnings
- Advanced scrap-EAF optimization systems

Maximize learning curve benefits:

- Rapid deployment of proven technologies accelerates cost reductions globally
- Technology and equipment exports support developing economy leapfrogging
- Open-source learnings from demonstration projects

9.3.2 For Developed Economies (The Innovators)

Technology leadership:

- Drive down hydrogen costs through electrolyzer innovation and renewable energy deployment
- Pioneer next-generation technologies (direct electrolysis) for post-2050
- Share learnings with global community to accelerate deployment

Market creation:

- Implement green procurement creating demand for low-carbon steel
- Harmonize carbon border adjustments to avoid distortions
- Establish price premiums through contracts-for-difference mechanisms

Climate finance:

- Support developing economy leapfrogging with technology transfer and capital
- Co-fund demonstration projects in emerging markets
- Facilitate access to low-cost financing for capital-intensive technologies

9.3.3 For Developing Economies (The Leapfroggers)

Avoid carbon lock-in:

- Skip coal-intensive BF-BOF in favor of DRI-EAF and hydrogen-ready designs
- Implement capacity controls from start preventing future overcapacity
- Build scrap infrastructure during early industrialization

Adopt best practices:

- Capacity replacement ratios adjusted for growth phase
- Equal replacement incentives for low-carbon technologies
- Transparent approval and monitoring systems
- BAT energy efficiency standards for all new capacity

Leverage international support:

- Access climate finance for capital-intensive technologies
- Participate in technology transfer agreements
- Join global green steel standard-setting processes

9.4 The Stakes

The iron and steel sector's decarbonization is essential for meeting Paris Agreement temperature targets. At 7% of global emissions and growing with industrialization, there is no path to 1.5°C or even 2°C that does not include deep steel decarbonization.

The tools now exist:

- Wu et al. provide the scientific roadmap identifying cost-optimal pathways
- October 2025 China policy demonstrates the regulatory architecture for implementation
- Technologies are maturing: EAF proven, CCS approaching viability, hydrogen on the horizon
- Economic case is strengthening: many interventions offer negative costs, others approaching competitiveness

The question is no longer *can* we decarbonize steel, but *will* we implement the pathways and policies fast enough?

China's experience over the next 2-5 years will be decisive. If the October 2025 policy successfully drives capacity reduction, accelerates EAF deployment, and launches hydrogen pilots while maintaining industry viability, it validates that aggressive industrial decarbonization is politically and economically feasible. Success would trigger policy emulation globally and accelerate technology cost reductions through learning curves.

Conversely, if implementation stalls due to economic headwinds, enforcement gaps, or technological challenges, it signals that the transition is harder than models suggest, requiring either longer timelines, greater financial support, or technological breakthroughs.

November 2025 may be remembered as the moment when the steel industry's decarbonization pathway crystallized from abstract projections into concrete policy. The convergence of rigorous science and revolutionary policy creates unprecedented opportunity. Whether that opportunity is seized or squandered will shape not only the steel industry but the global climate trajectory for decades to come.

References

[1] Wu, X., Meng, J., Liang, X., et al. (2025). Technological pathways for cost-effective steel decarbonization. *Nature*, 647, 93-101. https://doi.org/10.1038/s41586-025-09658-9

[2] Ministry of Industry and Information Technology, People's Republic of China. (2025, October). Implementation Measures for Capacity Replacement in the Steel Industry (Draft for Comments). Retrieved from https://www.miit.gov.cn/

[3] Transition Asia. (2024). Decoding China's Steel Capacity Replacement Policies. Retrieved from https://transitionasia.org/

[4] Mysteel Global. (2025, March 5). 'Two Sessions': China to maintain steel output control, industry restructuring in 2025. Retrieved from https://www.mysteel.net/

[5] Nakano, J. (2024, October 24). Circular Economy Solutions for China's Steel Industry: Addressing the Dual Challenge of Overcapacity and Emissions. *Center for Strategic and International Studies*. Retrieved from https://www.csis.org/

[6] Centre for Research on Energy and Clean Air. (2024, October 21). Turning point: China permitted no new coal-based steel projects in H1 2024 as policies drive decarbonisation. Retrieved from https://energyandcleanair.org/

[7] Centre for Research on Energy and Clean Air. (2025, July 23). Closing the loop: from stalled green steel targets to a strategic reset in China. Retrieved from https://energyandcleanair.org/

[8] GMK Center. (2025, August 29). China to cut steel production by at least 25 million tons in 2025. Retrieved from https://gmk.center/

[9] International Energy Agency. (2020). Iron and Steel Technology Roadmap: Towards More Sustainable Steelmaking. Paris: IEA.

[10] World Steel Association. (2023). Steel Statistical Yearbook 2023. Brussels: World Steel Association.

[11] State Council of the People's Republic of China. (2024, May 29). Energy Conservation and Carbon Reduction Action Plan for the 14th Five-Year Plan Period. Beijing: State Council.

[12] State Council of the People's Republic of China. (2023). Notice on Issuing the Action Plan for Continuous Improvement of Air Quality (State Council [2023] No. 24). Beijing: State Council.