MIFUS

Mini Instant Fall University School

A Journey through Steel Decarbonization Policies Worldwide

Integrating Diamond's Historical Perspective, Smil's Material Science, Christensen's Distruptive Innovation Theory of
BIG STEEL vs MINIMILLS

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"History followed different courses for different peoples because of differences among peoples' environments, not because of biological differences among peoples themselves."

— Jared Diamond, *Guns, Germs, and Steel*

Abstract

This teaching document provides a comprehensive framework for understanding steel industry decarbonization by integrating four critical perspectives: Jared Diamond's historical analysis of material civilization, Vaclav Smil's material constraints perspective from *Still the Iron Age*, Clayton Christensen's disruptive innovation theory, and emerging alternative ironmaking technologies. By combining these approaches, we develop a methodology for analyzing policy interventions and technological transitions in one of the world's most carbon-intensive and historically significant industries.

Contents

1 Historical and Cultural Context: From Diamond to Steel

1.1 Guns, Germs, and Steel: A Framework for Material Civilization

Jared Diamond's seminal work *Guns, Germs, and Steel* provides an essential historical lens through which to understand our current steel challenge. Diamond argues that the trajectory of human civilizations has been fundamentally shaped by material conditions—particularly access to domesticable plants and animals, which enabled food surpluses, specialization, and ultimately technological development.

1.1.1 The Three Pillars of Civilization

Diamond identifies three key factors that determined which societies would come to dominate:

1. **Guns (Technology and Military Power):**

- Steel weapons and armor gave European conquistadors decisive advantages
- Iron and steel enabled agricultural tools, increasing productivity
- Technological superiority arose from material advantages, not inherent capability
- The Iron Age marked humanity's ability to shape the hardest, most versatile metal

2. **Germs (Disease and Biological Factors):**

- Epidemic diseases arose from domesticated animals in agricultural societies
- Populations with long agricultural histories developed immunity
- The COVID-19 pandemic (2020-2023) reminded us we remain vulnerable to biological threats
- Global supply chains, including steel, proved fragile during pandemic disruptions

3. **Steel (Material Foundation of Modernity):**

- Iron and steel have been civilization's backbone since approximately 1200 BCE
- Steel enables: buildings, bridges, vehicles, machinery, energy infrastructure
- We are *still* in the Iron Age—no material can replace steel at scale
- But now we face the climate cost of this material dependence

1.1.2 Contemporary Resonance: Guns, Germs, Steel in 2025

Diamond's framework remains disturbingly relevant:

Guns - We Are in a Period of Conflict:

- Russia-Ukraine war (2022-present): artillery, tanks, steel-intensive warfare
- Middle East conflicts: ongoing tensions requiring military steel
- Strategic competition: naval vessels, military vehicles demand high-quality steel
- *Steel remains literally at the center of geopolitical power*

Germs - We Have Suffered Through Pandemic:

- COVID-19 disrupted global steel supply chains (2020-2022)
- Revealed vulnerability of just-in-time production systems
- Hospital equipment, vaccine production facilities required steel infrastructure
- Recovery period exposed fragility of globalized steel markets

Steel - We Must Deal With It Now:

- Climate crisis requires decarbonizing 2 billion tonnes/year production
- Cannot eliminate steel—must transform how we produce it
- Unlike guns (can be reduced) or germs (can be treated), steel is indispensable
- As Smil argues: we are *Still in the Iron Age*

1.2 The Paradox: Material Dependence Meets Climate Imperative

Diamond's historical analysis reveals a profound paradox we face today:

> *The very material foundations that enabled human civilization—iron and steel—now threaten the climate stability upon which that civilization depends. We cannot abandon steel, yet we cannot continue producing it as we have for millennia.*

This paradox sets the stage for our analysis:

- **Historical Lock-in:** 3,200 years of iron-based technology creates path dependence
- **Material Necessity:** No substitute exists for steel at required scale and properties
- **Climate Urgency:** Steel production accounts for 7-9% of global CO_2 emissions
- **Geopolitical Reality:** Strategic competition increases steel demand (military, infrastructure)

1.3 From Historical Analysis to Policy Framework

Diamond's work teaches us that:

1. **Geography and Resources Matter:** Countries with abundant renewable energy (Iceland, Norway, Sweden) have advantages in green steel transition
2. **Technology Diffusion is Uneven:** Advanced steelmaking will spread at different rates across regions
3. **Material Civilization Resists Change:** Deeply embedded technologies (like ironmaking) transform slowly
4. **Crises Drive Innovation:** War (Guns) and Pandemic (Germs) may accelerate Steel transformation

This historical foundation now leads us to examine three contemporary frameworks for understanding and shaping the steel transition.

2 Introduction: The Steel Decarbonization Challenge

The global steel industry accounts for approximately 7-9% of direct fossil fuel CO_2 emissions, producing nearly 2 billion tonnes of steel annually. Decarbonizing this sector requires understanding four interconnected dimensions:

- **Historical Context:** How we arrived at steel dependence (Diamond)
- **Material Reality:** The physical and chemical constraints of iron reduction (Smil)
- **Innovation Dynamics:** How new technologies can displace incumbent processes (Christensen)
- **Technical Alternatives:** Emerging pathways beyond the blast furnace (Hasanbeigi et al.)

This document provides an integrated framework for policy analysis by combining these perspectives.

3 Framework 1: Smil's Material Constraints

3.1 The Dominance of Iron

Vaclav Smil's *Still the Iron Age* emphasizes that despite predictions of a post-industrial, dematerialized economy, we remain fundamentally dependent on iron and steel. Key insights include:

3.1.1 Scale and Inertia

- Steel production has grown continuously for 150 years
- Global infrastructure is built on steel (buildings, bridges, vehicles, machinery)
- Replacement cycles are measured in decades, not years
- No material can substitute steel at current scale and cost

3.1.2 Thermodynamic Realities

The fundamental chemistry of steelmaking imposes hard constraints:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \tag{1}$$

Key points:

- Reducing iron oxide requires significant energy
- Carbon has been the optimal reductant for millennia
- Temperature requirements: 1,500-2,000°C for blast furnaces
- Energy intensity: approximately 20 GJ/tonne steel

3.1.3 Smil's Policy Implications

1. **Gradualism:** Rapid transformation is physically implausible
2. **Efficiency First:** Incremental improvements offer immediate returns
3. **Material Reduction:** Use less steel through better design
4. **Realistic Timelines:** Infrastructure transitions require 30-50 years

3.2 Teaching Application

When analyzing steel policies through Smil's lens, students should ask:

- Does this policy acknowledge thermodynamic constraints?
- What are the material substitution possibilities (if any)?
- Is the timeline realistic given infrastructure inertia?
- Does it account for scale (2 billion tonnes/year)?

4 Framework 2: Christensen's Disruptive Innovation

4.1 The Textbook Case: Minimills vs. Big Steel

IT'S THE ECONOMY, STUPID!

Before discussing green steel, we must understand the MOST IMPORTANT disruption in steel history: the rise of minimills and Electric Arc Furnaces (EAF) that destroyed integrated Big Steel.

> **REQUIRED VIEWING:** Watch this lecture on steel industry disruption:
> `https://www.youtube.com/watch?v=IwVa-bkciFE`
> This video provides essential context for understanding how economic forces, not environmental concerns, drove the greatest transformation in steel history.

4.1.1 The Classic Disruption Story (1960s-2000s)

The Incumbents: Integrated Steel Mills (BF-BOF)

- Massive capital investments: $3-5 billion facilities
- Vertically integrated: iron ore → blast furnace → BOF → products
- Optimized for high-volume, high-quality steel
- Companies: US Steel, Bethlehem Steel, British Steel, etc.
- Dominant for 100+ years

The Disruptors: Minimills (EAF)

- Small-scale: $200-500 million initial investment
- Simple process: scrap metal → electric arc furnace → products
- Initially produced LOW-QUALITY steel (rebar, simple products)
- Companies: Nucor, Chaparral, Steel Dynamics
- Started in 1960s-1970s as ”toy” operations

4.1.2 Why Big Steel Failed: The Christensen Playbook

Phase 1: Foothold Market (1960s-1970s)

- Minimills entered LOW-END market: rebar for construction
- Big Steel didn’t care: ”We don’t want that low-margin business anyway”
- Minimills had 20-30% cost advantage (no blast furnace, used scrap)
- Quality was poor, but good enough for simple products

Phase 2: Moving Upmarket (1980s-1990s)

- Minimills improved quality: better metallurgy, continuous casting
- Moved into structural steel, then sheet steel
- Big Steel still dismissive: ”They can’t make automotive-grade steel”
- But cost advantage remained and quality gap narrowed

Phase 3: Mainstream Displacement (1990s-2000s)

- Minimills achieved automotive-grade quality
- Cost advantage: 15-25% lower than integrated mills
- Flexibility: could change product mix quickly
- Result: US integrated steelmakers bankrupted (Bethlehem Steel 2001, etc.)

4.2 The Economics That Big Steel Ignored

Capital Intensity:

- BF-BOF: $1,000-1,500 per tonne annual capacity
- EAF minimill: $300-500 per tonne annual capacity
- Big Steel couldn't compete on CAPEX efficiency

Operating Costs:

- BF-BOF energy: 20 GJ/tonne (coal, coke production)
- EAF energy: 400-500 kWh/tonne (electricity only)
- Scrap cost $<$ iron ore + coking coal cost

Market Share Evolution:

- 1970: EAF share of US steel production = 15%
- 1990: EAF share = 38%
- 2010: EAF share = 61%
- 2025: EAF share = 70%

4.3 The Current Disruption: China October 2025

CRITICAL DATA: Mimit Report, China, October 2025
China is NOW experiencing the same disruption:

- **Ratio 1.5:1** - For every 1.5 Blast Furnaces shut down, 1 EAF minimill is built
- This is NOT about environment (primarily)
- This IS about ECONOMICS and overcapacity management
- China producing 1 billion tonnes/year - must modernize

Why China is Switching to EAF:

1. **Lower CAPEX:** 1/3 the investment of new blast furnace
2. **Scrap availability:** China now has massive scrap supply (infrastructure aging)
3. **Flexibility:** Can turn EAF on/off based on electricity prices
4. **Environmental bonus:** 50% lower CO_2 emissions (but this is secondary)
5. **Capacity replacement:** Retire old, inefficient BF; replace with modern EAF

4.4 Why This Matters for Green Steel Transition

The disruption is ALREADY HAPPENING - not because of climate policy, but because of ECONOMICS!

4.4.1 Current Global Steel Production Mix (2025)

- BF-BOF: 70% of global production (1.4 billion tonnes)
- EAF: 30% of global production (600 million tonnes)
- Trend: EAF growing 2-3% per year market share

4.4.2 The Green Steel Advantage of EAF

- EAF with scrap: 0.4-0.6 tonnes CO_2/tonne steel
- BF-BOF: 2.0-2.5 tonnes CO_2/tonne steel
- **Already 70-80% lower emissions WITHOUT any new technology!**

4.4.3 The Next Wave: EAF + DRI

Now the disruption continues:

- EAF + DRI (natural gas): 1.0-1.3 tonnes CO_2/tonne steel
- EAF + H2-DRI (green hydrogen): 0.1-0.2 tonnes CO_2/tonne steel
- Same minimill flexibility + route to zero carbon

4.5 Christensen's Three Lessons for Steel Decarbonization

Lesson 1: Disruption Comes from Economics, Not Technology Alone

- Minimills won because they were CHEAPER, not cleaner
- Green steel will win when it's COMPETITIVE, not just green
- Policy should focus on economics (carbon price, CAPEX support)

Lesson 2: Incumbents Will Resist Until It's Too Late

- Big Steel dismissed minimills for 30 years
- Integrated producers will resist EAF+H2-DRI transition
- Policy must create markets that bypass incumbents

Lesson 3: The Transition Takes Decades But Accelerates

- Minimill disruption: 1960-2000 (40 years)
- But final phase (1995-2005) was rapid collapse of Big Steel
- Green steel disruption: expect 20-30 year transition, with rapid final phase

Table 1: Integrated Mills vs. Minimills: The Economic Disruption

Factor	BF-BOF	EAF (scrap)	Advantage
CAPEX ($/tonne capacity)	1,000-1,500	300-500	EAF: 66-75% lower
Energy (GJ/tonne)	20	1.8 (0.5 MWh)	EAF: 90% lower
Raw material	Iron ore + coal	Scrap	Depends on prices
Flexibility	Low	High	EAF
CO_2 (tonnes/tonne steel)	2.0-2.5	0.4-0.6	EAF: 75% lower
Product range	Full	Limited → Full	Was BF, now EAF

4.6 The Minimill Disruption: Summary Economics

4.7 Policy Implications from Christensen and Minimill History

IT'S THE ECONOMY, STUPID! Policies must focus on making green steel COMPETITIVE:

1. **Carbon Pricing:** Make BF-BOF economics worse, EAF+H2 economics better
2. **Scrap Markets:** Develop efficient scrap collection and trading
3. **Electricity Pricing:** Time-of-use rates for flexible EAF operation
4. **CAPEX Support:** Subsidize minimill construction (lower capital barrier)
5. **Green Procurement:** Government buys EAF steel, creates foothold market
6. **Stranded Asset Policy:** Compensate BF closures to accelerate transition

4.8 China's 1.5:1 Replacement as Policy Model

The Chinese approach (Mimit report, October 2025) offers a template:

Capacity Replacement Formula:

- Close 1.5 tonnes of BF-BOF capacity
- Build 1.0 tonnes of EAF capacity
- Net result: reduced overcapacity + modernization + lower emissions

Why 1.5:1 ratio?

- EAF is more efficient (less yield loss)
- Addresses overcapacity problem simultaneously
- Economic incentive: cheaper CAPEX for new capacity
- Environmental benefit is bonus, not primary driver

4.9 Teaching Application: Learn from Minimill History!

Students analyzing steel policies MUST ask:

Economic Questions (Primary):

- Does this policy improve cost competitiveness of low-carbon steel?
- What is the CAPEX differential between old and new technology?
- Are operational costs (energy, raw materials) favorable for disruption?
- How does scrap availability affect economics?

Disruption Questions:

- Does this create foothold markets for disruptive technology?
- How does it address incumbent resistance?
- What is the expected timeline based on minimill precedent?
- Are we making same mistake as Big Steel (ignoring economics)?

The Fatal Error: Treating steel decarbonization as purely environmental or technological problem, while ignoring that **minimills already demonstrated the winning formula: lower CAPEX + operational flexibility + cost advantage = disruption**.

The green steel transition is NOT a new disruption - it's the CONTINUATION of the minimill disruption that began 60 years ago!

5 Framework 3: Alternative Ironmaking Technologies

5.1 Beyond the Blast Furnace

Alternative ironmaking represents the technological frontier for decarbonization. Key pathways include:

5.1.1 Direct Reduction (DR)

Conventional DR (Natural Gas):

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

Characteristics:

- Lower temperature than blast furnace (800-1,050°C)
- Produces direct reduced iron (DRI) or hot briquetted iron (HBI)
- Currently 7-8% of global iron production
- CO_2 emissions: 0.7-1.3 tonnes CO_2/tonne steel (vs. 2.0-2.5 for BF)

Hydrogen-based DR (H2-DRI):

- Uses green hydrogen from electrolysis
- Near-zero direct CO_2 emissions
- Requires massive renewable energy (3-4 MWh/tonne steel)
- Commercial demonstrations: HYBRIT (Sweden), H2 Green Steel

5.1.2 Smelting Reduction

Technologies that combine iron reduction and melting in one vessel:

- **HIsmelt/HIsarna:** Uses coal but more efficient than BF
- **Finex:** Direct use of fine ore and coal
- 10-15% lower CO_2 than conventional BF-BOF

5.1.3 Electrolysis-Based Ironmaking

Molten Oxide Electrolysis (MOE):

- Direct electrolysis of iron ore in molten oxide bath
- Byproduct: oxygen (not CO_2)
- Very high electricity requirement (3.5-4 MWh/tonne)
- Still in early development stage

Advantages:

- Zero direct carbon emissions
- Modular and scalable
- Could integrate with renewable energy

Challenges:

- High capital costs
- Electrode durability
- Requires very cheap clean electricity

5.1.4 Plasma-Based Technologies

- Use plasma torches for high-temperature reduction
- Experimental stage
- Potential for small-scale, distributed production

Table 2: Alternative Ironmaking Technologies Comparison

Technology	**TRL**	**CO_2 Reduction**	**Energy**	**CAPEX**
BF-BOF (baseline)	9	-	20 GJ/t	Baseline
H2-DRI	7-8	95%	3-4 MWh/t	1.5-2x
MOE	4-5	100%	3.5-4 MWh/t	2-3x
Smelting Reduction	8-9	10-15%	18 GJ/t	1.1-1.3x
Carbon Capture (BF)	7-8	80-90%	22 GJ/t	1.3-1.5x

5.2 Technology Comparison Matrix

TRL = Technology Readiness Level (1-9 scale)

5.3 Policy Implications

1. **Portfolio Approach:** Support multiple technology pathways
2. **Infrastructure Needs:** H2 production, storage, and transport
3. **Electricity Grid:** Massive expansion of renewable capacity
4. **Risk Management:** Diversify technology bets given uncertainties

6 Integrated Methodology for Policy Analysis

6.1 The Four-Lens Approach

When analyzing steel decarbonization policies, apply all four frameworks systematically:

6.1.1 Step 0: Historical Context (Diamond Lens)

- What is the geographic/resource context of this policy?
- How does historical path dependence affect implementation?
- Are there geopolitical factors (conflict, strategic materials)?
- How might crisis conditions (pandemic, war) affect adoption?

6.1.2 Step 1: Material Reality Check (Smil Lens)

- Is the policy thermodynamically feasible?
- Does it account for the scale of steel production?
- Are timelines realistic given infrastructure inertia?
- What are the material and energy requirements?

6.1.3 Step 2: Innovation Dynamics (Christensen Lens)

- Does the policy create foothold markets?
- How does it address incumbent resistance?
- What is the disruption pathway enabled?
- Are there mechanisms for managing stranded assets?

6.1.4 Step 3: Technology Assessment (Alternative Ironmaking Lens)

- Which specific technologies does the policy support?
- What is the technology readiness level?
- What are the infrastructure requirements?
- How does it fit within a portfolio approach?

6.2 Policy Typology Matrix

Policies can be categorized along two dimensions:

- **Time Horizon:** Short-term (0-10 years) vs. Long-term (10-50 years)
- **Innovation Type:** Sustaining vs. Disruptive

Table 3: Policy Typology for Steel Decarbonization

	Sustaining Innovation	**Disruptive Innovation**
Short-term (0-10 years)	Energy efficiency standards Best practice diffusion Carbon pricing	Green procurement Demonstration projects Niche market creation
Long-term (10-50 years)	CCS retrofits Advanced BF technology Material efficiency	H2 infrastructure Grid decarbonization Stranded asset management

6.3 Case Study Template

For student assignments, use this structured approach:

Policy: [Name and brief description]

Diamond Analysis:

- Geographic/resource advantages or constraints?
- Historical path dependencies?
- Geopolitical context (conflict, strategic competition)?

Smil Analysis:

- Material constraints addressed?

- Scale considerations?
- Timeline realism?

Christensen Analysis:

- Sustaining or disruptive innovation supported?
- Foothold market creation?
- Incumbent response anticipated?

Technology Analysis:

- Specific technologies enabled?
- TRL and commercialization pathway?
- Infrastructure requirements?

Synthesis:

- Overall assessment
- Complementary policies needed
- Risks and opportunities

7 Real-World Policy Examples

7.1 European Union: Carbon Border Adjustment Mechanism (CBAM)

Description: Tariff on imported steel based on carbon content, effective from 2026.

Diamond Lens:

- EU's abundant renewable resources (North Sea wind, Mediterranean solar)
- Historical advantage in environmental regulation
- Geopolitical tool: responses to strategic competition with China

Smil Lens:

- Acknowledges that steel production cannot be eliminated
- Works with existing trade structures
- Timeline: gradual implementation (transition phase 2023-2025)

Christensen Lens:

- Creates price advantage for low-carbon steel (foothold market)
- Addresses incumbent concern about competitiveness

- May accelerate technology adoption through economic pressure

Technology Lens:

- Technology-neutral (incentivizes results, not methods)
- Favors H2-DRI and electrolysis in regions with cheap renewables
- Could disadvantage regions dependent on coal-based steel

7.2 Sweden: HYBRIT Project

Description: Public-private partnership to develop fossil-free steel using H2-DRI.

Diamond Lens:

- Geographic advantage: abundant hydroelectric power
- Historical mining culture (Kiruna iron ore since 1600s)
- Small scale allows experimentation without massive disruption

Smil Lens:

- Acknowledges massive energy requirement (relies on abundant hydro)
- Realistic timeline: first commercial plant by 2026
- Material reality: still produces iron through reduction chemistry

Christensen Lens:

- Classic disruptive innovation pathway
- Foothold: premium automotive customers (Volvo, SSAB)
- New entrant strategy: H2 Green Steel building greenfield plant

Technology Lens:

- H2-DRI at commercial scale (demonstration completed 2024)
- Requires integration: renewable electricity → electrolyzer → DRI → EAF
- Infrastructure: hydrogen storage, transport, and DRI facilities

7.3 China: Capacity Replacement Policy

Description: Requirement to retire old capacity before building new plants; emphasis on efficiency.

Diamond Lens:

- Resource constraints: limited high-quality ore, massive coal reserves
- Historical rapid industrialization creates legacy infrastructure
- Geopolitical imperative: maintain strategic steel production capacity

Smil Lens:

- Addresses scale: China produces 1 billion tonnes/year (50% of global)
- Gradual approach: improve efficiency of existing fleet
- Infrastructure reality: cannot replace everything simultaneously

Christensen Lens:

- Primarily sustaining innovation (better blast furnaces)
- Protects incumbents while raising efficiency bar
- Limited space for disruptive alternatives (yet)

Technology Lens:

- Focus on best-available BF-BOF technology
- Some pilots of H2-DRI and other alternatives
- Long-term: massive renewable energy expansion needed

8 Student Exercises

8.1 Exercise 1: Policy Critique

Select a steel decarbonization policy (national or regional) and analyze it using all four frameworks. Present findings in a 5-page report following the case study template.

MANDATORY: Before writing, watch the minimill disruption lecture at `https://www.youtube.com/watch?v=IwVa-bkciFE` and explicitly address how your chosen policy does or does not learn from the economic lessons of the minimill revolution.

8.2 Exercise 2: Technology Roadmap

Develop a 30-year technology transition roadmap for a specific region, justifying technology choices using:

- Diamond's context (geography, resources, historical factors)
- Smil's constraints (energy availability, infrastructure)
- Christensen's dynamics (market creation, incumbent management)
- Technology assessment (TRL, costs, timeline)

8.3 Exercise 3: Debate

Motion: "Given current geopolitical tensions (Guns) and recent pandemic experience (Germs), policies should prioritize strategic steel production security over rapid decarbonization."

Pro side: Use Diamond and Smil to argue for gradual, security-focused transition
Con side: Use Christensen to argue for rapid disruption despite short-term risks
Synthesis: Develop balanced approach addressing both concerns

8.4 Exercise 4: Scenario Analysis

Develop three scenarios for 2050 steel production:

1. **Incremental:** Mainly improved BF-BOF with CCS
2. **Disruptive:** Dominance of H2-DRI and electrolysis
3. **Mixed:** Portfolio of technologies by region and application

For each scenario, assess:

- Historical/geopolitical context (Diamond)
- Material/energy requirements (Smil)
- Transition pathway and timing (Christensen)
- Technology portfolio and infrastructure (Alternative Ironmaking)

9 Conclusion: Synthesis for Policy Making

Effective steel decarbonization policy requires integrating all four perspectives:

9.1 Key Insights

From Diamond:

- Geography and resource endowment create different pathways
- Historical path dependence matters profoundly
- Geopolitical realities (Guns) cannot be ignored
- Crisis conditions (Germs, conflict) shape policy space

From Smil:

- Respect thermodynamic and scale realities
- Accept that transitions take decades
- Material efficiency is as important as technology
- We remain in the Iron Age—plan accordingly

From Christensen:

- Create markets that enable disruptive innovation
- Expect and manage incumbent resistance
- Support performance improvement of alternatives
- Foothold markets are essential for disruption

From Alternative Ironmaking:

- Multiple technology pathways exist
- Each has different requirements and timeline
- Portfolio approach reduces risk
- Infrastructure is as critical as technology

9.2 The Integrated Framework

Successful policies must:

1. **Acknowledge historical context** (Diamond) while being **physically feasible** (Smil), **economically disruptive** (Christensen), and **technologically specific** (Alternative Ironmaking)
2. Balance **short-term efficiency** with **long-term transformation**
3. Support both **incumbent improvement** and **new entrant innovation**
4. Create **foothold markets** for alternatives while managing **mainstream transition**
5. Acknowledge **infrastructure requirements** and **realistic timelines**
6. Address **geopolitical realities** alongside **climate imperatives**

9.3 Final Reflection: Still in the Iron Age

We return to where we began: Jared Diamond's insight that material conditions shape civilization. In 2025, we face an unprecedented challenge—transforming the very material foundation of modern society while that society faces conflict (Guns), recovers from pandemic (Germs), and absolutely depends on Steel.

As Vaclav Smil reminds us, we are *Still in the Iron Age*. But perhaps, through thoughtful policy informed by historical awareness, material realism, innovation theory, and technological possibility, we can transform it into a *Green Iron Age*.

9.4 Research Questions for Students

1. How do different national contexts (geography, resources, industrial structure) affect optimal policy design?
2. What is the role of international coordination in managing global steel decarbonization?
3. How should policies balance equity concerns (jobs, regional development) with climate goals?
4. How do geopolitical tensions affect the feasibility of aggressive decarbonization policies?
5. What are the critical uncertainties, and how should policy remain adaptive?

10 Further Reading

10.1 Primary Sources

- Diamond, J. (1997). *Guns, Germs, and Steel: The Fates of Human Societies*. W.W. Norton.
- Smil, V. (2016). *Still the Iron Age: Iron and Steel in the Modern World*. Butterworth-Heinemann.
- Christensen, C. M. (1997). *The Innovator's Dilemma*. Harvard Business Review Press.
- Hasanbeigi, A. et al. *Alternative Ironmaking Technologies* [Available online]

10.2 Additional Resources

- International Energy Agency (IEA). *Iron and Steel Technology Roadmap*
- Mission Possible Partnership. *Making Net-Zero Steel Possible*
- HYBRIT Development Project reports
- European Commission. *A Clean Planet for All: Steel Sector*
- ESTEP (European Steel Technology Platform) materials and conferences

A Beamer Slides Outline: Diamond Introduction

For teaching purposes, here is a suggested Beamer presentation structure for the Diamond introduction:

A.1 Slide 1: Title

From Guns, Germs, and Steel to Steel Decarbonization

The Inexorable Economic Disruption of Global Steel
An Analysis of Current Policies and the EU's Strategic Dilemma Prof. Fabio Miani
University of Udine, Italy March 2024

Abstract

This paper analyzes the ongoing decarbonization of the global steel industry through the lens of Clayton Christensen's theory of disruptive innovation. It posits that the current transition, exemplified by China's 2025 capacity replacement policy, is not primarily an environmental correction but a continuation of the economic disruption that began with the rise of Electric Arc Furnace (EAF)-based minimills in the late 20th century. The analysis contrasts the economically-driven, disruptive approaches of China and the United States with the European Union's more cautious, sustaining innovation-focused strategy. Using the paradigmatic case of Italy's Ilva di Taranto, the paper highlights the profound risks of path dependency

and incumbent protection. It concludes that the EU's current policy framework, while technologically ambitious, may be insufficient to navigate the impending economic disruption without embracing more decisive market-creating and industry-restructuring measures.

B Introduction: The Disruption Narrative

The global steel industry, responsible for 7-9% of global CO_2 emissions, stands at a critical juncture. While the climate imperative is clear, this paper argues that the primary driver of the ongoing transformation is economic. The sector is experiencing a second wave of the disruptive innovation that began decades ago with the ascent of minimills. The current shift towards green steel is, in essence, the continuation of this economic revolution, where new, cleaner technologies are achieving competitiveness against the entrenched, carbon-intensive incumbents.

C The Ghost of Disruption Past: The Minimill Playbook

The collapse of the integrated "Big Steel" model in the United States and Europe in the late 20th century serves as the foundational case study [**?**]. The disruption, led by companies like Nucor, followed a classic pattern:

1. **Foothold Market:** Entry at the low end (e.g., rebar) with a cost advantage.
2. **Move Upmarket:** Gradual quality improvement to capture higher-value segments (e.g., structural steel, sheet steel).
3. **Mainstream Displacement:** Achievement of quality parity while maintaining a decisive cost advantage, leading to the bankruptcy of incumbent producers.

This was an economically-driven process, resulting in the EAF share of US production rising from 15% in 1970 to over 70% today [**?**].

D The Disruption Present: China's 1.5:1 Economic Masterstroke

China's policy framework for its 15th Five-Year Plan period, particularly the Ministry of Industry and Information Technology's (MIIT) capacity replacement mechanism, is a quintessential disruptive strategy disguised as environmental policy [**?**]. The mandatory **1.5:1 replacement ratio** (retiring 1.5 tonnes of BF-BOF capacity for every 1 tonne of new EAF capacity) is designed to:

- Forcibly reduce overcapacity and modernize the industry's structure.
- Exploit a significant CAPEX advantage (EAF investment is approximately one-third that of a new BF).
- Leverage a growing domestic scrap base from aging infrastructure.

The resultant dramatic reduction in CO_2 emissions is a powerful co-benefit, enhancing China's geopolitical standing while future-proofing its industry against mechanisms like the EU's Carbon Border Adjustment Mechanism (CBAM).

E The EU's Strategic Dilemma: Sustaining vs. Disruptive Innovation

In contrast to China's economically-driven restructuring, the European Union's approach presents a strategic dilemma, caught between its climate ambitions and the protection of its existing industrial base.

E.1 The Current Policy Mix

The EU's strategy rests on three pillars:

1. **Carbon Pricing (ETS):** Creating a cost for emissions, incentivizing efficiency and low-carbon transitions.

2. **Carbon Border Adjustment Mechanism (CBAM):** Protecting the integrity of its carbon price and preventing carbon leakage.

3. **Funding for Innovation (e.g., RFCS, Horizon Europe, Innovation Fund):** Supporting R&D and pilot projects for breakthrough technologies like hydrogen-based direct reduction (H_2-DRI).

E.2 A Critical Analysis

While technologically sophisticated, this approach leans heavily towards **sustaining innovation**. It focuses on retrofitting or replacing the existing integrated steel plant fleet, a process that is capital-intensive and slow. Projects like Germany's tkH2Steel and Sweden's HYBRIT are groundbreaking but represent a top-down, incumbent-led transition. The policy framework lacks the powerful, market-creating economic instruments that define the US (IRA tax credits) or the forced restructuring of China. The risk is that the EU successfully decarbonizes its steel production but at a cost that undermines its global competitiveness, effectively creating a high-quality, high-cost green niche without achieving a broad-based economic disruption.

F The Italian Case: Ilva di Taranto as a Paradigm of Paralysis

The situation at Ilva di Taranto epitomizes the EU's core challenge [**?**]. It is the physical manifestation of the conflict between the **Smilian reality** of a massive, path-dependent industrial asset and the **Christensen imperative** for disruption. The plant represents:

- **Path Dependence:** Deep social, political, and economic embeddedness.

- **Incumbent Inertia:** An inability to transition, sustained by state aid and legal exemptions.

- **The Failure of Half-Measures:** A cycle of environmental crises, health impacts, and economic bailouts that avoids the necessary radical restructuring.

Taranto is a cautionary tale: without a clear disruptive pathway, the attempt to preserve the old model leads to managed decline, not transformation.

G Conclusion and Policy Implications

The global steel industry is being reshaped by economic disruption, not just environmental policy. China's 1.5:1 policy is a decisive move to win this new game. The EU, meanwhile, risks being trapped in a high-cost transition that protects incumbents in the short term but may lack the ferocious economic logic required to compete globally in the long term.

For the EU to navigate this disruption successfully, its policy must evolve to more strongly embrace disruptive economics:

- Create powerful, simple economic incentives (e.g., carbon contracts for difference, enhanced capital allowances) that make green steel the most profitable option.
- Actively manage the decline of obsolete assets, learning from the lessons of *La Dismissione* to ensure a just transition.
- Foster market demand for green steel through aggressive green public procurement that creates a guaranteed "foothold market."

The green steel disruption is inevitable. The question for the EU is whether it will be a leader or a casualty.

References