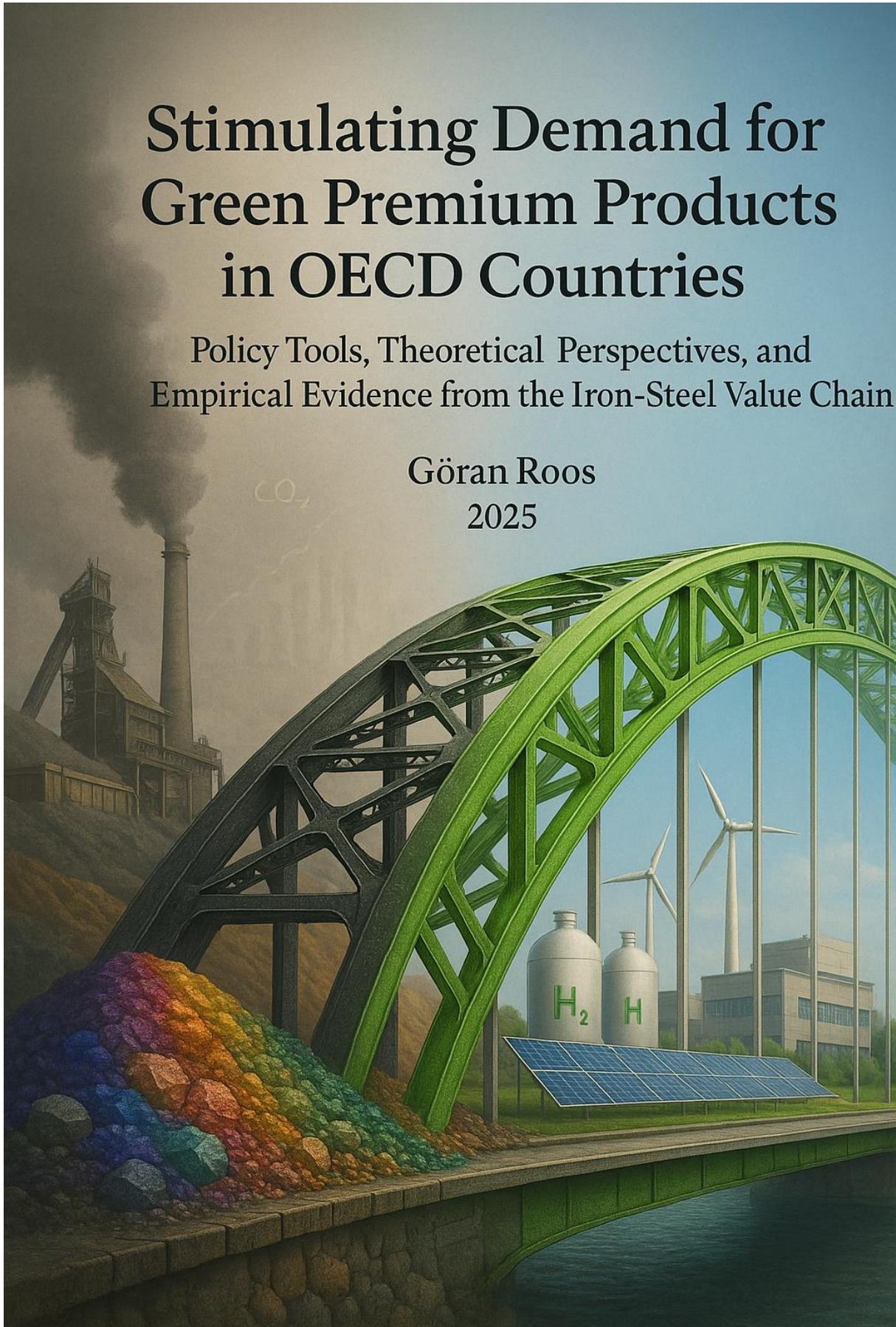


Stimulating Demand for Green Premium Products in OECD Countries

Policy Tools, Theoretical Perspectives, and
Empirical Evidence from the Iron-Steel Value Chain

Göran Roos
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Executive Summary

The green premium for low-carbon steel production presents an economic barrier, with costs exceeding conventional alternatives by 20-100%, adding approximately \$225 per tonne or \$203 per vehicle (Devlin & Yang, 2022; Transition Asia, 2023). This cost differential persists because market prices do not reflect the environmental costs of carbon emissions, whilst cleaner technologies require substantial infrastructure investment. Steel accounts for 7% of global carbon dioxide emissions, with 70% of production requiring technological transformation rather than incremental efficiency gains (IEA, 2020). Without policy intervention to address this price gap, market forces alone cannot drive the industrial decarbonisation required for climate objectives.

Analysis of OECD countries reveals that reliance on any individual instrument proves insufficient. Carbon pricing falls short even at €80-90 per tonne—modelling demonstrates that Swedish hydrogen steel may generate net social losses without complementary policies (Johansson & Kriström, 2025). This inadequacy stems from multiple, interconnected market failures: external environmental costs, asset specificity in new infrastructure, fundamental uncertainty about technological trajectories, information asymmetries preventing product differentiation, and path dependencies locking in established technologies (Williamson, 1985; Unruh, 2000; Akerlof, 1970). Each failure requires distinct policy responses, explaining why effective strategies combine multiple instruments addressing different barriers simultaneously.

Evidence from successful transitions, particularly Sweden's mobilisation of over €10 billion in five years, demonstrates three tool categories must operate together (Algers, 2024):

Demand creation through government procurement (14-20% of GDP in many OECD countries, potentially reducing emissions by 81% - Hasanbeigi & Sibal, 2024), private offtake agreements (mobilising €5+ billion for Swedish projects - Olsson & Nykvist, 2020), and carbon border adjustments (reducing leakage from 19% to near-zero whilst achieving net global emissions reductions - OECD, 2024a). These instruments provide guaranteed markets that justify investment in new capacity.

Production support through direct subsidies (requiring 30-45% of capital costs for commercial viability - Urban, 2023), concessional finance (enabling projects like H2 Green Steel's €1.2 billion facility - Swedish National Debt Office, 2023), research funding (advancing technologies achieving 33-95% emissions reductions - HYBRIT Development AB, 2024; Nippon Steel Corporation, 2024), and infrastructure investment (reducing hydrogen costs by 40% through coordinated deployment - HYBRIT Development AB, 2024). These mechanisms address capital barriers and technology risks that markets cannot resolve independently.

Market infrastructure through standardised certification (currently lacking harmonised thresholds - Clean Air Task Force, 2023), mandatory disclosure (driving substantive improvements beyond compliance - Borgstedt et al., 2019), and price transparency platforms (enabling efficient resource allocation). These tools address information asymmetries preventing effective market differentiation.

Policy effectiveness varies by technology maturity, requiring dynamic adjustment: early demonstration phases need supply-side support; commercialisation requires demand-side instruments; mature markets benefit from information provision (Öhman et al., 2022). International coordination proves essential—unilateral measures risk carbon leakage and competitive disadvantage without border adjustments and technology transfer (Fontagné &

Schubert, 2023). Equity implications demand explicit attention through workforce transition support, scaled mechanisms for small enterprises, and just transition policies addressing regional impacts.

Industrial decarbonisation requires coordinated policy packages, not single instruments. State strategic direction, value chain coordination, and public-private alignment enable transformation impossible through fragmented approaches (Mazzucato, 2013). Adaptive governance with robust monitoring allows course corrections as evidence accumulates. However, production greening alone proves insufficient—effective policy must combine decarbonisation with demand management through material efficiency, recycling, and potential consumption moderation (Watari et al., 2020; Allwood & Cullen, 2012). Evidence demonstrates feasibility: with appropriate design and implementation, green premiums can be addressed, enabling industrial transformation consistent with climate objectives whilst maintaining competitiveness.

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The Concept of Green Premiums in the B2B Context

Green premiums represent the additional cost that business-to-business purchasers must pay for products manufactured with lower carbon intensity compared to conventional alternatives. In industrial contexts, green premiums emerge when production processes incorporate cleaner technologies, renewable energy, or carbon capture systems that reduce greenhouse gas emissions but increase manufacturing costs (Devlin & Yang, 2022; Björsne & Cederlund, 2025). The premium arises because market prices for carbon-intensive goods do not fully reflect environmental costs and because producers of clean alternatives face early-stage scale and infrastructure constraints.

Unlike consumer markets where brand values and ethical considerations may justify price differentials, business-to-business purchasers typically operate under strict cost constraints and procurement protocols that prioritise price competitiveness and technical specifications (Szwajlik, 2024). In business-to-business transactions, the buyer pays a higher price for materials with lower embodied emissions in exchange for reputational benefits, compliance with procurement standards, and early access to technologies that may become mandatory as carbon prices rise.

The magnitude of green premiums varies substantially across industrial sectors and production routes. For steel, estimates suggest green premiums ranging from 20% to over 100% depending on the decarbonisation pathway employed, with hydrogen-based direct reduction routes commanding higher premiums than electric arc furnace routes using renewable electricity (Devlin & Yang, 2022; Material Economics, 2019). Hydrogen-based direct reduction steel can reduce emissions by up to 95% relative to blast-furnace steel but requires expensive hydrogen and new plant investment; the resulting green premium is estimated at about US\$225 per tonne of steel, adding roughly US\$203 to the price of a passenger car (Transition Asia, 2023).

Approximately 70% of global steel production utilises the primary route from iron ore, necessitating technological transformation rather than incremental efficiency improvements to achieve deep emissions reductions (IEA, 2020). OECD countries house many of the world's most technologically advanced steel producers and possess the institutional capacity, financial resources, and policy frameworks necessary to pioneer green steel transitions (Guevara Opinska et al., 2021).

Success in stimulating demand for green steel offers transferable lessons for decarbonising cement, aluminium, chemicals, and other energy-intensive industries where green premiums create market barriers (Material Economics, 2019). Demand for green steel is therefore a lever for driving investment in low-emission technologies such as hydrogen-based direct reduction, electric arc furnaces, and increased scrap recycling. Policy interventions to stimulate demand are needed to offset the current green premium and to create lead markets that enable first movers to scale technologies, reduce costs, and build supply chains.

Policy Tools and Policies for Addressing Green Premiums in OECD Countries

OECD governments deploy three broad categories of policy tools to address green premiums in industrial markets: demand-side instruments that create or enhance market pull for low-carbon products; supply-side measures that reduce production costs or risks for green technologies;

and information-provision mechanisms that improve market transparency and enable differentiation between conventional and low-carbon alternatives (OECD, 2024a; Hasanbeigi & Springer, 2019). This review systematically examines each category with specific reference to the iron-steel sector whilst incorporating empirical evidence from analogous business-to-business markets and green transitions in other industries.

Demand-Side Tools

Carbon Pricing Mechanisms (Taxes, Emissions Trading Systems)

Carbon pricing internalises the external costs of greenhouse gas emissions through taxes or cap-and-trade systems, thereby narrowing or eliminating green premiums by raising the cost of carbon-intensive alternatives. Building on Pigou's (1920) theoretical framework for addressing externalities, carbon pricing has become a cornerstone of climate policy. The European Union Emissions Trading System, established in 2005, represents the world's largest carbon market, covering approximately 40% of the EU's emissions including the steel sector (European Commission, 2023).

The EU ETS has undergone progressive reforms to tighten caps and phase out free allocation. The revised system for 2021-2030 reduces the cap by 2.2% annually, with carbon prices reaching approximately €85-90 per tonne CO₂-equivalent in 2024 and projected to range between €100-150 by 2030 (Carboneer, 2023; OECD, 2024a). For the steel sector, free allocation phases out between 2026 and 2034 in conjunction with the Carbon Border Adjustment Mechanism implementation, creating stronger price signals favouring low-carbon production (European Parliament & Council of the European Union, 2023; Göb & Schuldt, 2023).

Empirical evidence on carbon pricing effectiveness reveals mixed results. Lilliestam et al. (2021) found that whilst carbon pricing can drive incremental efficiency improvements, it often fails to induce breakthrough technological change necessary for deep decarbonisation. Van den Bergh and Savin (2021) demonstrate that carbon pricing effectiveness depends on price levels and complementary policies. Evidence suggests carbon pricing above €80 per tonne CO₂ begins materially affecting investment decisions in heavy industry, though effectiveness depends on expectations regarding price trajectories and regulatory stability (OECD, 2024a).

However, modelling by Johansson and Kriström (2025) indicates that even with EU ETS reforms and carbon prices of €80, hydrogen-based steel production in Sweden may generate substantial social losses unless accompanied by complementary demand-side and supply-side policies. This highlights limitations of carbon pricing alone in nascent green technology markets. Carbon pricing therefore represents a necessary but insufficient tool requiring complementation by instruments explicitly creating demand for low-emission materials (Clean Air Task Force, 2023).

Green Public Procurement

Green public procurement leverages government purchasing power to create stable demand for low-carbon materials in public construction and infrastructure projects. Public procurement accounts for 10–20% of GDP in many OECD countries and represents roughly 14–20% of gross domestic product across the European Union (OECD, 2024a). Cheng et al. (2018) identify green public procurement as an environmental policy instrument addressing market failures in green technology adoption.

A 2024 OECD survey found that 92% of 38 participating countries have adopted national green public procurement frameworks, though perceived higher costs and lack of data impede uptake (OECD, 2024a). The OECD's 2023 assessment found only 12 out of 32 OECD countries with green public procurement policies (38%) report on their impact and can therefore understand how they contribute to meeting sustainability goals (OECD, 2023). Japan, for example, has developed processes to estimate CO₂ savings generated by green public procurement.

Buy Clean policies typically establish maximum embodied carbon thresholds for construction materials. California's Buy Clean California Act, enacted in 2017 and implemented from 2022, established the United States' first state-level embodied carbon standards for public procurement (California Department of General Services, 2025). The legislation initially covered structural steel (hot-rolled sections, hollow structural sections, plate), concrete reinforcing steel, flat glass, and mineral wool insulation, with structural steel hot-rolled sections limited to 1.95 kg CO₂e per kilogramme of product (California Department of General Services, 2025; American Institute of Steel Construction, 2022).

At the federal level, the United States launched the Federal Buy Clean Initiative in 2021 under Executive Order 14057, with the Inflation Reduction Act allocating more than US\$4 billion for federal agencies to procure low-carbon materials (Office of the Federal Chief Sustainability Officer, 2023). The federal government's >\$630 billion annual purchasing power provides substantial market leverage (GSA, 2024).

Hasanbeigi and Sibal (2024) demonstrate that strategic implementation of Buy Clean policies can achieve substantial emissions reductions whilst supporting domestic industry competitiveness. The Industrial Deep Decarbonisation Initiative under UNIDO estimates that adopting advanced procurement criteria across Canada, Germany, the United Kingdom, and the United States could reduce emissions from public steel procurement by 81% by 2050 (Hasanbeigi & Sibal, 2022).

Subsidies, Tax Credits, and Rebates for B2B Purchasers

Direct financial incentives to business-to-business purchasers reduce effective green premiums by offsetting incremental costs. Building on Acemoglu et al.'s (2012) framework for directed technical change, targeted demand-side subsidies can complement supply-side measures by accelerating market formation and reducing coordination failures between producers and purchasers.

The U.S. Inflation Reduction Act's Section 45V hydrogen production tax credit and production tax credits for clean manufacturing reduce the cost of hydrogen used in hydrogen-based direct reduction steel, lowering the premium by up to US\$115 per tonne of steel (Transition Asia, 2023). Japan's government subsidises clean energy vehicles incorporating green steel, with automakers receiving ¥50,000 per vehicle when demonstrating use of low-emission steel and transparent carbon accounting (Russell, 2025).

The limited adoption of business-to-business purchase subsidies for green steel likely reflects concerns about market distortion, state aid regulations (particularly in the EU context), administrative complexity, and preferences for upstream production support or procurement standards over downstream subsidies (European Commission, 2023).

Offtake Agreements and Advance Market Commitments

Offtake agreements and advance market commitments address demand uncertainty constraining investment in green steel capacity. These mechanisms involve purchasers committing to purchase specified quantities at predetermined price premiums, providing revenue certainty during commercialisation phases (Energy Transitions Commission, 2021).

Sweden's HYBRIT initiative and Stegra (formerly H2 Green Steel) have secured multiple offtake agreements with automotive manufacturers. Volvo, Daimler, and Mercedes-Benz have announced commitments to purchase fossil-free steel, with Volvo incorporating HYBRIT-produced steel in commercial vehicles from 2022 (SSAB, 2021; Duckett, 2024). Olsson and Nykvist (2020) demonstrate that these agreements have been essential for mobilising the €5+ billion investments required for commercial-scale hydrogen steel production.

Advance market commitments, successfully demonstrated in vaccine markets, are now being considered for green materials. Kremer et al. (2020, 2022) show that advance market commitments can effectively stimulate investment by providing guaranteed demand at scale. The \$1.5 billion pneumococcal vaccine advance market commitment successfully accelerated vaccine development and deployment, providing a model for industrial applications (Kremer et al., 2022).

The First Movers Coalition, established at COP26 in 2021, brings together multinational corporations committing to purchase green steel and other low-carbon materials, aggregating demand and signalling market viability to producers (World Economic Forum, 2024). Member companies commit to sourcing specific percentages of steel with emissions below defined thresholds by target dates.

Green Content Mandates

Whilst not yet implemented for steel, mandatory green content requirements have proven effective in other sectors. Carley et al. (2018) empirically evaluate renewable portfolio standards in the United States, finding that well-designed mandates effectively increase renewable capacity deployment. Their analysis of stringency and design features shows that technology-specific carve-outs and credit trading mechanisms enhance effectiveness whilst managing costs.

Application to industrial materials would require careful design to avoid trade disputes and ensure technology neutrality whilst driving adoption. The theoretical foundation from command-and-control regulation (Stavins, 2003) suggests mandates can be effective when market failures prevent price signals alone from driving optimal outcomes.

Carbon Contracts for Difference

Carbon contracts for difference guarantee minimum carbon price floors, de-risking investments in low-carbon production. Richstein and Neuhoff (2022) demonstrate that carbon contracts for difference can effectively address multiple market failures simultaneously: carbon price uncertainty, technology risks, and coordination failures between infrastructure and production investments.

Germany and the United Kingdom are developing carbon contract for difference programmes for industrial decarbonisation. Rilling et al. (2022) systematically review design proposals,

finding that effectiveness depends on contract duration, strike price determination, and integration with existing support schemes. Their analysis suggests 15-year contracts with technology-specific strike prices optimally balance investor certainty with public cost containment.

Trade Measures and Carbon Border Adjustments

The EU Carbon Border Adjustment Mechanism, entering definitive operation in 2026, represents the most significant trade-related demand-side tool for addressing green premiums. Building on theoretical foundations by Fontagné and Schubert (2023) regarding border adjustments' economic rationale, the mechanism applies carbon prices to imports equivalent to those under the EU ETS.

OECD (2024a) modelling indicates the mechanism effectively prevents carbon leakage, reducing leakage rates from 19% without the adjustment to near-zero with implementation. The mechanism can reverse carbon leakage: without border adjustment, stricter EU ETS measures would lead to 0.19 tonnes of carbon leakage per tonne avoided; with the mechanism, a net global reduction of 0.54 tonnes per tonne avoided is expected (OECD, 2024a). Mörsdorf (2022) empirically demonstrates that the mechanism's environmental effectiveness depends on accurate emissions measurement and broad product coverage.

The mechanism covers €8.2 billion in annual steel trade and embedded emissions of 52 million tonnes CO₂-equivalent, generating substantial EU budget revenue (OECD, 2024a; World Bank, 2025).

Reverse Auctions

Whilst not yet applied to green steel, reverse auctions have successfully reduced costs in renewable energy markets. Winkler et al. (2018) analyse auctions across Brazil, France, Italy, and the Netherlands, finding cost reductions of 20–50% compared to feed-in tariffs whilst maintaining deployment rates. Matthäus (2020) demonstrates that multi-criteria auctions balancing price with non-price factors (local content, grid integration) achieve superior outcomes to price-only designs.

Application to green materials would require adaptation for product heterogeneity and quality standards but could efficiently discover market-clearing premiums for different decarbonisation levels.

Supply-Side Tools

Direct Subsidies and Grants

Direct grants and subsidies for green steel production facilities are widespread across OECD countries. Building on Rodrik's (2014) framework for green industrial policy addressing market failures in technology development, these instruments reduce capital costs and technology risks for novel production routes.

OECD (2023) research shows cash grants constitute 76% of steel subsidy instruments, with tax benefits (11%) and subsidised financing (4%) also common. The European Union's Innovation

Fund provided €143 million to Sweden's HYBRIT Demonstration project for constructing a hydrogen-based direct reduction facility with 1.3 million tonnes annual capacity (European Commission, 2023; Warwick, 2022).

Urban (2023) analyses the effectiveness of production subsidies for industrial decarbonisation, finding that grants exceeding 30% of capital costs are typically required to achieve commercial viability for first-of-a-kind plants. The analysis shows diminishing marginal effectiveness above 50% subsidy levels, suggesting optimal support ranges between 30–45% of capital expenditure.

Low-Interest Loans and Credit Guarantees

Concessional finance mechanisms address market failures identified by Stiglitz and Weiss (1981) regarding credit rationing under imperfect information. The Swedish National Debt Office's credit guarantee covering 80% of H2 Green Steel's €1.2 billion loan exemplifies effective risk-sharing, enabling construction of a plant cutting emissions by up to 95% (Swedish National Debt Office, 2023).

Evidence from analogous sectors demonstrates effectiveness. Shrimali et al. (2017) analyse India's accelerated depreciation policy for wind energy, finding it more effective than generation-based incentives for deployment, though potentially reducing generation efficiency. This highlights trade-offs between deployment speed and operational performance requiring careful policy design.

Research, Development and Demonstration Support

Research, development, and demonstration funding addresses knowledge gaps and technology barriers, building on Arrow's (1962) insights regarding underinvestment in innovation due to knowledge spillovers. Nelson's (1959) framework for basic research economics provides theoretical justification for public support of pre-commercial technology development.

Sweden's HYBRIT pilot produced over 5,000 tonnes of hydrogen-reduced sponge iron, demonstrating technical feasibility and characterising process parameters (Duckett, 2024). Japan's Super COURSE50 project achieved 33% CO₂ reduction in blast furnace trials, the highest demonstrated globally (Nippon Steel Corporation, 2024).

Empirical assessment shows targeted research, development, and demonstration support accelerates technology maturation. The progression from laboratory to pilot to demonstration scales typically requires 10–15 years, with public funding during early stages when private returns remain uncertain (Government of Japan, 2024).

Infrastructure Investment

Decarbonising steel production requires complementary infrastructure that individual firms cannot economically develop independently. Haller's (2016) analysis of networks as public infrastructure demonstrates how positive externalities justify public investment in shared facilities.

HYBRIT demonstrated hydrogen storage in lined rock caverns, reducing variable operating costs of hydrogen production by up to 40% (HYBRIT Development AB, 2024). The EU Hydrogen Strategy targets 40 gigawatts of renewable hydrogen electrolysis capacity by 2030, with

coordinated infrastructure investments under the Connecting Europe Facility (European Commission, 2020).

Evidence from energy infrastructure development shows network effects amplify individual investment returns. Springel (2021) analyses electric vehicle charging networks, finding that coordinated infrastructure deployment generates network externalities worth 30–50% of direct investment value.

Cluster and Ecosystem Development

Industrial cluster strategies leverage agglomeration economies theorised by Marshall (1890) and empirically validated by Porter (2000). Northern Sweden's green steel cluster combines iron ore mining (LKAB), steel production (SSAB, H2 Green Steel), renewable electricity generation (Vattenfall), and supporting industries in an integrated ecosystem (Algers, 2024; Stockholm Environment Institute, n.d.).

The cluster benefits from knowledge spillovers, shared infrastructure, and coordinated investments. Algers (2024) estimates the cluster generates agglomeration benefits worth €500–750 million annually through reduced transaction costs, accelerated innovation, and skilled labour pooling.

Technology-Specific Support Mechanisms

Feed-in tariffs and similar guaranteed price mechanisms, whilst not applied to industrial materials, offer relevant lessons. Dijkgraaf et al. (2018) empirically test feed-in tariff effectiveness for solar photovoltaics across 30 OECD countries, finding that well-designed tariffs accelerate deployment 2–3 times faster than tax credits alone. Menanteau et al. (2003) demonstrate that price-based instruments provide greater investor certainty than quantity-based mechanisms during early technology deployment phases.

Application to green steel would require adaptation for business-to-business markets, potentially through production-based premiums or guaranteed price floors for certified low-carbon output.

Information-Provision and Hybrid Tools

Certification and Labelling Schemes

Certification schemes address information asymmetries identified by Akerlof (1970) in markets with quality uncertainty. Spence's (1973) signalling theory provides the framework for understanding how certification enables market differentiation. Environmental Product Declarations quantify lifecycle impacts of steel products, though Clean Air Task Force (2023) notes current schemes lack harmonised carbon intensity thresholds distinguishing truly low-carbon steel.

ResponsibleSteel provides standards for responsible production but does not yet include stringent carbon thresholds. Germany's Green Steel Definition framework proposes percentage-based reduction categories (30%, 50%, 70%, 95% below baseline), though formal adoption remains incomplete (WV Stahl, 2022).

Disclosure Frameworks and Sustainability Reporting

Mandatory disclosure creates transparency incentives for low-carbon procurement. The EU's Corporate Sustainability Reporting Directive, applicable from 2024–2025, requires reporting of Scope 1, 2, and 3 emissions (European Commission, 2023). Borgstedt et al. (2019) demonstrate through longitudinal analysis of German companies that mandatory disclosure drives substantive environmental improvements beyond symbolic compliance.

OECD (2024a) assessment finds disclosure mandates most effective when combined with standardised methodologies, third-party verification, and clear penalties for non-compliance. Integration with financial reporting enhances impact by making environmental performance material to investor decisions.

ESG Standards and Market Ratings

Environmental, Social, and Governance ratings create indirect procurement incentives through capital market pressures. Building on stakeholder theory (Freeman, 2010), ESG frameworks recognise multiple constituencies affected by corporate environmental performance. MSCI ESG Research LLC (2024) data shows companies with superior ESG scores enjoy 50–100 basis points lower cost of capital, creating financial incentives for green procurement.

Voluntary Agreements and Industry Coalitions

Voluntary initiatives aggregate demand signals and create industry momentum, though Delmas and Montes-Sancho (2010) identify free-rider problems and enforcement challenges. The First Movers Coalition demonstrates how voluntary commitments can catalyse market transformation when combined with transparent reporting and reputational incentives (World Economic Forum, 2024).

Market Transparency and Price Discovery

Low-carbon material markets suffer from limited price transparency hampering efficient resource allocation. Building on Grossman and Stiglitz's (1980) paradox of efficient markets, price discovery mechanisms must balance information revelation with incentives for information production.

S&P Global Commodity Insights (2025) launched green steel price assessments tracking premiums across production routes and regions. Evidence from carbon markets demonstrates importance of liquidity for price discovery. Wu and Qin (2021) analyse China's emissions trading pilots, finding that market efficiency improves substantially when daily trading volumes exceed 10,000 tonnes CO₂-equivalent.

Commodity Exchanges and Standardised Trading

Whilst not yet implemented for green steel, standardised commodity exchanges could enhance market liquidity. Glosten and Milgrom (1985) demonstrate how market makers facilitate price discovery even with information asymmetries. Application to green materials would require standardised product definitions, quality specifications, and delivery terms.

Premium Pooling and Socialisation Mechanisms

Germany's Renewable Energy Act surcharge mechanism provides a model for socialising green premiums across all consumers. Gawel et al. (2015) analyse distributional impacts, finding that whilst regressive in absolute terms, the surcharge successfully mobilised €200+ billion for renewable energy deployment. Weitzman's (1974) theoretical framework suggests such mechanisms can be optimal when individual willingness-to-pay varies substantially but social benefits are broadly distributed.

Demand Aggregation and Group Purchasing

Group purchasing organisations achieve scale economies in procurement. Ahmadi et al. (2019) model healthcare group purchasing organisations, demonstrating 15–20% cost reductions through aggregated negotiating power and reduced transaction costs. Cabral and Salant's (2014) analysis shows group purchasing organisations are most effective when product standardisation is high and quality verification straightforward—conditions potentially challenging for heterogeneous green steel specifications.

Price Support and Guarantee Mechanisms

Agricultural price support programmes offer relevant lessons for industrial materials. Guda et al. (2021) analyse guaranteed support prices in developing economies, finding they effectively stimulate investment when set 15–25% above market prices. However, Newbery's (1989) analysis of missing markets suggests price guarantees may create inefficiencies if not carefully calibrated to actual production costs and market conditions.

Integrated Policy Approaches and Effectiveness Assessment

The evidence demonstrates that addressing green premiums requires coordinated policy packages rather than individual instruments. Successful transitions combine demand creation through procurement and mandates, supply-side support reducing production costs, and information provision enabling market differentiation.

Sweden's green steel transformation exemplifies effective policy integration: carbon pricing through EU ETS creates baseline incentives; public research, development, and demonstration funding supports technology development; infrastructure investments enable hydrogen production; cluster policies leverage agglomeration benefits; and offtake agreements provide demand certainty. This approach has mobilised over €10 billion in green steel investments within five years (Algers, 2024).

Policy effectiveness varies by technology maturity and market conditions. During early demonstration phases, supply-side support and research, development, and demonstration funding prove most important. As technologies approach commercialisation, demand-side instruments become increasingly important for market formation. Information provision and certification gain relevance as markets mature and product differentiation becomes feasible.

Conclusions and Policy Implications

This analysis reveals that effectively addressing green premiums in industrial markets requires carefully sequenced and coordinated policy interventions. No single instrument proves

sufficient; rather, complementary packages addressing multiple market failures simultaneously demonstrate greatest effectiveness.

Key policy design principles emerging from the evidence include:

Technology-specific differentiation: Optimal policy mixes vary by technology maturity, with early-stage technologies requiring greater supply-side support whilst mature technologies benefit more from demand-side instruments.

Dynamic adjustment: Policy instruments should evolve as technologies mature and markets develop, with support levels declining as learning effects reduce costs.

International coordination: Trade measures like the Carbon Border Adjustment Mechanism prove essential for maintaining industrial competitiveness whilst preventing carbon leakage, but require multilateral cooperation for optimal effectiveness.

Information infrastructure: Standardised certification, transparent pricing, and mandatory disclosure create foundations for market-based green premium reduction.

Risk allocation: Successful policies appropriately allocate technology, market, and policy risks between public and private actors based on their respective capacities to manage uncertainty.

The transition to green steel and other low-carbon industrial materials represents one of the defining challenges of industrial decarbonisation. The evidence suggests that with appropriate policy design and implementation, green premiums can be effectively addressed, enabling industrial transformation consistent with climate objectives whilst maintaining economic competitiveness.

Theoretical Perspectives

Different schools of economic thought offer distinct frameworks for conceptualising green premiums, market failures, and appropriate policy responses. This section examines theoretical traditions and their relevance to demand stimulation for green steel and other industrial products.

Neoclassical Economics

Market Failures, Externalities, Pigouvian Taxes

Neoclassical economics conceptualises green premiums as resulting from negative production externalities—costs imposed on society via climate damages that are not reflected in market prices (Pigou, 1920; Baumol & Oates, 1988). Steel producers utilising carbon-intensive processes do not bear full social costs of their emissions in the absence of corrective policies. This leads to overconsumption of carbon-intensive steel and underproduction of green alternatives (Stern, 2007).

The Pigouvian solution prescribes taxes or permit systems setting carbon prices equal to marginal social damages, internalising externalities and restoring allocative efficiency (Pigou, 1920; Nordhaus, 2007). At optimal carbon prices, green premiums disappear as conventional steel prices rise to reflect climate costs, whilst green steel remains at production cost (Nordhaus, 2017). Neoclassical models assume rational agents will choose lower-cost options when prices reflect external costs. If carbon prices exceed the cost differential of green steel, firms will switch to low-emission suppliers.

Estimating social cost of carbon presents empirical challenges, complicated by discounting, uncertainty, and distributional considerations. Political feasibility of imposing Pigouvian tax levels and dynamic inefficiencies when technology costs are falling but externality prices are static create additional complications (Acemoglu et al., 2012; Helm, 2010). Evidence from the EU ETS indicates that allowance prices and free allocations have not delivered sufficient investment signals (Clean Air Task Force, 2023).

New Institutional Economics

Transaction Costs and Governance Structures

Transaction cost economics, developed by Coase (1937) and Williamson (1985), provides insights into green steel market organisation. Asset specificity in hydrogen infrastructure and production facilities creates hold-up problems between green steel producers and buyers, potentially necessitating vertical integration or long-term contracts rather than spot market transactions (Nygaard, 2022). High transaction costs of negotiating and monitoring green steel specifications, carbon accounting, and supply chain verification may impede market formation despite favourable price signals.

Long-term offtake agreements for green steel exhibit characteristics of relational contracting. Incomplete contracts and bilateral dependency require governance structures beyond simple market exchange (Williamson, 1985). Transaction cost considerations explain why early green

steel projects often involve equity partnerships or joint ventures between producers and major consumers, as observed in the HYBRIT consortium structure (SSAB, 2021). The specificity of investments in hydrogen infrastructure and uncertainty surrounding technology performance create transaction hazards that market prices alone cannot resolve.

Keynesian and Post-Keynesian Economics

Demand Management and Counter-Cyclical Public Spending

Keynesian economics emphasises aggregate demand management and the state's role in coordinating investment during periods of underemployment or structural transformation (Keynes, 1936). Green transitions requiring large-scale infrastructure and industrial investments create opportunities for public expenditure to stimulate employment and growth whilst achieving environmental objectives (Jackson, 2009; Pollin, 2015).

Public procurement programmes and infrastructure investments can create guaranteed demand for green steel during early commercialisation phases when private market demand may be insufficient to justify capacity expansion. Government purchases reduce demand uncertainty, enabling producers to commit to investments with long payback periods (Mazzucato, 2013; Rodrik, 2014).

Post-Keynesian analyses stress fundamental uncertainty regarding technological trajectories and market evolution. Coordination failures and animal spirits influence investment decisions as much as price signals (Keynes, 1936; Minsky, 1986). State-led investment and credit guarantees crowd in private finance and initiate new industries. Sweden's loan guarantee for Stegra (formerly H2 Green Steel) exemplifies this approach (Swedish National Debt Office, 2023).

State-Led Investment Multipliers in Green Industries

Keynesian multiplier theory suggests government spending on green steel infrastructure and research and development generates multiplied effects through induced consumption and investment (Kahn, 1931; Keynes, 1936). Pollin et al. (2014) estimate green infrastructure investments yield employment multipliers of 1.5 to 2.0, comparable to conventional infrastructure but with additional environmental benefits.

Public investments in hydrogen infrastructure, renewable electricity capacity, and demonstration plants create demand for complementary goods and services in the steel sector, stimulating economic activity beyond direct project expenditures (Pollin, 2015). Critics question whether green investment multipliers exceed alternative uses of public funds and whether crowding-out effects offset stimulus benefits in full-employment economies (Barro, 1989).

Public Choice Theory

Rent-Seeking and Regulatory Capture

Public choice theory analyses environmental policy through the lens of self-interested political actors and interest group competition (Buchanan & Tullock, 1962). Green steel policies create

opportunities for rent-seeking where firms expend resources to capture subsidies and regulatory advantages rather than improving technology or efficiency (MacKenzie, 2017). Incumbent steel producers may engage in regulatory capture, influencing carbon pricing mechanisms and allocation rules to maintain competitive advantages whilst appearing to support decarbonisation.

Concentrated benefits of green steel subsidies accrue to specific producers whilst diffuse costs are borne by taxpayers and consumers, creating asymmetric incentives for political mobilisation (Olson, 1965). Such dynamics explain why green industrial policies often favour large incumbent firms with lobbying capacity over innovative start-ups (Choi & Storr, 2019). The European steel industry's success in maintaining free allocation under the EU ETS exemplifies how concentrated interests shape environmental policy design (Böhringer et al., 2022).

Bootleggers and Baptists Coalitions

The "bootleggers and baptists" framework explains how environmental regulations gain support from unusual coalitions of morally motivated advocates and profit-seeking firms (Yandle, 1983). Environmental non-governmental organisations advocate for stringent carbon standards in green steel markets whilst established producers with green technology capabilities support regulations that disadvantage competitors. This dynamic can accelerate policy adoption but may result in suboptimal designs favouring specific technologies or incumbents (MacKenzie, 2017).

Austrian Economics

Knowledge Problems and Entrepreneurial Discovery

Austrian economics, particularly Hayek's knowledge problem framework, challenges centralised green transition planning (Hayek, 1945; Kiesling, 2015). Dispersed knowledge about production costs, technological possibilities, and consumer preferences cannot be aggregated by central planners. Market processes rather than government direction should determine optimal green technologies (Leeson & Rouanet, 2023).

The entrepreneurial discovery process implies that competition among multiple green steel technologies reveals efficient solutions through profit-and-loss signals (Kirzner, 1973). Hydrogen reduction, carbon capture, and electrolysis compete in this process. Government selection of specific technologies or production routes may preclude discovery of superior alternatives. Austrian perspectives caution against assuming policy-makers possess sufficient knowledge to design optimal transition pathways and advocate instead for institutional frameworks enabling spontaneous order and innovation (Vanberg, 1994).

Development Economics

Infant Industry Arguments and Late-Comer Advantages

Development economics perspectives highlight challenges and opportunities for developing countries in green steel transitions. The infant industry argument suggests temporary protection may enable domestic green steel industries to achieve scale and learning effects before

competing internationally, though this remains controversial (Chang & Andreoni, 2020). Countries like India and Brazil face tensions between industrial development objectives and environmental commitments where green premiums potentially constrain competitiveness.

Late-comer advantages may enable developing countries to leapfrog carbon-intensive technologies and install green steel capacity without stranded asset legacies (Aiginger & Rodrik, 2020). Technology transfer mechanisms and capability building become essential for enabling this transition. Developed country carbon border adjustments risk imposing standards that developing countries cannot immediately meet (Chang & Andreoni, 2020). International climate policy design must balance environmental objectives with development needs through differentiated responsibilities or technology transfer provisions (Juhász et al., 2023).

Financial Economics

Green Finance and Capital Market Mechanisms

Financial economics examines how capital markets price and allocate resources for green transitions. Green bonds have emerged as instruments for financing green steel projects, with issuance reaching \$500 billion globally in 2023 (Huang, 2024). Development of taxonomies defining "green" investments reduces information asymmetries and transaction costs in sustainable finance markets (Driessen, 2024).

Environmental, Social, and Governance investing increasingly influences capital costs for steel producers. High-emission firms face higher borrowing costs and restricted investor bases (Jónsdóttir et al., 2021). Stranded asset risks affect investment decisions and asset valuations as carbon-intensive steel plants may become economically unviable before technical obsolescence (Scott Cato & Fletcher, 2020). Financial markets thus create price signals complementing policy interventions, though critics question whether ESG metrics effectively distinguish genuine green transitions from greenwashing.

International Trade Theory

Carbon Leakage and Border Adjustments

International trade theory illuminates challenges of unilateral climate policies in globally traded commodities like steel. Carbon leakage occurs when production shifts to unregulated jurisdictions, undermining environmental effectiveness and industrial competitiveness (Fontagné & Schubert, 2023). The EU's Carbon Border Adjustment Mechanism, operational from 2023, attempts to address leakage by imposing carbon costs on imports equivalent to domestic production (Mörsdorf, 2022).

Trade models indicate that border adjustments can reduce leakage but create implementation challenges around carbon content verification, potential trade disputes, and development impacts (Böhringer et al., 2022). Effectiveness depends on design details including coverage scope, calculation methodologies, and revenue recycling mechanisms. Cameron and Baudry (2023) find economists generally support border adjustments theoretically but acknowledge practical difficulties. Green steel trade may bifurcate into premium markets with verified emissions and commodity markets where price dominates.

Regional and Spatial Economics

Agglomeration Economies and Industrial Clusters

Regional economics perspectives highlight spatial dimensions of green steel transitions. Agglomeration economies arise when co-location of green steel producers, renewable energy generators, and hydrogen infrastructure creates cost advantages through shared infrastructure, knowledge spillovers, and specialised labour markets (Song et al., 2021). Industrial clusters around ports with renewable energy access and hydrogen production potential may emerge as green steel hubs.

First-mover regions can establish competitive advantages through learning effects, infrastructure development, and institutional capabilities (Liu et al., 2024). Spatial concentration of green industrial activity raises questions about regional inequality and just transition policies for areas dependent on carbon-intensive steel production. Evidence from China's high-tech industrial zones demonstrates how targeted regional policies can accelerate green industrial transformation through coordinated infrastructure investment and technology transfer (Chen et al., 2019).

Network Economics and Platform Theory

Two-Sided Markets and Standards Competition

Network economics provides insights into market formation for green materials. Green steel markets exhibit characteristics of two-sided platforms connecting producers investing in new technology with buyers seeking low-carbon inputs (Martin et al., 2017). Network effects arise as more producers and buyers participate, reducing search costs and improving liquidity. Digital platforms for carbon accounting, certification, and trading may accelerate market development.

Standards competition between different green steel definitions and certification schemes creates coordination challenges (Cohen & Zhang, 2022). Establishment of dominant standards generates winner-take-all dynamics, potentially locking in suboptimal definitions. Market thickness problems in early stages involve insufficient buyers and sellers for efficient price discovery and may require platform subsidies or market-making interventions (Hinz et al., 2020). Intermediaries play an essential role in aggregating demand and standardising contracts for market development.

Institutional and Evolutionary Economics

Path Dependency, Lock-In, and Transitions

Institutional economics emphasises historical contingency, path dependency, and the role of institutions in shaping economic outcomes (Veblen, 1899; North, 1990). Established technologies in industrial sectors benefit from accumulated learning, infrastructure compatibility, institutional support, and network effects that create lock-in even when superior alternatives emerge (Arthur, 1989; David, 1985).

Blast furnace steel production exhibits strong path dependency. Sunk capital in existing facilities with operational lifetimes exceeding 40 years, specialised supply chains, workforce skills, and regulatory frameworks designed around incumbent technologies reinforce this pattern (Unruh, 2000; Öhman et al., 2022). Breaking carbon lock-in requires coordinated interventions that address technological, institutional, and economic dimensions simultaneously (Seto et al., 2016).

Innovation Systems and Mission-Oriented Policies

Evolutionary economics, extending Schumpeterian analysis of innovation, views economic progress as driven by technological change, learning, and selection processes (Schumpeter, 1942; Nelson & Winter, 1982). Innovations diffuse through complex systems involving firms, research institutions, financial markets, regulations, and user communities (Lundvall, 1992; Freeman, 1987).

Green steel transitions require transformation of innovation systems through mission-oriented policies that direct resources towards societal goals (Mazzucato, 2013; Foray et al., 2012). Mission-oriented policies represent a coordinated approach to innovation governance that establishes clear, ambitious objectives and mobilises diverse stakeholders across public and private sectors toward shared societal goals (Larrue, 2021). These policies serve as strategic frameworks that align science, technology, and innovation efforts with regulatory measures to drive targeted, collaborative solutions to complex challenges (Mazzucato, 2018). The European Union's Clean Hydrogen Partnership exemplifies this approach through its mission to accelerate clean hydrogen development by bringing together governments, industry, research organisations, and civil society to achieve specific 2030 climate targets and support the broader goal of climate neutrality by 2050. Similarly, Japan's Green Innovation Fund demonstrates mission-oriented coordination by providing sustained support for ambitious decarbonisation goals shared between public and private sectors, with the government committing 2 trillion yen over ten years to align diverse actors around carbon neutrality objectives by 2050 (METI, 2021).

Behavioural and Experimental Economics

Bounded Rationality in Procurement Decisions

Behavioural economics challenges neoclassical assumptions of perfect rationality and documents systematic deviations from optimising behaviour due to cognitive limitations, heuristics, and biases (Kahneman & Tversky, 1979; Simon, 1955). Bounded rationality in business-to-business procurement manifests through status quo bias, satisficing behaviour, and organisational routines that slow adoption of novel alternatives even when economically advantageous (Kahneman et al., 1991; Tversky & Kahneman, 1974).

Souza et al. (2025) demonstrated that environmental awareness and regulatory pressures substantially influence sustainable operations adoption in Brazilian business-to-business steel procurement decisions, challenging traditional assumptions about rational economic behaviour. Their study of the Brazilian steel industry's business-to-business context found that organisational environmental culture and regulatory compliance factors override purely economic decision-making processes, with companies prioritising regulatory adherence and sustainability goals rather than pure lifecycle cost considerations. The research revealed that

compliance requirements and environmental consciousness take precedence over traditional cost-based optimisation, indicating that stakeholder-driven and sustainability-oriented factors influence procurement choices more substantially than cost optimisation alone.

A 2017 OECD report shows that behavioural interventions can complement traditional instruments. Providing timely feedback, framing information, and using social comparisons can encourage energy conservation and investment in efficient technologies (OECD, 2017). For business-to-business green steel markets, behavioural interventions might include framing procurement as reputationally beneficial, publishing leaderboards of companies adopting green steel, or providing default options for low-carbon materials.

Framing Effects, Signalling, and Reputational Incentives

Framing effects—changes in decision outcomes based on how options are presented—offer opportunities for influencing business-to-business procurement through strategic communication (Tversky & Kahneman, 1981). Emphasising risks of stranded assets, supply chain disruptions, or regulatory changes can motivate precautionary procurement of green steel beyond what price signals alone would generate (Geels et al., 2016).

Signalling theory suggests that early adoption of green steel by prestigious firms signals quality and reduces uncertainty for followers, facilitating broader diffusion (Spence, 1973). Volvo's high-profile use of HYBRIT fossil-free steel in commercial vehicles provides demonstration effects that encourage other automotive manufacturers to follow (SSAB, 2021). Reputational incentives increasingly influence corporate procurement as stakeholders scrutinise supply chain emissions.

Marxist and Political Economy Approaches

Power Relations, Class Interests, and Capital Accumulation in Green Transitions

Marxist political economy analyses green transitions through lenses of capital accumulation, class conflict, and state-capital relations (Marx, 1867/1990; Harvey, 2010). Green steel policies operate within contexts of competing interests where industrial capital seeks profitability, labour seeks employment security, financial capital seeks returns, and environmental movements press for decarbonisation (Newell & Paterson, 2010).

Carbon pricing and green premiums redistribute costs across economic actors, creating winners and losers that shape political coalitions supporting or opposing policies (Geels, 2014). Marxist critiques argue that capitalism commodifies nature and generates ecological crises, with policies such as emissions trading creating new markets for pollution rather than transforming production relations.

State policies reflect outcomes of political struggles among these interests, with institutional structures and discursive framings mediating these outcomes (Meadowcroft, 2011). Sweden's green steel leadership partly stems from state ownership of key firms such as Vattenfall and LKAB, which aligns corporate strategies with national decarbonisation objectives, reducing conflicts between profitability and environmental goals (Algers, 2024).

State-Capital Bargaining and Industrial Transformation

Political economy approaches emphasise bargaining between states and capital over terms of industrial transformation (Levy & Newell, 2005). Governments provide subsidies, regulatory protections, and market support whilst receiving corporate commitments to domestic investment, employment, and decarbonisation in exchange (Newell & Paterson, 2010).

Japan's Green Innovation Fund operates through explicit performance contracts requiring firms to meet technological and commercial targets, with clawback provisions if commitments are unfulfilled (METI, 2021). Analysts caution that without strong labour and community participation, green industrial strategies may lead to job losses in legacy industries whilst large corporations may benefit disproportionately (Besley & Persson, 2023).

Ecological Economics

Strong vs Weak Sustainability

Ecological economics distinguishes between weak sustainability and strong sustainability. Weak sustainability allows substitution of natural capital with manufactured capital, whilst strong sustainability requires preservation of critical natural capital stocks (Neumayer, 2010; Daly, 1996). In green steel contexts, weak sustainability perspectives accept continued steel consumption at current or growing levels provided production processes decarbonise. Strong sustainability emphasises material efficiency, recycling, and potential consumption reductions (Jackson, 2009).

Green premiums under weak sustainability frameworks incentivise cleaner production technologies but do not challenge underlying material throughput (Daly, 1996). Ecological economists challenge the assumption that technological innovation can decouple economic growth from environmental impact, stressing that natural capital cannot be substituted by man-made capital.

Watari et al. (2020) argue that global steel production cannot continue to grow within a Paris-aligned carbon budget. Decarbonisation requires phasing out blast furnaces, increasing scrap recycling, and reducing demand for steel. From this perspective, policies to stimulate demand for green steel must be accompanied by measures to reduce overall material consumption, promote material efficiency, and support circular economy practices.

Degrowth, Sufficiency, and Resource Constraints

Degrowth perspectives, prominent in ecological economics, argue that sustainable development requires deliberate reductions in material and energy throughput in high-income economies, which is incompatible with perpetual growth (Kallis, 2011; Hickel & Kallis, 2020). Applied to steel, degrowth emphasises demand reduction through enhanced material efficiency, extended product lifetimes, sharing economies, and altered consumption patterns, as production greening alone is insufficient (Allwood et al., 2011; Allwood & Cullen, 2012).

Policies aligned with sufficiency and degrowth include design standards promoting durability and repairability, taxation of virgin materials favouring recycled content, and planning systems reducing infrastructure expansion (Haas et al., 2015). Critics note political implausibility of

degrowth in competitive global economies and highlight potential adverse effects on employment and living standards (Victor, 2008).

Complexity and Systems Perspectives

Non-Linear Dynamics in Industrial Transitions

Complexity economics analyses economic systems as adaptive, evolving networks that exhibit non-linear dynamics, path dependency, and emergent properties (Arthur, 2015; Farmer et al., 2019). Industrial transitions involve multiple interconnected elements where technologies, firms, institutions, infrastructures, and user practices co-evolve through feedback loops and tipping points (Geels & Schot, 2007).

Green steel transitions exhibit characteristics of complex system change. Positive feedbacks accelerate adoption once thresholds are reached through network effects and learning curves. Path dependencies create lock-in and inertia. Emergent outcomes arise from interactions among components (Farmer et al., 2019; Geels, 2002).

Systems models highlight feedback loops, tipping points, and co-evolutionary dynamics across technology, policy, and markets. For green steel, tipping points might arise when hydrogen costs reach parity with coal, when green steel supply surpasses a threshold enabling economies of scale, or when regulatory changes such as full Carbon Border Adjustment Mechanism implementation shift competitive dynamics (Dechezleprêtre et al., 2025).

Policy Mixes and Adaptive Governance

Systems perspectives emphasise policy mixes—combinations of instruments addressing different barriers and leverage points—rather than single policies (Rogge & Reichardt, 2016; Flanagan et al., 2011). Effective green steel transitions require coordinated deployment of multiple instruments where carbon pricing internalises externalities, public procurement creates demand, research and development support advances technology, infrastructure investment enables deployment, and standards and information tools facilitate market functioning (Öhman et al., 2022; Material Economics, 2019).

Policy sequencing and timing prove essential. Early-stage technologies require research and development and demonstration support. Scaling-up phases benefit from procurement and offtake agreements. Mature technologies may need only carbon pricing and regulatory frameworks (Öhman et al., 2022). Adaptive governance is needed to adjust instruments as technologies evolve and market responses become clearer. Complexity frameworks counsel humility regarding policy predictability and control, recommending experimentation, diversity of approaches, and flexibility to respond to unexpected developments (Colander & Kupers, 2014).

Empirical Examples in OECD Countries

Green Steel and Metals

Sweden: HYBRIT

The Hydrogen Breakthrough Ironmaking Technology initiative represents the world's most advanced hydrogen-based steel production project. Launched in 2016 as a joint venture among SSAB (steelmaker), LKAB (iron ore miner), and Vattenfall (energy utility), HYBRIT aims to replace coking coal with hydrogen in iron ore reduction, potentially reducing Sweden's total CO₂ emissions by 10% and Finland's by 7% (SSAB, 2021; Stockholm Environment Institute, n.d.).

HYBRIT's pilot plant in Luleå operated from 2018 to 2024, producing over 5,000 tonnes of hydrogen-reduced sponge iron through 61 weeks of trials testing 175 different process conditions (Duckett, 2024; HYBRIT Development AB, 2024). The hydrogen-based direct reduction process achieved emissions of approximately 5 kg CO₂ per tonne of steel (from graphite electrode oxidation), compared to 2,200 kg CO₂ per tonne in conventional blast furnaces—a 99.7-99.8% reduction (Duckett, 2024; HYBRIT Development AB, 2024).

The consortium is building a commercial-scale hydrogen-based steel plant with €143 million from the EU Innovation Fund; the project will produce 1.35-1.3 Mt of hydrogen-reduced iron and reduce emissions by 14.3 Mt over ten years (HYBRIT Development AB, 2021; Warwick, 2022; European Commission, 2023). Key technical achievements include demonstration of commercial alkaline electrolyser operation for hydrogen production (9,000+ hours), successful hydrogen storage in lined rock caverns reducing costs by 40%, and production of high-quality sponge iron with superior properties to conventional blast furnace iron (HYBRIT Development AB, 2024; Duckett, 2024).

Demand-side mechanisms supporting HYBRIT include offtake agreements with Volvo, Daimler, Mercedes-Benz, and others; public procurement of fossil-free steel for Swedish government infrastructure projects; and SSAB's premium pricing strategy leveraging brand differentiation (SSAB, 2021; Algers, 2024; Volvo Group, 2021). Supply-side support includes Swedish Energy Agency funding for pilot operations and access to abundant low-cost renewable electricity (Warwick, 2022; Stockholm Environment Institute, n.d.).

Karltorp and Maltais note that financing is not the major barrier; rather, demand for green products, infrastructure availability, and permitting are essential (Karltorp & Maltais, 2024). The Swedish government supports early projects through credit guarantees (covering 80% of a €1.2 billion loan) (Swedish National Debt Office, 2023). Sweden's advantage lies in abundant renewable energy (hydro and wind), supportive policy, and corporate offtake commitments.

Germany: SALCOS

Salzgitter AG's SALCOS (Salzgitter Low CO₂ Steelmaking) programme, initiated in 2015, targets full decarbonisation of the company's 7 million tonne annual steel capacity by 2050 (Salzgitter AG, 2024). The concept, developed in 2015, will gradually replace coke-based ironmaking with direct reduction using green hydrogen (Salzgitter AG, 2024).

Phase 1 involved demonstrating hydrogen use in existing blast furnaces, achieving 30% reduction in CO₂ emissions through hydrogen injection (Salzgitter AG, 2022). Phase 2, currently underway, constructs a first direct reduction plant with electric arc furnace, targeted for operation in mid-2020s with 1 million tonne capacity (Guevara Opinska et al., 2021). The project has been allocated €2.3bn (€1bn public) but was delayed 3 years due to hydrogen infrastructure gaps (Hasanbeigi & Sibal, 2022).

German federal and state governments provide substantial financial support through grants, loans, and guarantees under climate and innovation programmes (Federal Ministry for Economic Affairs and Climate Action, 2023). ArcelorMittal's German operations experienced cancellations despite €1.3bn approval, demonstrating supply-side funding inadequacy without demand policies (EUROMETAL, 2025).

EU Hydrogen Alliance Initiatives

The European Commission established the European Clean Hydrogen Alliance in 2020 to accelerate hydrogen deployment, bringing together industry, member states, and civil society to develop hydrogen value chains (European Commission, 2020). The EU Hydrogen Strategy targets 40 GW electrolyser capacity by 2030, producing 10 million tonnes of renewable hydrogen annually, supplemented by 10 million tonnes of imports (European Commission, 2020).

The EU Innovation Fund has allocated €3.6bn to various projects (European Commission, 2023). Connecting Europe Facility and Trans-European Networks for Energy provide funding for cross-border hydrogen infrastructure, facilitating supply to industrial clusters (European Commission, 2020).

North America

California Buy Clean

California's Buy Clean California Act (AB 262), enacted 2017 and implemented from July 2022, established maximum global warming potential limits for structural steel, concrete reinforcing steel, flat glass, and mineral wool insulation used in state-funded public works projects (California Department of General Services, 2025). California's \$10 billion annual procurement budget provides substantial market leverage, with public works consuming approximately 45-50% of state construction materials (Hasanbeigi & Khutal, 2021).

The U.S. Buy Clean programme has procured \$4bn worth of materials (Construction Dive, 2022). Implementation challenges include limited availability of facility-specific Environmental Product Declarations, verification costs and administrative burdens, exemptions for small producers, and initial limits set at average levels rather than best-practice benchmarks (American Institute of Steel Construction, 2022; Feraldi, 2023).

Federal Buy Clean Initiative

President Biden's Federal Sustainability Plan (2021) and Executive Order 14057 launched the Federal Buy Clean Initiative, prioritising low-carbon construction materials (steel, concrete,

asphalt, flat glass) in federal procurement and federally-funded projects (Executive Office of the President, 2021; GSA, 2024).

The Federal-State Buy Clean Partnership, announced 2023, includes 13 states committed to coordinating procurement standards and harmonising demand signals (GSA, 2024). The Inflation Reduction Act provides \$3/kg hydrogen credit (Green Hydrogen Organisation, 2022) and Industrial Demonstrations received \$6.3bn (Clean Air Task Force, 2023).

Inflation Reduction Act Green Steel Support

The Inflation Reduction Act (2022) continues to provide substantial indirect support for green steel via the Clean Hydrogen Production Tax Credit (Section 45V), the Qualifying Advanced Energy Project Investment Tax Credit (Section 48C), and Department of Energy industrial decarbonisation programs. Treasury and the Internal Revenue Service finalised 45V rules in January 2025, confirming tiered credits up to \$3/kg for hydrogen with lifecycle emissions below 0.45 kg CO₂e/kg H₂ and adopting DOE's 45VH2-GREET model (Navarrete, 2025; U.S. Department of the Treasury, 2025). The final rules require annual energy attribute certificate matching until 2030, followed by hourly matching, and maintain incrementality and deliverability requirements for grid electricity-backed hydrogen, alongside prevailing wage and apprenticeship conditions to achieve full credit value (Navarrete, 2025; U.S. Department of the Treasury, 2025).

Under 48C, the Department of Energy and Internal Revenue Service allocated \$10 billion across two rounds (2024 and 2025) to more than 200 projects nationwide, with a substantial share in energy communities and a defined certification and in-service schedule that applies to industrial decarbonisation efforts in iron and steel (U.S. Department of Energy, n.d.-b).

In the Department of Energy's Industrial Demonstrations Program, two flagship U.S. green steel proposals announced in 2024 proceeded to award negotiations: SSAB's hydrogen-based direct reduction in Mississippi and Cleveland Cliffs' direct reduction/electric arc furnace transition at Middletown, Ohio. In January 2025, SSAB withdrew from federal award negotiations, whilst Cleveland Cliffs received \$9.5 million and remains committed to the project, though it will initially run on fossil gas and gradually transition to hydrogen when supplies become available (Gallucci, 2025; U.S. Department of Energy, n.d.-a). These developments underscore that whilst Inflation Reduction Act incentives have clarified the policy foundation and improved project economics, U.S. green steel timelines continue to hinge on reliable low-carbon hydrogen supply, power market integration, and market demand for near-zero steel.

Asia-Pacific

Japan: Green Innovation Fund and Steel Decarbonisation

Japan's ¥2 trillion (\$16 billion) Green Innovation Fund, established 2021 through the New Energy and Industrial Technology Development Organisation, provides 10-year continuous support for decarbonisation initiatives from research and development through commercialisation (NEDO, 2024; METI, 2021; Government of Japan, 2023).

The Green Innovation Fund achieved 43% CO₂ reduction in test furnace (Government of Japan, 2024). The Super COURSE50 project, led by Nippon Steel in consortium with JFE Steel, Kobe

Steel, and the Japan Research and Development Center for Metals, targets 50% CO₂ reduction in blast furnaces through heated hydrogen injection and other innovations (Government of Japan, 2024).

Japan's hydrogen strategy targets 12 million tonnes annual consumption by 2040, with substantial allocation to industrial sectors including steel (Nagashima, 2018; DLA Piper, 2024). The government provides subsidies to automobile manufacturers for vehicles containing low-emission steel (¥50,000 per vehicle) (Russell, 2025).

South Korea

South Korea's Hydrogen Economy Roadmap (2019) and subsequent Green New Deal (2020) position hydrogen as central to industrial decarbonisation including steel (Ministry of Trade, Industry and Energy, 2019; Ministry of Economy and Finance, 2020). The country has allocated ₩150bn in funding (ResponsibleSteel, 2023). POSCO, South Korea's largest steelmaker, announced plans to achieve carbon neutrality by 2050 through hydrogen-based steelmaking, targeting 7 million tonnes green steel capacity (POSCO, n.d.).

Korea's Mandatory Purchase of Green Products and Minimum Green Standard Product Programme promote environmental goods but do not include steel. The country is developing a Low-Carbon Product Certification for steel, which requires a 3.3% emissions reduction over three years rather than an absolute carbon limit (Hasanbeigi & Bhadbhade, 2023).

Australia: Hydrogen Industry Leadership and Technology Cooperative Research Centre

Australia's abundant renewable energy potential and existing iron ore mining sector position it as a potential green iron and steel exporter. The Hydrogen Industry Leadership and Technology Cooperative Research Centre, established 2022, brings together industry, government, and research organisations to develop hydrogen production and utilisation technologies including direct reduction of iron ore (Heavy Industry Low-carbon Transition Cooperative Research Centre, n.d.).

The Cooperative Research Centre received \$39M + \$175M investment (University of Adelaide, 2021; Australian National University, 2021). The Australian Renewable Energy Agency has funded \$59.1 million across 21 projects (ARENA, 2024, 2025b, 2025c, 2025d, 2025e).

Fortescue Metals Group announced plans to develop green iron production facilities in Western Australia, targeting hydrogen-based direct reduction of high-grade magnetite (Fortescue Metals Group, 2023). Australian government support includes \$2 billion Hydrogen Headstart programme providing production grants (Department of Climate Change, Energy, the Environment and Water, 2024).

Western Australia (38% global iron ore, 934 Mt production) is accelerating Renewable Hydrogen Strategy implementation linking Mid-West/Pilbara hubs to green iron (Government of Western Australia, 2024, 2025). NeoSmelt received \$75M (ARENA, 2025a; Government of Western Australia, 2024), and the state is leveraging 100% renewable electricity targets (Minerals Research Institute of Western Australia, 2025). There are also initiatives at Fortescue Christmas Creek.

South Australia (18 Bt magnetite, renewable energy leader) is implementing Green Iron Strategy 2030 direct reduction plant (Government of South Australia, Department for Energy and Mining, n.d.-a, n.d.-b). Liberty Steel's low-carbon electric arc furnace transition is being supported (Austrade, 2023; Government of South Australia, 2023), and the Magnetite Mines Razorback-Port Pirie export corridor is being developed (Port Pirie Regional Council, 2024; Mining Technology, 2020).

At the federal level, the Hydrogen Production Tax Incentive \$2/kg has been implemented (Australian Taxation Office, 2025; Department of Climate Change, Energy, the Environment and Water, 2025; Reuters, 2025).

Other Green Premium B2B Markets

Low-Carbon Cement and Concrete Procurement (Europe, U.S.)

Cement production contributes approximately 8% of global CO₂ emissions. Green procurement for cement is emerging with green public procurement potential of €5.15bn EU lead market with 81-85% emission reductions achievable (Bellona Europa, n.d.). California's Buy Clean covers concrete and sets maximum global warming potential thresholds, and the U.S. federal government will spend billions on low-carbon concrete (Office of the Federal Chief Sustainability Officer, 2023).

Canada, Germany, and the UK could reduce emissions from public cement procurement by 81% through technology investments and stringent Industrial Deep Decarbonisation Initiative targets (Hasanbeigi & Sibal, 2022). South Korea's green public procurement programmes include green cement labels but need carbon intensity metrics (Hasanbeigi & Bhadbhade, 2023).

Certified Sustainable Aluminium in Aerospace and Automotive Supply Chains

Aluminium production, particularly primary smelting, is highly electricity-intensive, with emissions varying widely based on electricity source (IEA, 2021). The Aluminium Stewardship Initiative, an industry-led certification programme, establishes standards for sustainable aluminium production including environmental performance criteria (Aluminium Stewardship Initiative, n.d.).

Major aerospace and automotive manufacturers increasingly specify Aluminium Stewardship Initiative-certified aluminium in supply contracts, creating demand differentiation (Aluminium Stewardship Initiative, n.d.; Boeing, 2022). Aluminium Stewardship Initiative certification appears in Mercedes (70% reduction) and BMW (100% green power wheels 2022–2024) (Mercedes-Benz Group, 2023; Aluminium Stewardship Initiative, n.d.).

Apple, Audi, and BMW have announced commitments to source only aluminium smelted with renewable electricity, leveraging procurement power to drive greening (Apple Inc., 2023; BMW Group, 2023). Hydro's CIRCAL aluminium alloy contains at least 75% post-consumer scrap and has a certified carbon footprint of 1.9 kg CO₂e/kg (Norsk Hydro ASA, n.d.; Fastmarkets, 2024).

Renewable Energy Components (Turbines, Solar PV with Green Metals)

Renewable energy industries—wind turbines, solar photovoltaics, battery storage—increasingly incorporate sustainability requirements for component materials including steel, aluminium, and rare earths (IEA, 2021). Vestas and ArcelorMittal have established wind turbine steel partnerships (Vestas, 2024).

Wind turbine manufacturers including Vestas, Siemens Gamesa, and GE Renewable Energy have announced commitments to source certified sustainable steel and aluminium, driven by customer requirements, Environmental, Social, and Governance considerations, and supply chain risk management (Vestas, 2024; Siemens Gamesa Renewable Energy, 2023). Some European tenders include "green steel content" as a scoring factor.

Cross-Sectoral Lessons

Transferability of Demand-Side Mechanisms Across Sectors

Comparative analysis across sectors indicates that demand-side mechanisms can be transferred from steel to other heavy materials. Buy Clean policies, offtake agreements, and carbon contracts-for-difference provide predictable demand and encourage investment. Market transformation theory demonstrates that demand-side programmes such as rebates function as temporary market interventions that reduce barriers and financial risks for market participants until sufficient market adoption drives economies of scale and cost reductions (Gibbs & Townsend, 2000). This theoretical framework is supported by extensive research showing that market transformation strategies, including rebates and upstream interventions, serve as transitional support mechanisms designed to accelerate technology adoption and market development (Nadel & Latham, 1998). The literature confirms that demand-side management approaches and resource acquisition programs can effectively bridge the gap between early market intervention and sustainable market transformation, demonstrating their applicability across multiple sectors and technology types (Prahl & Schlegel, 1994).

Green public procurement innovation spillovers include 0.046% patent increase per 1% green public procurement, 30% private adoption increase, and 11.1 percentage point higher innovation probability for winners (Ghisetti, 2017; Orsatti et al., 2020; Simcoe & Toffel, 2014).

Buy Clean policies can straightforwardly extend coverage to additional materials by establishing embodied carbon thresholds, requiring Environmental Product Declarations, and incorporating limits into procurement specifications (WRI, 2024–2025). The Carbon Border Adjustment Mechanism's extension to all EU ETS sectors by 2030, including potential inclusion of organic chemicals, polymers, and other products, demonstrates regulatory scalability (European Parliament & Council of the European Union, 2023).

However, sectoral specificities require tailoring: cement faces unique calcination emissions not addressable through energy switching; aluminium's electricity-intensity creates different priority interventions than steel's process emissions; chemicals' product diversity complicates standardisation (IEA, 2020; Material Economics, 2019).

Limits of Policy Effectiveness in Different Trade and Industrial Contexts

Policy effectiveness varies based on trade exposure, market structure, institutional capacity, and political economy contexts. Jurisdictions with large domestic markets and strong regulatory capacity (EU, California) can implement ambitious procurement or trade policies with greater impact and feasibility than smaller or weaker jurisdictions (OECD, 2024a).

Trade-exposed sectors face competitiveness constraints limiting unilateral policy stringency absent border adjustment mechanisms (Carbon Border Adjustment Mechanism) or international coordination (Climate Clubs) (OECD, 2024a; Nordhaus, 2015). Industries with concentrated production and few large firms (steel, cement) enable coordination but may exercise political influence resisting regulation, whereas fragmented sectors face collective action problems (Geels, 2014).

Evidence suggests that policies alone cannot eliminate the green premium. Carbon pricing often remains too low and uncertain (Clean Air Task Force, 2023). Asia-Pacific case studies highlight that without explicit carbon intensity criteria, procurement programmes may certify minor improvements rather than drive transformational change (Hasanbeigi & Bhadbhade, 2023). Ecological economics warns that focusing solely on green premium products without reducing overall material demand may fail to achieve sustainability goals (Watari et al., 2020).

Voluntary commitments are insufficient (2-4% automotive vs 25% needed) (International Council on Clean Transportation, 2024). Supply-side funding alone proves inadequate without demand policies, as ArcelorMittal cancellations demonstrate (EUROMETAL, 2025).

Conclusion

This paper has examined policy tools and theoretical perspectives for addressing green premiums in business-to-business markets across OECD countries, with primary focus on the iron-steel value chain where green premiums range from 20% to over 100% depending on the decarbonisation pathway employed. The analysis reveals that green premiums emerge when production processes incorporate cleaner technologies that reduce greenhouse gas emissions but increase manufacturing costs, creating a fundamental market failure where prices for carbon-intensive goods do not fully reflect environmental costs.

Three categories of policy tools—demand-side, supply-side, and information-provision mechanisms—address different dimensions of market failures preventing green steel adoption. Demand-side instruments including carbon pricing (EU ETS at €85-90/tonne), green public procurement (covering 14-20% of GDP in many OECD countries), offtake agreements, advance market commitments, carbon contracts for difference, and trade measures like the Carbon Border Adjustment Mechanism create market pull through various mechanisms. Evidence demonstrates that whilst carbon pricing above €80 per tonne begins materially affecting investment decisions, it alone proves insufficient—modelling by Johansson and Kriström (2025) indicates hydrogen-based steel may generate substantial social losses without complementary policies.

Supply-side tools including direct subsidies (constituting 76% of steel subsidy instruments per OECD data), concessional finance, research and development support (with projects demonstrating 33-99.8% emissions reductions), infrastructure investment, and cluster development reduce production costs and technology risks. Sweden's HYBRIT initiative exemplifies effective integration: the pilot produced over 5,000 tonnes of hydrogen-reduced sponge iron achieving 99.7-99.8% emissions reduction, supported by €143 million EU Innovation Fund grants, state credit guarantees covering 80% of loans, and coordinated infrastructure including hydrogen storage in lined rock caverns reducing operating costs by 40%.

Information-provision and hybrid mechanisms including certification schemes, mandatory disclosure frameworks (EU Corporate Sustainability Reporting Directive covering Scope 1-3 emissions), Environmental, Social, and Governance standards, voluntary agreements like the First Movers Coalition, market transparency platforms, and premium pooling mechanisms address information asymmetries and facilitate market functioning. However, current certification schemes lack harmonised carbon intensity thresholds, with only 38% of OECD countries with green public procurement policies reporting on their impact.

Theoretical perspectives illuminate why policy packages prove necessary. Neoclassical economics emphasises Pigouvian solutions but underestimates transaction costs and path dependencies. Transaction cost economics reveals asset specificity in hydrogen infrastructure creates hold-up problems requiring relational contracting. Keynesian frameworks highlight state coordination and multiplier effects (1.5-2.0 for green infrastructure). Austrian economics warns against centralised technology selection. Development economics raises infant industry considerations. Behavioural economics documents bounded rationality and status quo bias in business-to-business procurement. Political economy perspectives reveal rent-seeking risks and bootleggers-baptist coalitions. Ecological economics questions whether technological substitution suffices without addressing material consumption levels. Complexity perspectives emphasise non-linear dynamics and adaptive governance needs.

Empirical evidence from OECD countries demonstrates diverse approaches reflecting institutional contexts. Sweden's state-led transformation through HYBRIT and Stegra (formerly H2 Green Steel) mobilised over €10 billion in five years through integrated policies. California's Buy Clean Act established embodied carbon standards with structural steel limited to 1.95 kg CO₂e/kg. The U.S. Inflation Reduction Act's Section 45V provides up to \$3/kg hydrogen credits reducing premiums by \$115/tonne steel. Japan's ¥2 trillion Green Innovation Fund requires performance accountability across 10-year horizons. The EU's Carbon Border Adjustment Mechanism, covering €8.2 billion annual steel trade, can reduce carbon leakage from 19% to near-zero whilst generating net global emissions reductions of 0.54 tonnes per tonne avoided.

Cross-sectoral analysis reveals transferability of mechanisms with appropriate tailoring. Green public procurement innovation spillovers include 0.046% patent increases per 1% green public procurement spending, 30% private adoption increases, and 11.1 percentage point higher innovation probability for winners. Voluntary commitments prove insufficient (2-4% automotive adoption versus 25% needed), whilst supply-side funding alone fails without demand policies as ArcelorMittal cancellations demonstrate.

Substantial evidence gaps persist. Rigorous evaluations of Buy Clean programmes remain limited. Green premium estimates vary substantially based on hydrogen costs, electricity prices, and scale assumptions. Business-to-business purchasers' willingness to pay remains poorly understood. Optimal policy sequencing, distributional impacts on small and medium enterprises and workers, and the fundamental debate between green growth advocates and ecological economists requiring absolute consumption reductions remain unresolved.

The analysis yields clear implications for industrial policy. Single instruments prove insufficient; effective strategies require policy mixes addressing multiple barriers simultaneously. Sweden's success demonstrates benefits of state strategic direction-setting, value chain coordination, and public-private alignment. Policies must balance initial ambition with feasibility, establishing credible trajectories whilst enabling broad participation. Multi-level governance coordination proves essential, as does addressing equity implications through workforce training and transition assistance. Adaptive, experimental approaches with monitoring and adjustment mechanisms enable course corrections as evidence accumulates.

The iron-steel value chain's decarbonisation represents a microcosm of broader industrial transformation challenges. Lessons from green steel—the necessity of coordinated policy packages combining demand creation with supply support, the importance of state coordination breaking path dependencies, the requirement for international cooperation preventing carbon leakage, and the imperative of adaptive governance managing uncertainties—inform approaches to decarbonising cement, aluminium, chemicals, and other hard-to-abate sectors. Achieving mid-century climate neutrality requires not incremental efficiency improvements but fundamental industrial restructuring enabled through policy frameworks that simultaneously address market failures, coordinate investments, manage transitions equitably, and guide outcomes towards sustainable industrial transformation.

Insights for Policy Makers and Business Executives

The Challenge

Industrial decarbonisation faces a fundamental economic barrier: producers of low-carbon materials such as green steel must charge substantially more than their carbon-intensive competitors. Evidence from multiple production routes demonstrates that this price differential, termed the "green premium," ranges from 20% to over 100% depending on the technology employed (Devlin & Yang, 2022; Material Economics, 2019). This wide range reflects genuine cost differences between approaches—hydrogen-based direct reduction requires expensive hydrogen infrastructure and new plant investments, whilst electric arc furnace routes using renewable electricity involve lower but still substantial additional costs. The implication is clear: without policy intervention to address this price gap, market forces alone will not drive the industrial transformation required for climate goals.

The steel sector exemplifies the urgency of this challenge. Analysis of global production patterns reveals that approximately 70% of steel manufacturing relies on primary production from iron ore, a process fundamentally incompatible with deep emissions reductions through incremental efficiency improvements alone (IEA, 2020). This finding matters because steel production accounts for roughly 7% of global carbon dioxide emissions. The scale of required transformation becomes apparent when examining specific cost impacts: hydrogen-based production can achieve emissions reductions of up to 95% relative to conventional blast furnaces, yet this environmental benefit comes with an estimated cost of approximately \$225 per tonne of steel (Transition Asia, 2023). For manufacturers, this translates into real economic consequences—adding roughly \$203 to the production cost of a single passenger vehicle. These figures demonstrate why private sector actors, operating under competitive market pressures and procurement protocols prioritising price competitiveness, face genuine structural barriers to voluntary adoption of green alternatives (Szwajlik, 2024).

What the Evidence Shows

Analysis of policy approaches across OECD countries yields a consistent finding: reliance on any single policy instrument fails to overcome green premiums effectively. This conclusion emerges most clearly from examining carbon pricing mechanisms, often promoted as the theoretically optimal solution. The European Union Emissions Trading System, the world's largest carbon market, has achieved prices of €85-90 per tonne of carbon dioxide equivalent in 2024, with projections suggesting levels of €100-150 by 2030 (Carboneer, 2023; OECD, 2024a). Economic theory suggests that such price levels should begin materially affecting investment decisions in heavy industry. However, detailed modelling of Swedish hydrogen-based steel production reveals a troubling outcome: even with EU ETS reforms and carbon prices of €80, these investments may generate substantial social losses unless accompanied by complementary policies addressing other market failures (Johansson & Kriström, 2025). This finding challenges the assumption that carbon pricing alone can drive technological transformation, suggesting instead that price signals prove necessary but insufficient for inducing the breakthrough changes required for deep decarbonisation.

The inadequacy of single instruments becomes comprehensible when examining the multiple, interconnected market failures plaguing green industrial transitions. Carbon-intensive

production imposes external costs not reflected in market prices, creating the classic problem that Pigouvian taxes attempt to address (Pigou, 1920). Yet this represents only one barrier amongst several. Asset specificity in hydrogen infrastructure creates hold-up problems between producers and buyers, a challenge that carbon pricing cannot resolve (Williamson, 1985). Fundamental uncertainty regarding technological trajectories and market evolution inhibits private investment regardless of price signals (Keynes, 1936). Information asymmetries prevent efficient market differentiation between conventional and low-carbon products (Akerlof, 1970). Path dependencies and carbon lock-in—stemming from accumulated learning, infrastructure compatibility, and institutional support for established technologies—resist change even when price incentives shift (Unruh, 2000). Each of these failures requires distinct policy responses, explaining why effective strategies necessarily combine multiple, complementary instruments addressing different dimensions of the problem simultaneously.

Required Policy Approaches

Evidence from successful early movers demonstrates that three categories of tools must operate together, each addressing specific market failures whilst reinforcing the effectiveness of others.

Creating Market Demand

Government purchasing power represents one of the most direct and immediate levers available to policymakers. Public procurement accounts for 14-20% of gross domestic product across many OECD countries, providing substantial market leverage for creating demand for low-carbon materials (OECD, 2024a). The logic supporting procurement-based approaches rests on straightforward economic reasoning: when governments commit to purchasing materials meeting specific carbon intensity standards, they create guaranteed demand that reduces market uncertainty for producers and enables investment in new capacity. California's Buy Clean California Act demonstrates this approach at scale, with the state's \$10 billion annual procurement budget establishing maximum embodied carbon thresholds for structural steel, concrete reinforcing steel, flat glass, and mineral wool insulation used in publicly funded projects (California Department of General Services, 2025; Hasanbeigi & Khutal, 2021). Analysis by the Industrial Deep Decarbonisation Initiative suggests the potential impact of coordinated procurement: adoption of advanced procurement criteria across Canada, Germany, the United Kingdom, and the United States could reduce emissions from public steel procurement by 81% by 2050 (Hasanbeigi & Sibal, 2022). This figure represents not mere aspiration but a calculation based on available technologies and projected public sector materials demand.

Private sector offtake agreements complement public procurement by aggregating demand and providing revenue certainty during phases of commercialisation. Sweden's HYBRIT initiative exemplifies this mechanism's effectiveness. The project secured multiple offtake agreements with automotive manufacturers including Volvo, Daimler, and Mercedes-Benz, with these commitments proving essential for mobilising the €5+ billion in investments required for commercial-scale hydrogen steel production (Olsson & Nykvist, 2020). The economic logic underpinning such agreements addresses a specific coordination failure: producers hesitate to invest in new capacity without assured demand, whilst buyers hesitate to commit without assured supply. Long-term purchase commitments at predetermined price premiums break this

deadlock by providing producers with revenue certainty that justifies the substantial upfront capital requirements of first-of-a-kind facilities.

The European Union's Carbon Border Adjustment Mechanism addresses a different but equally important market failure: carbon leakage and competitive disadvantage from unilateral climate policies. The mechanism, covering €8.2 billion in annual steel trade and embedded emissions of 52 million tonnes of carbon dioxide equivalent, applies carbon prices to imports equivalent to those faced by domestic producers under the EU Emissions Trading System (OECD, 2024a; World Bank, 2025). Economic modelling indicates the mechanism's effectiveness in preventing carbon leakage, with projections showing reductions in leakage rates from 19% without border adjustment to near-zero with implementation (OECD, 2024a). More remarkably, the analysis suggests the potential for net global emissions reductions: without border adjustment, stricter EU climate measures would lead to 0.19 tonnes of carbon leakage per tonne avoided domestically; with the mechanism in place, a net global reduction of 0.54 tonnes per tonne avoided becomes achievable (OECD, 2024a). These figures demonstrate how well-designed trade measures can transform unilateral climate action into drivers of global emissions reductions rather than mere displacement of production to less regulated jurisdictions.

Supporting Production Cost Reduction

Direct financial support for production facilities addresses capital cost barriers and technology risks that market mechanisms alone cannot overcome. Analysis of OECD country support structures reveals that cash grants constitute 76% of steel subsidy instruments, reflecting policymakers' recognition that breakthrough technologies require substantial public investment during early deployment (OECD, 2023). The European Union's Innovation Fund provided €143 million to Sweden's HYBRIT Demonstration project for constructing a hydrogen-based direct reduction facility with 1.3 million tonnes annual capacity (European Commission, 2023; Warwick, 2022). Research on production subsidy effectiveness indicates that grants exceeding 30% of capital costs typically prove necessary to achieve commercial viability for first-of-a-kind plants, with diminishing marginal effectiveness above 50% subsidy levels (Urban, 2023). This finding suggests an optimal support range between 30-45% of capital expenditure, a threshold that balances public cost containment with sufficient risk reduction to enable private investment.

Concessional finance mechanisms address distinct market failures stemming from imperfect information and credit rationing. Private lenders, unable to fully assess novel technology risks and facing asymmetric information about project viability, often decline financing or demand prohibitively high interest rates even for economically sound projects (Stiglitz & Weiss, 1981). The Swedish National Debt Office's credit guarantee covering 80% of H2 Green Steel's €1.2 billion loan exemplifies effective public risk-sharing that enables construction of facilities achieving up to 95% emissions reductions (Swedish National Debt Office, 2023). The guarantee's structure reflects careful policy design: by covering the majority but not entirety of the loan, it maintains private sector due diligence whilst reducing risk to commercially acceptable levels. Evidence from analogous sectors demonstrates concessional finance effectiveness, though with important caveats about potential trade-offs between deployment speed and operational performance requiring careful design (Shrimali et al., 2017).

Research, development, and demonstration funding addresses underinvestment in innovation stemming from knowledge spillovers—the economic reality that firms cannot fully capture

returns from innovations that competitors can observe and replicate (Arrow, 1962). Sweden's HYBRIT pilot, which produced over 5,000 tonnes of hydrogen-reduced sponge iron whilst demonstrating technical feasibility and characterising process parameters, illustrates public research and development support's role in advancing technology maturation (Duckett, 2024). Japan's Super COURSE50 project achieved 33% carbon dioxide reduction in blast furnace trials, the highest demonstrated globally, through public funding enabling experimentation that individual firms would not undertake given uncertain private returns (Nippon Steel Corporation, 2024). Analysis of technology development pathways indicates that progression from laboratory to pilot to demonstration scales typically requires 10-15 years, with public funding proving essential during early stages when private returns remain uncertain and technology risks peak (Government of Japan, 2024).

Infrastructure investment addresses coordination failures and positive externalities that prevent individual firms from economically developing necessary complementary systems. HYBRIT's demonstration of hydrogen storage in lined rock caverns, reducing variable operating costs of hydrogen production by up to 40%, exemplifies infrastructure's cost-reduction potential (HYBRIT Development AB, 2024). The European Union Hydrogen Strategy targets 40 gigawatts of renewable hydrogen electrolysis capacity by 2030, with coordinated infrastructure investments under the Connecting Europe Facility creating network effects that amplify individual investment returns (European Commission, 2020). Evidence from energy infrastructure development demonstrates these network effects' magnitude: coordinated infrastructure deployment can generate network externalities worth 30-50% of direct investment value (Springel, 2021).

Industrial cluster strategies leverage agglomeration economies—the cost advantages arising when related firms co-locate, enabling knowledge spillovers, shared infrastructure, and coordinated investments (Marshall, 1890; Porter, 2000). Northern Sweden's green steel cluster combines iron ore mining (LKAB), steel production (SSAB, H2 Green Steel), renewable electricity generation (Vattenfall), and supporting industries in an integrated ecosystem that analysis estimates generates agglomeration benefits worth €500-750 million annually through reduced transaction costs, accelerated innovation, and skilled labour pooling (Algers, 2024). These figures demonstrate how strategic clustering creates value beyond individual firm investments, justifying public coordination that individual actors cannot achieve independently.

Enabling Market Function

Certification schemes and labelling address information asymmetries that prevent market differentiation between conventional and low-carbon products (Akerlof, 1970; Spence, 1973). Without credible, standardised definitions and third-party verification, buyers cannot reliably identify genuinely low-carbon materials, creating the classic "lemons problem" where quality uncertainty prevents premium pricing. Current certification schemes face substantial limitations: analysis by the Clean Air Task Force notes that existing Environmental Product Declarations lack harmonised carbon intensity thresholds distinguishing truly low-carbon steel from marginal improvements (Clean Air Task Force, 2023). Germany's proposed Green Steel Definition framework, establishing percentage-based reduction categories (30%, 50%, 70%, 95% below baseline), represents progress toward standardisation, though formal adoption remains incomplete (WV Stahl, 2022). These gaps matter because effective market differentiation requires both credible measurement and clear thresholds enabling purchasers to distinguish meaningful emissions reductions from incremental changes.

Mandatory disclosure frameworks create transparency incentives complementing voluntary certification. The European Union's Corporate Sustainability Reporting Directive, applicable from 2024-2025 and requiring reporting of Scope 1, 2, and 3 emissions, exemplifies this approach (European Commission, 2023). Longitudinal analysis of German companies demonstrates that mandatory disclosure drives substantive environmental improvements beyond symbolic compliance, with assessment finding disclosure most effective when combined with standardised methodologies, third-party verification, and clear penalties for non-compliance (Borgstedt et al., 2019; OECD, 2024a). The mechanism through which disclosure influences behaviour operates through multiple channels: investor pressure as environmental performance becomes material to capital allocation decisions, reputational incentives as stakeholders scrutinise supply chain emissions, and competitive dynamics as transparency enables benchmarking and comparison across firms.

Market transparency platforms and price discovery mechanisms address limited price transparency hampering efficient resource allocation in nascent low-carbon materials markets. S&P Global Commodity Insights launched green steel price assessments tracking premiums across production routes and regions, providing the public price signals necessary for market development (S&P Global Commodity Insights, 2025). Evidence from carbon markets demonstrates liquidity's importance for price discovery: market efficiency improves substantially when daily trading volumes exceed 10,000 tonnes of carbon dioxide equivalent (Wu & Qin, 2021). This threshold suggests that green materials markets require both standardised product definitions and sufficient transaction volumes to achieve efficient price formation, a coordination problem that platforms and market-making can help resolve during early market development.

What Success Requires

Sweden's green steel transformation demonstrates the power of integrated policy approaches. The country combined carbon pricing through the EU Emissions Trading System creating baseline incentives; public research, development, and demonstration funding supporting technology advancement; infrastructure investments enabling hydrogen production and storage; cluster policies leveraging agglomeration benefits; and offtake agreements providing demand certainty. This coordinated strategy mobilised over €10 billion in green steel investments within five years, a pace impossible through any single instrument alone (Algers, 2024). The success stems from addressing multiple market failures simultaneously whilst ensuring policy coherence across instruments—each tool reinforcing rather than contradicting others.

Policy effectiveness varies systematically by technology maturity and market conditions, necessitating dynamic adjustment of instrument mixes over time. During early demonstration phases, supply-side support and research funding prove most important for advancing technology readiness and reducing technical risks. As technologies approach commercialisation, demand-side instruments become increasingly important for market formation and capacity deployment. Information provision and certification gain relevance as markets mature and product differentiation becomes technically feasible (Öhman et al., 2022). This progression implies that optimal policy packages evolve as industries transition, with support levels declining as learning effects reduce costs and markets achieve self-sustaining growth.

International coordination proves essential for maintaining industrial competitiveness whilst preventing carbon leakage. Trade measures such as the Carbon Border Adjustment Mechanism demonstrate feasibility, yet effectiveness depends on multilateral cooperation, transparent implementation, and attention to development impacts on lower-income countries (Fontagné & Schubert, 2023). The tension between environmental objectives and development needs requires careful navigation: border adjustments risk imposing standards that developing countries cannot immediately meet, potentially limiting their industrial development. Resolution demands differentiated responsibilities, technology transfer provisions, and recognition that developed countries bear both greater historical responsibility for emissions and greater current capacity to finance transitions (Chang & Andreoni, 2020).

Equity implications require explicit attention throughout policy design and implementation. Workforce training and transition assistance prove necessary for managing employment impacts in legacy industries whilst building capacity for new production approaches. Small and medium-sized enterprises face distinct challenges compared to large firms with greater financial resources and technical capacity, suggesting the need for scaled support mechanisms. Regional considerations matter given spatial concentration of both legacy production and emerging green industrial clusters, with just transition policies required to address geographical inequality (Besley & Persson, 2023).

The Path Forward

Industrial decarbonisation represents not an incremental challenge but a fundamental restructuring requiring coordinated policy packages combining demand creation, supply support, and market infrastructure development. The evidence demonstrates feasibility: multiple OECD countries have mobilised substantial investment, achieved substantial emissions reductions, and begun commercial deployment of breakthrough technologies. Yet substantial gaps persist. Rigorous evaluation of buy clean programmes remains limited, constraining evidence-based refinement. Green premium estimates vary substantially based on assumptions about hydrogen costs, electricity prices, and deployment scale. Business-to-business purchasers' willingness to pay for emissions reductions remains poorly understood, hampering demand forecasting and policy calibration.

The fundamental debate between technological optimism emphasising production greening and ecological economics perspectives requiring absolute consumption reductions remains unresolved. Steel demand cannot continue growing within planetary boundaries, regardless of production methods employed (Watari et al., 2020). This reality suggests that effective policy must combine production decarbonisation with demand management through enhanced material efficiency, extended product lifetimes, increased recycling, and potential consumption moderation in high-income economies (Allwood & Cullen, 2012). The political challenges of such approaches exceed those of production-focused strategies, yet avoiding this reality risks failure to achieve climate objectives even with fully decarbonised production.

For policymakers and business leaders, the implications prove clear: single instruments will fail; coordinated packages combining multiple tools addressing different market failures offer the only viable path. State strategic direction, value chain coordination, and public-private alignment enable transformation impossible through fragmented approaches (Mazzucato, 2013). Policies must balance initial ambition with feasibility, establishing credible trajectories whilst enabling broad participation. Multi-level governance coordination across national,

regional, and local authorities proves essential. Adaptive, experimental approaches with robust monitoring and adjustment mechanisms enable course corrections as evidence accumulates and circumstances evolve. The transition to green steel and other low-carbon industrial materials represents one of the defining challenges of industrial decarbonisation, yet with appropriate policy design and implementation, evidence suggests green premiums can be effectively addressed, enabling industrial transformation consistent with climate objectives whilst maintaining economic competitiveness.

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