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The Role of Trade in Global Energy Transition

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ABSTRACT

This article explores how international trade can accelerate global decarbonization and reduce its costs. It proposes integrating the concepts of green comparative advantage (Le Moigne, 2023) and powershoring (Arbache, 2022). Powershoring refers to the relocation of energy-intensive industrial sectors seeking to decarbonize to regions with abundant and competitively priced renewable energy. This integration enables global carbon arbitrage, optimizing geographic specialization and reducing transition costs, particularly in hard-to-abate sectors. The article demonstrates that eliminating tariff and non-tariff barriers to green goods and services, along with reducing regulatory fragmentation, could expand green production and exports, thereby significantly reducing global emissions. Countries endowed with exceptional renewable resources can leverage and industrialize their green comparative advantages, generating millions of jobs, accelerating technology transfer, curbing green inflation, boosting industrial competitiveness, and promoting inclusive economic development. The article calls for coordinated policies, harmonized taxonomies and standards, and the creation of integrated green hubs. Strategically structured trade can be an exceptionally efficient mechanism for accelerated decarbonization—delivering corporate, economic, social, and environmental benefits.

Keywords: international trade, energy transition, green comparative advantage, powershoring, decarbonization.

JEL Codes: F18, Q56, O13, F43.

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EXECUTIVE SUMMARY

The transition to a decarbonized economy faces two critical obstacles that threaten the achievement of the Paris Agreement targets: insufficient speed of implementation and prohibitive costs. This transformation requires annual investments of trillions of dollars to decarbonize the electricity sector, thereby creating significant fiscal, inflationary, and competitive pressures. This paper proposes a fundamental reconceptualization: international trade, traditionally seen as an obstacle to decarbonization due to carbon leakage, can become a catalyst to accelerate and scale the global energy transition while reducing its economic and social costs. The central thesis argues that the strategic integration between properly structured international trade and climate objectives represents a realistic and economically efficient path to achieve the necessary decarbonization.

The article integrates two transformative concepts that redefine the relationship between trade and sustainability. The first is Green Comparative Advantage (GCA), proposed by Le Moigne (2023), a theoretical framework recognizing that environmental sustainability has become a primary driver of competitiveness in the 21st century. GCA operates through interconnected mechanisms that reveal extraordinary disparities across regions in their embedded carbon intensities. For example, aluminum production can vary from less than 4 tCO_2e per ton in regions powered by hydroelectric or geothermal energy to more than 20 tCO_2e in coal-based systems, thereby creating massive opportunities for carbon arbitrage through international trade.

The second concept is Powershoring, a concept introduced by Arbache (2022), which represents the strategic location of energy-intensive industries in regions with abundant, secure, and competitively priced renewable resources. Powershoring redefines the determinants of foreign direct investment by promoting renewable energy and sustainability as priority factors for industrial location. The theoretical integration between GCA and Powershoring creates synergies that simultaneously amplify both economic and climate benefits.

The concept of global carbon arbitrage emerges as the core of this theoretical convergence: when production is relocated from high-carbon regions to renewable-rich regions, the resulting difference represents a net global emissions reduction regardless of the final consumption location, creating a virtuous circle of economic and environmental benefits without imposing additional costs on the final consumer. This mechanism demonstrates how international trade can simultaneously reduce costs and accelerate decarbonization, transforming the energy transition from a fiscal burden into an economic opportunity. Empirical evidence presented in the paper confirms that this transformation is not aspirational but is already underway.

Despite its transformative potential and evidence of feasibility, trade barriers and regulatory fragmentation continue to be obstacles that artificially raise the costs of global decarbonization. Since 2020, approximately 200 new trade-restrictive measures related to low-carbon technologies and goods have been introduced.

The convergence between climate urgency, technological advances, and geopolitical realignment shows that transforming international trade toward sustainability is not a utopian aspiration but an ongoing process driven by inevitable structural pressures: rising costs of extreme weather events, increasing energy volatility, growing demand for resilient value chains, and the competitive advantages of clean production. The question is not whether this transformation will occur, but how quickly and at what scale it will be implemented. Properly structured international trade—through the systematic removal of barriers and the harmonization of standards—represents an efficient and readily available mechanism to accelerate the decarbonization needed to contain global warming, while reducing its economic and social costs and promoting a new pattern of development.

1. INTRODUCTION

One of the greatest civilizational challenges of our era lies in containing global warming. This goal is not merely a negotiable political aspiration but rather a critical scientific threshold to avoid more catastrophic and irreversible impacts of climate change. To achieve it, science is unequivocal: it is imperative to systematically address the main global source of greenhouse gas emissions—energy production and consumption—which account for approximately 75% of worldwide emissions.

The historical dependence on fossil fuels, built over more than two centuries of industrialization, requires a shift that is not only dramatic but also fundamentally accelerated toward a predominantly renewable energy matrix. However, this transition faces two structural obstacles that threaten its temporal feasibility: high costs and a slow pace of implementation.

The quantitative scale of the challenge is extraordinary. According to the International Energy Agency (IEA), the world will need to nearly triple its installed renewable generation capacity by 2030 to align with carbon neutrality targets. Over the same period, global electricity demand is projected to rise by about 75% through 2050, driven especially by artificial intelligence and the electrification of sectors such as transport, industry, and buildings. This requires annual investments of trillions of dollars in green infrastructure, while the costs of inaction, including extreme climate events, biodiversity loss, and adaptation expenses, will far exceed the preventive investments required.

Traditionally, the global climate agenda has treated international trade as an obstacle or, at best, a secondary consideration. The central concern has been the phenomenon of "carbon leakage," in which stringent environmental policies simply shift carbon-intensive production to jurisdictions with more permissive regulations, transferring emissions without reducing them globally.

This article proposes a reconceptualization of this relationship. Drawing on recent theoretical developments and emerging empirical evidence, we argue that international trade, when properly structured, can become a powerful tool to expand and accelerate global decarbonization while significantly lowering its economic and social costs.

The article's central thesis is grounded in the convergence of two phenomena already shaping the foundations of global competitiveness: GCA (Le Moigne, 2023), which transforms environmental sustainability into a primary source of competitive advantage, and powershoring (Arbache, 2022), a corporate strategy of relocating energy-intensive industries and supply chains—under growing environmental compliance pressures—to regions with abundant and competitively priced renewable resources.

The systemic integration of these movements can accelerate global decarbonization, creating a multiplier effect whereby firms that combine green competitive advantages with renewable-energy-optimized locations not only reduce operational costs and regulatory risks but also establish durable sources of competitive differentiation that are difficult for fossil-fuel-dependent competitors to replicate.

The paper is structured to examine this proposition through eleven interconnected analytical dimensions. First, we examine the GCA framework, its economic theory foundations, and its implications for reconfiguring international trade. Second, we analyze the emerging powershoring thesis, its economic and technological drivers, and its potential to foster a new industrial geography based on renewable energy resources. Third, we demonstrate how the convergence of GCA and powershoring creates transformative synergies that can accelerate decarbonization through market mechanisms. Fourth, we assess their strategic convergence as catalysts for global decarbonization. Fifth, we evaluate how trade based on this convergence can generate large-scale impacts on the economic development of emerging countries rich in renewable energy and related attributes.

Sixth, we document the emergence of structural geopolitical transformations and present empirical evidence and case studies where this convergence is already producing measurable impacts in accelerating decarbonization, reducing operational costs, and creating a new geography of green investment. Seventh, we analyze trade barriers that hinder the global optimization of decarbonization. Eighth, we present Brazil as a paradigmatic case of green-energy convergence, showing how the country could emerge as a global green power. Ninth, we explore the European case, examining how cooperation strategies and green trade and investment alliances can reduce inflationary pressures, democratize access to sustainable technologies, and promote business competitiveness.

Tenth, we propose policy frameworks to foster global green trade. Eleventh, we analyze future perspectives and the economic inevitability of the global green trade transformation, including technological evolution scenarios. Finally, we conclude with a synthesis of the implications for public policy and business strategy, showing how international trade can become a catalyst for global decarbonization.

The article offers three main contributions. Theoretically, it develops an integrated framework connecting comparative advantage theory with decarbonization imperatives, demonstrating how environmental sustainability can become a source of durable competitive advantage while examining the powershoring concept. Empirically, it provides evidence of how this convergence is already transforming industrial investment patterns and global trade flows. Methodologically, it offers a systematic approach for identifying and evaluating powershoring opportunities and trade policies that accelerate decarbonization.

2. GREEN COMPARATIVE ADVANTAGE

2.1 THEORETICAL FOUNDATIONS AND PARADIGM SHIFT

A conceptual framework is emerging that seeks to redefine the relationship between international trade and environmental sustainability. The concept goes beyond incremental adaptations, amounting to a reformulation that recognizes environmental sustainability as a primary driver of competitiveness in the 21st century (Le Moigne, 2023; Le Moigne et al., 2025).

Le Moigne (2023) and Le Moigne et al. (2025) demonstrate that international trade plays a fundamental role in combating climate change when countries specialize according to their environmental comparative advantage. Using a quantitative model of production and international trade with 64 countries and 48 economic sectors, the research simulates the effects of a uniform global carbon tax of US$100 per ton of CO_2 which would result in a 27.5% reduction in global emissions with minimal economic impact (only a 2.6% drop in gross output and 0.7% in real income). The most relevant finding indicates that 36% of this emission reduction is achieved specifically through the environmental gains of trade (the "green sourcing effect"), while the remaining 64% derives from scale and sectoral composition effects. This green sourcing effect operates by connecting consumers to the cleanest producers globally, promoting production relocation toward countries and sectors with lower emission intensities, showing that the solution lies not in reducing international trade but in enhancing it through carbon pricing mechanisms that incentivize specialization based on environmental criteria.

The GCA framework is based on three integrated theoretical pillars that transform the traditional understanding of international trade. The first pillar, the theory of environmental comparative advantage, constitutes an advanced extension of David Ricardo's classical theory, incorporating environmental factors as determinants of comparative advantage.

From this perspective, countries with lower carbon intensity in their production structures, greater availability of renewable energy resources, more advanced sustainability regulatory frameworks, and superior technological capabilities in green sectors can develop natural comparative advantages in an increasingly sustainability-oriented global economy.

Empirical applications of this theory reveal striking disparities that open opportunities for carbon arbitrage through international trade. For example, greenhouse gas emission intensity in primary aluminum production exhibits strong heterogeneity, largely depending on the electricity mix used in electrolysis. In contexts dominated by hydroelectric or geothermal energy, such as Iceland, Norway, and Canada, the carbon footprint can be below 4 tCO_2e per ton of aluminum, whereas in coal-dependent systems it can exceed 20 tCO_2e, according to the International Aluminium Institute and recent studies like Tan et al. (2025). This variation reflects both differences in electric carbon intensity and the efficiency of electrolytic and alumina refining processes. The second theoretical pillar builds on the environmental Porter hypothesis, originating from the seminal work of Michael Porter (1991), which suggests that well-structured environmental regulations can trigger waves of innovation that not only offset compliance costs but generate net systemic benefits.

The World Trade Organization (WTO) operationalizes this perspective by promoting environmental standards that stimulate technological innovation, productive efficiency, and the development of products that simultaneously meet market and environmental objectives. This approach recognizes that long-term competitiveness increasingly derives from the ability to anticipate and comply with progressively stringent environmental regulations.

When applied to international trade, this hypothesis implies that countries implementing advanced environmental regulations can gain first-mover advantages in technologies and processes that later become global standards, generating substantial economic benefits through exports of technology and know-how.

The third pillar, the theory of global public goods, acknowledges that climate stability, air quality, and biodiversity are global public goods that require effective international coordination (Kaul et al., 1999). GCA seeks to create market incentives aligning private interests with the provision of these goods, overcoming traditional free-rider problems that characterize their under-provision.

This approach is based on the recognition that isolated markets often fail to internalize global environmental externalities, leading to situations where profitable private activities impose substantial social costs. The GCA framework can correct these failures through trade mechanisms that reward environmentally beneficial behavior and penalize harmful activities.

Practical implementation of GCA occurs through interconnected operational mechanisms that reinforce each other. The Environmental Goods Agreement (EGA) is a plurilateral initiative under WTO negotiation, launched in 2014 with 18 members representing about 46 economies. Its original goal is to eliminate or reduce import tariffs on a set of environmental goods, including renewable energy equipment, energy efficiency technologies, and pollution control devices. Although negotiations stalled in 2016 without reaching completion, the EGA represents a significant effort to harmonize trade and environmental policies, potentially reducing costs and expanding the international competitiveness of green technologies.

The WTO projects that a successful EGA outcome could deliver a triple win: accelerating the diffusion of clean technologies, expanding dynamic new markets, and facilitating access to technologies that drive sustainable growth. The agreement originally identified about 450 environmental products for potential tariff elimination, ranging from wind turbines to water treatment systems.

Climate-focused Trade Policy Reviews (TPRs) conducted under the WTO represent a significant institutional innovation, integrating environmental considerations into regular reviews of member countries' trade policies. Empirical research indicates that climate-oriented TPRs substantially foster corporate adoption of green technologies by influencing managerial perceptions of political, regulatory, and market risk (Tanveer et al., 2024).

The Environmental Database (EDB) is an analytical tool that systematically documents environmental policies and their intersection with trade flows, often compiled by academic researchers or think tanks. Analyses of the EDB reveal a robust correlation between green technological innovation and trade performance, where patents in environmental technologies are statistically significant predictors of future exports in green products.

A key aspect of the framework is developing methodologies to account for the "embedded carbon" in internationally traded products (Sato, 2013, inter alia). This approach recognizes that product-related emissions vary substantially across locations, energy mixes, technologies, and production practices.

Embedded carbon accounting reveals systemic inefficiencies in which countries with strict climate policies import carbon-intensive goods, merely transferring emissions without reducing them globally. This dynamic not only undermines the effectiveness of national climate policies but also creates competitive distortions that penalize companies committed to decarbonization.

In the steel sector, for example, disparities are dramatic. Blast furnace–basic oxygen furnace (BF–BOF) steel production emits approximately 1.8–2.2 tons of CO_2per ton of crude steel, whereas electric arc furnaces (EAF) powered by renewable energy can reduce emissions to 0.27–0.36 tons of CO_2per ton of steel (Ren et al., 2023). In cement, global average emissions are about 900 kg CO_2per ton of cement, with significant regional variations depending on energy mix and technologies used (Andrew, 2019). The production of polysilicon and ingots for solar panels—a highly energy-intensive activity—is largely concentrated in regions powered almost entirely by coal, such as Xinjiang and Inner Mongolia. As a result, China accounts for virtually all global emissions associated with solar panel manufacturing. According to the IEA (2022a), if those panels were hypothetically produced in countries such as Costa Rica, Brazil, or Norway, which have renewable-based power matrices, emissions would represent only a fraction of those generated in China.

The transparency provided by embedded carbon accounting enables countries and firms with genuine environmental advantages to capture value in markets that reward low-carbon intensity. This dynamic generates strong economic incentives for investment in renewable energy, clean technologies, and energy efficiency.

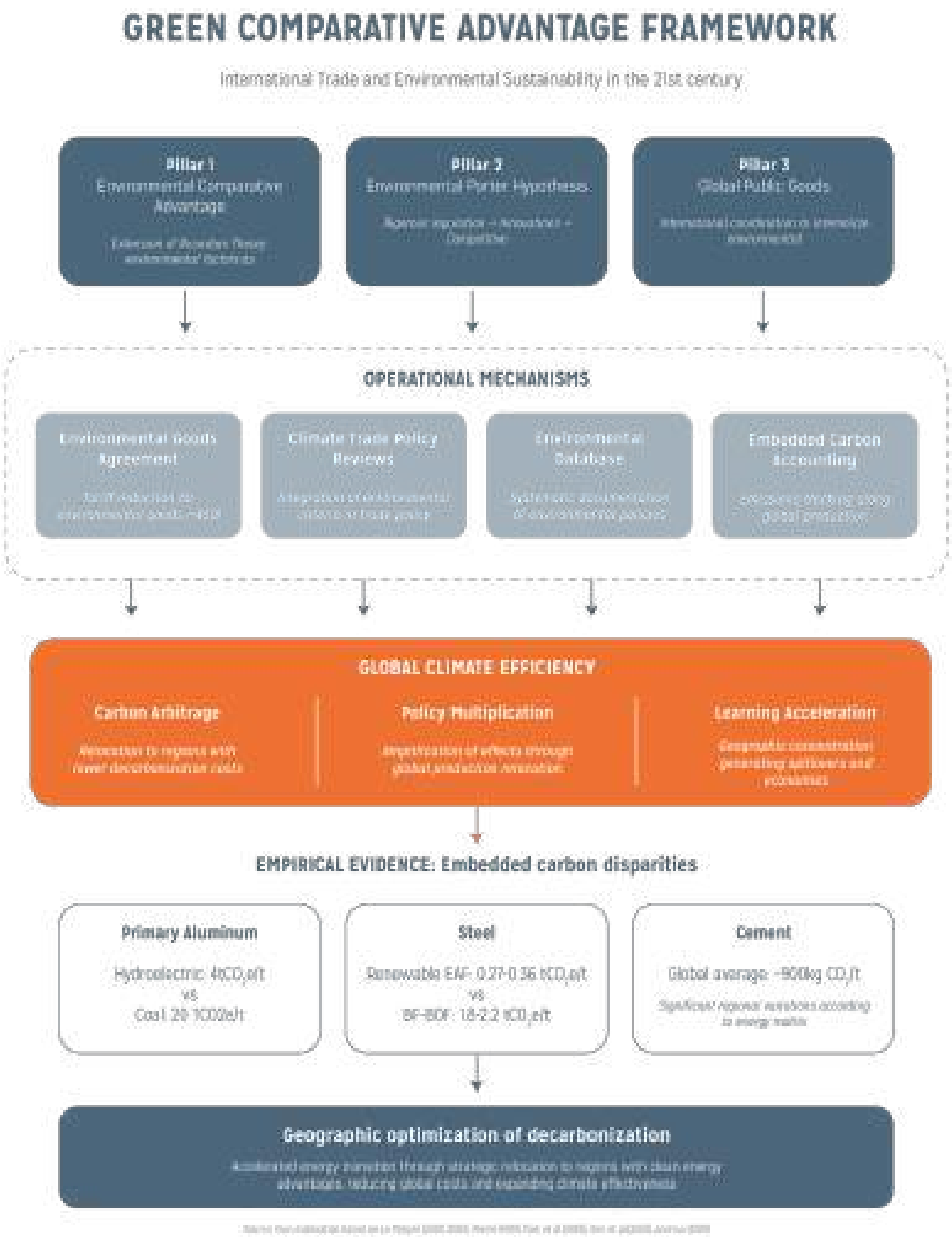
Building on the trade–climate framework, this paper introduces the term "geographic decarbonization optimization" to describe the idea that the global energy transition can be accelerated and its costs reduced by strategically locating production in regions with renewable energy advantages. This approach relies on the empirical observation that both the costs and pace of energy transitions vary greatly across regions, creating opportunities for optimization through international trade. While some regions face high costs and extended timelines due to fossil fuel dependency and geographic constraints, others already possess consolidated infrastructure or exceptionally favorable conditions for renewable energy.

The concept of "global climate efficiency" can be understood as the configuration in which resources, technologies, and production flows are organized to minimize the aggregate cost of global decarbonization. This efficiency manifests through three interdependent, mutually reinforcing mechanisms. The first is carbon arbitrage, which reduces global mitigation costs by locating production in jurisdictions where emissions can be abated most economically, taking advantage of regional differences in renewable energy costs and regulatory frameworks.

The second mechanism, climate policy multiplication, amplifies the effects of domestic policies through incentivized global production, where stringent national measures create competitive advantages for countries with renewable energy matrices. This dynamic enables countries with ambitious climate policies to influence global production patterns through demand effects.

The third mechanism, acceleration of learning curves, results from the geographic concentration of green industries, speeding technological development through knowledge spillovers, agglomeration economies, and the creation of specialized industrial ecosystems. This concentration fosters collaborative innovation, investment partnerships, risk reduction, and the development of advanced technological solutions.

The figure below synthesizes the core ideas of the GCA framework.



2.2 EMPIRICAL EVIDENCE

Recent empirical evidence underscores a strong and positive link between advanced environmental strategies and superior corporate performance. Tanveer et al. (2024), analyzing Trade Policy Reviews (TPRs) and green technology adoption across 30 countries from 2009 to 2019, find that firms operating in economies with more frequent TPRs are significantly more likely to implement green technologies. Their longitudinal analysis reveals that climate-oriented TPR entries reduce managerial perceptions of uncertainty and risk, fostering an institutional environment conducive to long-term investments in environmental innovation. This mechanism operates by signaling credible government commitment to sustainability and by mitigating regulatory volatility that often deters private investment in low-carbon transitions.

Although estimates of valuation premiums and ESG fund volumes vary across data sources and methodologies, converging evidence from both academia and industry consistently points to positive trends. Sustainability-oriented strategies often translate into tangible operational gains through lower consumption of energy, water, and raw materials—though the scale of savings remains highly dependent on sectoral context, geographic location, and the maturity of corporate sustainability practices.

Consumer and business markets are increasingly demonstrating a readiness to pay for sustainability. PwC's Voice of the Consumer Survey 2024 reports that global consumers are willing to pay, on average, 9.7% more for sustainably produced or sourced goods (PwC, 2024). In parallel, Bain & Company (2024) shows that sustainability has already entered the top three procurement criteria for corporate buyers, with 36% indicating they would discontinue relationships with suppliers failing to meet environmental performance expectations—specifically those linked to the Scope 1–3 framework of the GHG Protocol. These findings highlight a structural shift in market preferences, although substantial challenges persist in achieving widespread implementation and verification of sustainability standards.

The empirical results also indicate that climate-related TPRs, when coupled with greater adoption of green technologies, lead to measurable reductions in greenhouse gas emissions. This evidence supports the view that trade policy instruments—traditionally associated with market access and competitiveness—can serve as powerful catalysts for technological diffusion and large-scale decarbonization.

3. POWER RESHORING: THE NEW GEOGRAPHY OF ENERGY COMPETITIVENESS

3.1 CONCEPTUALIZATION AND THEORETICAL DEVELOPMENT

By placing decarbonization and access to renewable energy at the core of industrial location and foreign direct investment (FDI) decisions, powershoring represents an innovative theoretical contribution to understanding the new global economic geography (Arbache, 2022; Arbache & Esteves, 2023; Arbache & La Rovere, 2023). Unlike approaches focused on geographic proximity (nearshoring), geopolitical alignment (friendshoring), or production repatriation (reshoring), powershoring recognizes that in the 21st-century economy, secure, abundant, and competitively priced renewable energy has become a decisive productive factor for energy-intensive industries seeking or needing to decarbonize. This emerging logic reflects a profound shift in the determinants of global competitiveness, in which energy transition capacity increasingly shapes patterns of specialization, investment, and trade.

Grounded in the theory of dynamic comparative advantage, powershoring highlights how renewable energy resources can generate cumulative and sustainable competitive advantages through learning effects, economies of scale and agglomeration, and the formation of specialized industrial ecosystems. The underlying economic rationale stems from the empirical observation that regions differ widely in their renewable energy endowments, creating long-lasting cost arbitrages. While some areas remain burdened by fossil dependency and structural barriers to expanding renewable capacity, others benefit from consolidated infrastructure, favorable geography, and the potential to offer competitively priced clean energy on a stable basis.

By reconfiguring FDI determinants, powershoring elevates energy costs and environmental sustainability from secondary considerations to primary factors in location strategies. This transformation operates through several interconnected channels. Market-seeking FDI gains added motivation when multinational firms face compliance obligations under mechanisms such as the Carbon Border Adjustment Mechanism (CBAM), encouraging them to locate production in jurisdictions where low-carbon profiles ensure automatic or near-automatic conformity. Efficiency-seeking FDI, traditionally driven by labor and logistics costs, now increasingly values long-term predictability of renewable energy prices—an attribute that mitigates exposure to fossil fuel volatility. Resource-seeking FDI, in turn, expands beyond conventional natural resources to include renewable energy availability as a central determinant, particularly for electro-intensive sectors. Finally, strategic asset-seeking FDI incorporates access to green technologies, renewable energy expertise, and favorable regulatory environments as key strategic assets in global competition.

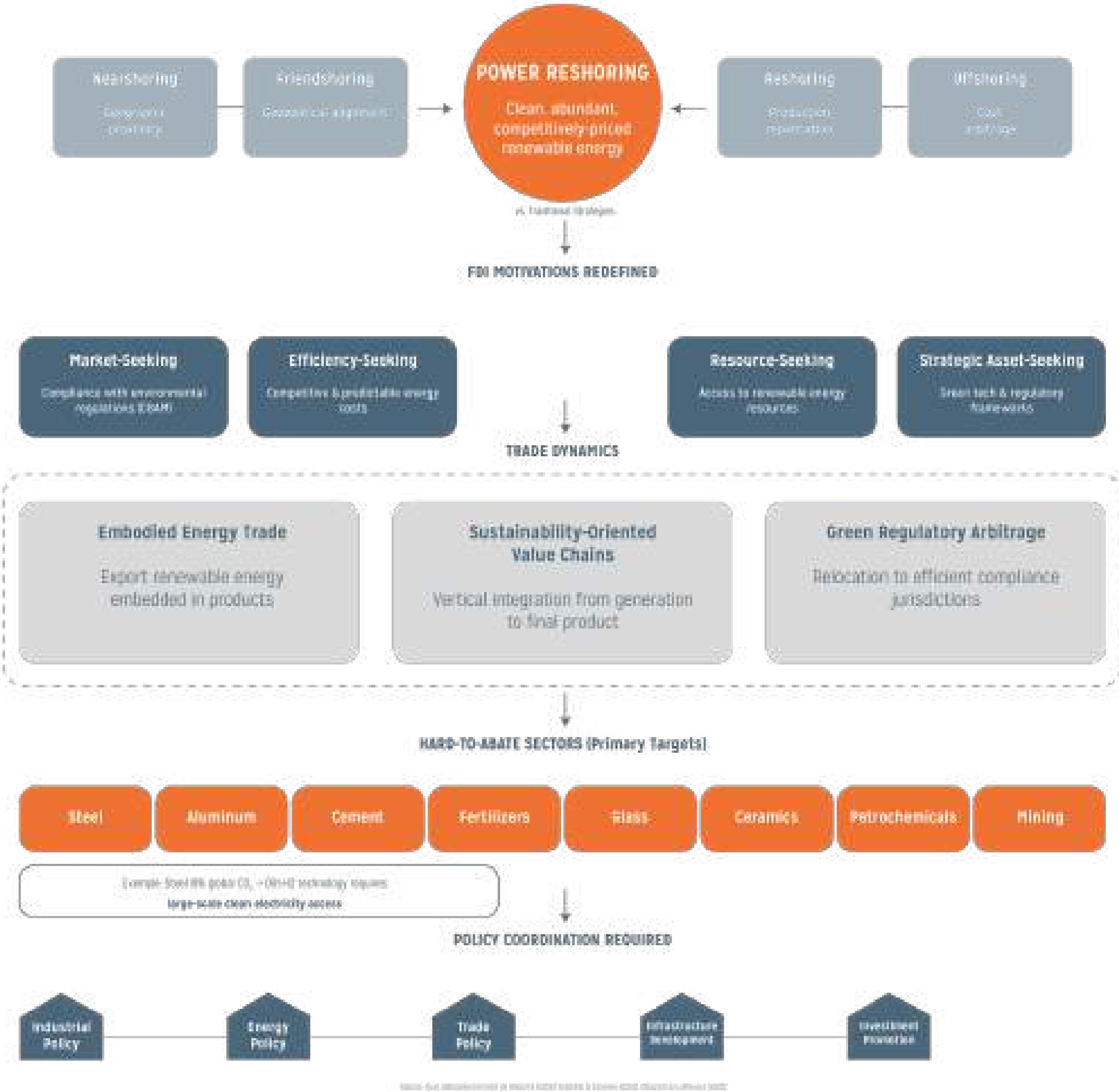
Powershoring also transforms trade patterns and value chain dynamics. Embodied energy trade emerges as a defining concept, as countries begin exporting renewable energy embedded in energy-intensive products, effectively monetizing their clean energy advantage while circumventing the physical limitations of transmission and storage. Importing economies, in turn, benefit from products with lower carbon footprints, enabling progress toward climate targets without equivalent domestic infrastructure investment. Simultaneously, sustainability-oriented value chains are reshaping global trade flows through vertical integration—from renewable generation to final product—to internalize emissions control, secure green premiums, and enhance ESG transparency. This structural integration reduces regulatory risk, strengthens brand credibility, and consolidates long-term competitiveness. In parallel, green regulatory arbitrage incentivizes firms to establish operations in jurisdictions where environmental compliance is inherently more efficient, creating trade flows shaped by differences in institutional and regulatory capacities for decarbonization.

These dynamics are particularly relevant for hard-to-abate sectors such as steel, aluminum, cement, fertilizers, glass, ceramics, petrochemicals, and mining—industries facing steep technical and financial barriers to decarbonization. Regulatory pressures, investor expectations, and emerging market premiums for low-carbon products are generating tangible economic incentives for relocation. The steel sector, which accounts for roughly 8% of global CO_2 emissions, exemplifies this transformation. New production technologies such as Direct Reduced Iron (DRI) using green hydrogen (H_2V) depend on massive and competitively priced renewable electricity, giving clear comparative advantages to regions endowed with exceptional renewable potential. Realizing the promise of powershoring requires coordinated and forward-looking policymaking that integrates industrial, energy, trade, infrastructure, and investment agendas. Countries with renewable energy advantages must design comprehensive strategies combining infrastructure expansion, industrial capacity building, favorable regulatory frameworks, and targeted trade and investment promotion mechanisms to capture this transformative opportunity. Such coordination demands multi-level government alignment and strong public–private partnerships to develop competitive industrial ecosystems. Investment attraction must be coupled with programs for specialized workforce training, R&D centers, and regulatory streamlining to facilitate the operation of electro-intensive industries.

The figure below synthesizes the conceptual structure and transmission mechanisms of powershoring.

POWER RESHORING FRAMEWORK

Renewable Energy as Primary Driver of Industrial Location and FDI Flows



3.2 INDUSTRIALIZING COMPARATIVE ADVANTAGES: GREEN HUBS AS CATALYSTS

Powershoring integrates seamlessly with the broader concept of *industrializing comparative advantages* (Arbache & Drummond, 2025), which transcends traditional commodity-export approaches by articulating strategies that accelerate global decarbonization through the industrial transformation of resources and natural capital. This perspective is grounded in the premise that profound structural shifts in the relative prices of resources, natural capital, and renewable energy are underway—driven by the convergence of climate pressures, geopolitical constraints, surging demand, and the increasing scarcity of critical resources such as water. In this context, powershoring provides an analytical and policy framework through which nations can leverage these evolving price structures to promote sustainable industrialization, enhance competitiveness, and contribute to global emission reductions.

Shifts in relative prices are transmitted through multiple reinforcing vectors. The global energy transition amplifies demand for critical minerals and renewable energy, raising their relative value vis-à-vis fossil fuels, whose long-term trajectories show structural decline. Intensifying climate regulations introduce persistent premiums for low-carbon goods, altering global competitiveness equations, risk assessments, and return profiles. Meanwhile, geopolitical fragmentation diminishes substitution elasticities among suppliers, strengthening the bargaining power of countries endowed with strategic resources and motivating multinational firms to diversify production toward more sustainable and geopolitically stable regions. The transformation of global value chain strategies—from a narrow focus on efficiency toward *resilience-conditioned efficiency*—further drives the geographic diversification and even redundancy of operations, favoring countries rich in natural resources and renewable potential, and insulated from major geopolitical frictions (Arbache, 2025a).

This reconfiguration of relative prices creates unprecedented opportunities for countries endowed with abundant resources, natural capital, and renewable energy to design *integrated green hubs* that simultaneously advance domestic industrialization and global decarbonization. Unlike historical commodity booms driven by cyclical demand, the rise in green relative prices appears structural, underpinned by physical resource constraints and reinforced by technological, institutional, and political imperatives. Within this structural dynamic, both host nations and investors can capture value through strategic partnerships that combine local natural assets with international capital, technology, and market access.

In the energy domain, *industrializing comparative advantages* implies that countries with plentiful renewable resources can develop green hubs as spatially integrated industrial ecosystems that align renewable generation, productive capacity, and export logistics to create shared and enduring value. These hubs constitute geographically optimized configurations in which multiple energy-intensive industries cluster together, share common infrastructure, and exploit agglomeration economies to enhance competitiveness while collectively lowering global decarbonization costs.

The structural advantages of green hubs are multidimensional. The geographic concentration of sustainable industries enables large-scale efficiencies in shared infrastructure such as renewable power generation and transmission systems, dedicated port terminals, energy storage, and integrated waste management, thus reducing capital and operational costs for all participants. For instance, a single H_2V plant could be jointly developed by several industrial ventures to supply their respective hydrogen needs, spreading investment risks and accelerating technology deployment. Proximity among complementary industries also facilitates circular economy linkages, where by-products from one process become valuable inputs for another—maximizing resource efficiency and minimizing environmental impact. For example, residual heat from aluminum production could be used to warm agricultural greenhouses, while oxygen generated during electrolysis for H_2V could feed into steelmaking processes.

Complementary approaches such as *renewable pools*—collective renewable energy systems supplying multiple industrial users through shared generation and transmission infrastructure—further illustrate how coordinated access to clean energy can enhance competitiveness and facilitate industrial decarbonization. These schemes enable firms to secure stable and competitively priced renewable power while promoting systemic efficiency and broader integration of low-carbon resources (Samadi et al, 2023).

Through this integrated model, powershoring and the industrialization of comparative advantages jointly redefine the interface between trade, energy, and industrial policy. They enable countries rich in renewable potential to position themselves as strategic nodes of the emerging low-carbon economy—exporting not only energy and materials, but also decarbonization capacity embedded within industrial production.

3.3 CONVERGING ECONOMIC AND TECHNOLOGICAL DRIVERS

Multiple converging factors are accelerating the global powershoring trend, reshaping the geography of industrial competitiveness. The rising economic viability of renewable energy technologies has transformed solar and onshore wind from costly alternatives into primary, market-competitive energy sources. Between 2010 and 2023, the Levelized Cost of Energy (LCOE) for utility-scale photovoltaic solar declined by approximately 90%, from US$0.460/kWh to around US$0.044/kWh, while onshore wind costs fell nearly 70%, from about US$0.111/kWh to US$0.033/kWh over the same period. These extraordinary declines, driven by rapid technological innovation, larger turbine sizes, higher capacity factors, and sharply reduced installation, operation, and financing costs, have redefined the geography of energy competitiveness—turning regions with high renewable potential into emerging industrial hubs (IRENA, 2024).

At the same time, the mounting energy intensity of the digital economy, artificial intelligence, and advanced manufacturing has created unprecedented global demand for stable, low-cost electricity. Energy-intensive processes such as advanced materials fabrication, semiconductor production, large-scale data center operation, and hydrogen (H_2V) manufacturing now depend critically on secure and affordable renewable energy. For these sectors, energy costs represent not merely an input but a decisive factor for economic feasibility and international competitiveness.

Regulatory dynamics and ESG imperatives reinforce this transformation. The tightening of environmental standards and the increasing scrutiny of investors and consumers have created concrete incentives for firms to relocate operations to jurisdictions where renewable energy availability enables production with a significantly lower carbon footprint. The CBAM epitomizes this new regime of climate-aligned trade incentives, as it converts environmental compliance from a cost burden into a competitive asset. Production located in regions with renewable abundance can thus gain measurable advantages in export markets by meeting decarbonization requirements inherently rather than through compensatory mechanisms.

Adding to these forces, the growing volatility of fossil fuel prices—magnified by geopolitical tensions, supply disruptions, and climate-induced shocks—enhances the appeal of renewable energy as a source of long-term cost stability and predictability. Industries exposed to energy price fluctuations are increasingly prioritizing renewable-based power systems to hedge operational risks and sustain competitiveness in uncertain global markets. The ongoing technological progress in renewables, storage, and grid management further amplifies these effects, consolidating powershoring as a rational, efficiency-driven response to the structural transformation of global energy economics.

3.4 STRATEGIC SECTORS AND PRIORITY OPPORTUNITIES

Powershoring finds its most immediate and strategic application in hard-to-abate sectors, where decarbonization entails substantial technical challenges but also presents significant economic opportunities. Primary aluminum production, as previously discussed, exemplifies this dynamic due to its extremely high energy intensity, which makes access to secure, competitively priced renewable energy a decisive factor for global competitiveness.

Mineral refining represents one of the most energy-intensive stages in industrial value chains. As highlighted by Aramendia et al. (2023), pyrometallurgical processes operate at extremely high temperatures—typically between 500 °C and 2 000 °C—and primary metal production, including refining, accounts for roughly 5 % to 10 % of total global primary energy consumption. These characteristics underscore the strategic relevance of locating refining activities in regions endowed with abundant and competitively priced renewable energy, where powershoring can significantly reduce production costs and emissions intensity.

Similarly, the fertilizer industry—particularly ammonia production, which relies on highly energy-intensive processes—can undergo transformative decarbonization through hydrogen-based (H_2) technologies. Achieving economic viability in this sector requires regions with abundant renewable energy to supply the large and continuous energy demand. Regions that meet these criteria can develop enduring competitive advantages in this strategically essential sector, which underpins global food security and industrial fertilizer supply chains.

The cement sector presents distinct challenges, as its emissions originate both from fuel combustion and from intrinsic chemical processes during clinker production. Emerging solutions, such as carbon capture and utilization (CCU) technologies, are highly energy-intensive, further reinforcing the importance of locating production in areas with abundant, cost-competitive renewable energy. By aligning technical feasibility with energy resource availability, powershoring enables these sectors to reduce carbon intensity, lower production costs over the long term, and position themselves competitively in the global low-carbon economy.

3.5 GEOECONOMIC IMPACTS AND INDUSTRIAL TRANSFORMATION

Powershoring is driving a profound reconfiguration of global industrial geography, creating opportunities for regions that were previously peripheral to emerge as new industrial powers. North Africa, for example, is strategically positioned to become a hydrogen-based (H_2V) hub for Europe, leveraging abundant solar resources and geographic proximity to develop energy corridors that could reshape Euro-Mediterranean economic relations (IEA, 2025a; Arbache, 2025b). Similarly, Patagonia possesses exceptional potential for energy-intensive industries due to some of the world's most consistent and intense wind resources, offering opportunities for large-scale renewable-powered industrial development.

Brazil's Northeast is increasingly attracting global investor attention, thanks to highly competitive solar and wind costs, natural seasonal complementarity between resources, and strategic logistical infrastructure serving multiple international markets (Ceplan, 2025). In parallel, countries traditionally reliant on fossil fuel exports are implementing ambitious renewable energy-based diversification strategies to retain economic relevance amid the global energy transition. The United Arab Emirates and Saudi Arabia exemplify this shift, investing heavily in renewable capacity and H_2V technologies to leverage existing energy expertise in a post-oil context. These initiatives represent one of the largest capital reallocations in modern economic history, with significant implications for global energy stability and geopolitics.

Iceland illustrates the potential of full industrial transformation anchored in renewable resources. The country's abundant geothermal and hydropower capacity attracts large-scale aluminum production and hosts sustainable data centers for global companies, leveraging 100% renewable energy and natural cooling. Icelandic aluminum, with a substantially lower carbon footprint than coal-based production, accounts for roughly 30% of national exports, demonstrating how energy endowments can be monetized through strategic industrialization rather than mere electricity exports.

Chile is emerging as a global renewable-industrial hub by exploiting exceptional solar resources in the Atacama Desert. The country has set an ambitious target of 25 GW of electrolysis capacity for H_2V, with projected production costs around US$1.50/kg. Flagship initiatives include the HIF-Porsche partnership for e-fuel production and AES Andes projects developing integrated renewable energy–electrolysis complexes, complemented by strategic collaborations with multinational mining firms. Large-scale copper and lithium operations are increasingly leveraging competitive solar energy, creating synergistic linkages between mineral extraction and renewable-powered industrial processes.

Norway exemplifies the effective transition of offshore oil expertise to H_2V development. By combining abundant hydropower with advanced maritime technical know-how, local and multinational firms—including Equinor, Norsk Hydro, and Yara—are investing in renewable energy, low-carbon solutions, and green aluminum and fertilizer projects. The Northern Lights project, the world's first commercial carbon capture and storage initiative, demonstrates how offshore operational competencies can be applied to advanced decarbonization technologies, fostering a new industrial sector grounded in transferable expertise, consistent with Hausmann and Hidalgo's economic complexity framework.

3.6 POWERSHORING IN PRACTICE: FROM THEORY TO GLOBAL IMPLEMENTATION

Powershoring has moved beyond a purely conceptual framework and is increasingly materializing across multiple geographies and sectors. Industrial projects anchored in renewable energy are emerging in Europe, the Americas, Africa, and Asia, mobilizing governments, corporations, investment funds, and other stakeholders around the convergence of energy competitiveness and decarbonization objectives. The proliferation of H_2V projects—from Patagonia to North Africa, from the Persian Gulf to Northeast Brazil—demonstrates how countries with renewable energy advantages are actively seeking to capture industrial value chains in hard-to-abate sectors. For example, Chile is advancing international partnerships to become a leading exporter of synthetic fuels, while Iceland and Norway leverage their renewable energy bases to attract green steel, aluminum, and fertilizer production. These developments confirm that powershoring is evolving into a structuring axis in the global industrial reconfiguration.

The growing interest from institutional investors further signals that powershoring is emerging as a new asset class. Sovereign wealth funds, investment funds, family offices, asset managers, multilateral banks, and private investors are increasingly designing dedicated vehicles to finance green hubs and low-carbon industrial value chains. This investment appetite is supported by the predictability of returns tied to long-term energy supply contracts and low-carbon industrial outputs. Regulatory pressures in developed markets, such as the CBAM, alongside rising corporate demand for automated carbon compliance solutions, reinforce the economic rationale for such investments. In this context, powershoring emerges as a strategic asset not only for host countries and industries but also for investment portfolios seeking to align financial returns with positive climate impact.

Although still in its early stages, the trend exhibits clear signs of institutionalization. Several countries are embedding powershoring principles into industrial and sectoral policies, establishing regulatory frameworks and fiscal incentives that encourage renewable-energy-driven industrial localization, as exemplified by Brazil. The intensifying competition among nations to attract low-carbon, energy-intensive industries suggests that powershoring is likely to follow a trajectory similar to other structural FDI transformations, consolidating as a distinct domain of analysis, regulation, and investment. Despite its nascent status, the process already generates cumulative effects through learning, technology adoption, economies of scale, and coordinated action between public and private actors, indicating strong potential for rapid global expansion and strategic consolidation.

4. THE STRATEGIC CONVERGENCE: GCA AND POWERSHORING AS CATALYSTS FOR GLOBAL DECARBONIZATION

4.1 STRATEGIC CONVERGENCE: GCA AND POWERSHORING AS CATALYSTS FOR GLOBAL DECARBONIZATION

The convergence of GCA and powershoring represents more than the overlap of two economic concepts; it constitutes a transformative synergy in how international trade can accelerate global decarbonization. This convergence operates through the systemic articulation of environmental competitive advantages and the strategic location of energy-intensive production, forming an integrated framework that enhances both economic efficiency and climate effectiveness.

GCA provides the theoretical foundation that legitimizes and quantifies competitive advantages derived from lower carbon footprints, advanced regulatory frameworks, and access to clean technologies, while powershoring delivers the operational mechanism through which these advantages materialize in the real economy via strategic industrial localization. When combined, these concepts define a market-based model of decarbonization that aligns private incentives with global climate objectives, overcoming the constraints of approaches reliant solely on regulation or subsidies.

The theoretical convergence rests on an empirically validated premise: the global energy transition can be significantly optimized through geographic specialization based on renewable energy resources. In this configuration, countries with environmental comparative advantages attract energy-intensive industries through competitive costs, streamlined regulatory compliance, and privileged access to key markets. Such specialization not only reduces global decarbonization costs through energy-efficiency arbitrage but also accelerates progress by concentrating investment, expertise, and technological innovation in regions with optimal conditions for clean production.

Over time, these dynamics create a self-reinforcing process in which initial advantages are amplified by agglomeration effects, economies of scale, learning curves, and the development of specialized industrial ecosystems that attract additional capital and stimulate technological advancement. The convergence of GCA and powershoring thus produces cumulative effects that magnify both competitiveness and climate impact, reinforcing the global diffusion of low-carbon technologies.

This synergy manifests through five interrelated mechanisms that generate economic value while accelerating global decarbonization. The first is simultaneous cost and sustainability optimization, enabling companies to reduce operational expenses and carbon footprints by locating in regions with abundant, competitively priced renewable energy. This dual optimization makes decarbonization economically attractive rather than burdensome: powershoring strategies typically deliver lower energy costs and reduced emissions, creating a twin advantage that strengthens market positioning while fulfilling corporate sustainability goals.

The second mechanism is the acceleration of technological learning curves. The geographic clustering of green industries in powershoring regions fosters knowledge spillovers, process improvements, and collaboration among specialized firms, thereby reducing costs and driving innovation. This effect is especially evident in emerging technologies such as hydrogen electrolysis (H_2V), where industrial clusters—such as those developing in Chile—can achieve efficiency breakthroughs that accelerate global adoption and cost reduction, benefiting both local competitiveness and global climate objectives.

The third mechanism is the creation of premium markets for low-carbon products. The convergence encourages the development of differentiated markets in which goods produced in powershoring regions using renewable energy command higher prices, reflecting rising consumer and corporate demand for sustainability. Although still emerging, certified "green" or "carbon-neutral" products already capture price premiums in advanced markets, generating tangible incentives that compensate for higher location or certification costs and creating a virtuous cycle that drives new investment.

The fourth mechanism involves anticipation and facilitation of regulatory compliance. Firms operating in low-carbon powershoring regions inherently meet or exceed tightening environmental regulations, including border carbon adjustments such as the EU's CBAM. This preemptive compliance significantly reduces regulatory costs and ensures continued access to high-standard markets. The financial implications are substantial: European steel producers, for instance, will face significant CBAM costs starting in 2026, with current EU carbon prices ranging from €65–100 per ton and projections reaching €146 per ton by 2030, whereas production in renewable-energy regions can mitigate these costs through lower embodied emissions (Maliszewska et al., 2025).

Finally, the fifth mechanism is the global multiplication of environmental benefits. The convergence generates multiplier effects that extend beyond direct emission reductions, operating through the substitution of carbon-intensive goods in world markets, the demonstration of commercial viability for clean technologies, and the acceleration of global learning curves that further reduce costs.

Together, these dynamics position GCA and powershoring as mutually reinforcing levers for aligning economic competitiveness with climate ambition. By combining theoretical insight with practical applicability, the convergence provides a coherent pathway for market-driven global decarbonization—one that transforms sustainability from a policy constraint into a foundation for the next wave of industrial and trade competitiveness.

4.2 GLOBAL CARBON ARBITRAGE: THE CORE OF THE CONVERGENCE

The concept of global carbon arbitrage lies at the heart of the convergence between GCA and powershoring, serving as the mechanism through which regional disparities in carbon intensity become sources of tradable competitiveness and measurable climate benefits. This process unfolds when firms relocate production from high-emission regions to areas endowed with abundant renewable energy, thereby simultaneously achieving reductions in operational costs, capturing price premiums for low-carbon products, ensuring facilitated regulatory compliance, and mitigating exposure to future environmental regulations and carbon pricing.

Carbon arbitrage transcends the simple geographic relocation of production; it represents a systemic optimization process that reduces net global emissions by enhancing both productive and energy efficiency. For example, producing one ton of aluminum in Iceland using geothermal energy (emitting approximately 4 tCO_2) instead of in China with coal-based power (emitting over 20 tCO_2) leads to a net global reduction of more than 16 tCO_2 per ton, regardless of where the product is ultimately consumed. This differential illustrates how the spatial reallocation of industrial production can function as a powerful mechanism of global climate efficiency.

Such arbitrage mechanisms generate virtuous cycles that reinforce themselves over time. Companies that relocate operations to renewable-energy regions benefit from multiple convergent advantages: lower and more predictable energy costs; enhanced access to markets increasingly valuing certified low-carbon goods; facilitated compliance with stringent environmental regulations; and substantial reduction in long-term exposure to carbon-related financial risks. Through these combined effects, global carbon arbitrage becomes both a driver of competitiveness and a strategic instrument for aligning industrial geography with the imperatives of global decarbonization.

4.3 INTEGRATED INDUSTRIAL ECOSYSTEMS: MANIFESTATION OF THE CONVERGENCE

The convergence between GCA and powershoring takes tangible form through the emergence of integrated industrial ecosystems that bring together multiple energy-intensive industries in strategic geographic proximity. These ecosystems mark an evolution from isolated powershoring initiatives toward systemic configurations designed to maximize energy efficiency, minimize waste through circular economy practices, and accelerate technological progress via inter-firm collaboration. By operating as interconnected industrial clusters, they translate renewable energy advantages into sustained competitive gains and broader climate impact.

A representative example involves an ecosystem integrating hydrogen production through electrolysis, hydrogen-based steelmaking, and carbon capture facilities that repurpose industrial $CO_2$for synthetic fuels or construction materials. In such configurations, overall energy efficiency surpasses the sum of individual plant efficiencies due to systemic optimization, thermal synergies, and reduced transmission and conversion losses. Close cooperation among firms with complementary inputs, outputs, and technical challenges accelerates innovation and diffusion of advanced technologies, reinforcing the competitiveness of the entire system.

The ecosystemic model also improves financial and operational resilience. Investment risks are distributed across multiple participants, lowering entry barriers for smaller companies and facilitating financing through diversified revenue streams. This interconnected structure enhances the stability of returns and cushions firms against sectoral or market volatility. For global technology and equipment providers, these ecosystems represent concentrated, high-value markets that justify the deployment of tailored solutions, specialized R&D, and advanced technical support. Concentrated demand for innovation in energy-intensive applications generates cumulative learning and technology refinement, creating feedback loops that strengthen local competitiveness while enabling the global replication of efficient, low-carbon industrial systems.

4.4 TRANSFORMATION OF GLOBAL VALUE CHAINS

The convergence of GCA and powershoring is set to drive a structural transformation in global value chains (GVCs), where traditional determinants of industrial location—such as labor costs, market access, and logistics—will increasingly be complemented or even replaced by factors related to carbon intensity, renewable energy availability, and compliance with tightening environmental standards. This marks a fundamental reorganization of global production toward climate efficiency as a new axis of competitiveness.

This shift materializes through the emergence of “green value chains”: production systems explicitly designed to minimize total carbon footprints by optimizing each stage according to environmental comparative advantages. In these chains, leading firms strategically allocate production across regions based on renewable energy potential, regulatory predictability, and environmental performance, thereby achieving simultaneous optimization of cost, quality, speed, and sustainability.

The reconfiguration of GVCs under the GCA–powershoring convergence unfolds through three interlinked dynamics. First, companies in carbon-sensitive industries are systematically redesigning supply chains to incorporate suppliers from low-emission regions, even at the cost of additional coordination or logistical complexity. The strategic inclusion of low-carbon partners reduces overall supply-chain emissions and strengthens resilience against future regulatory or reputational risks. Second, specialized suppliers are actively upgrading their capacities to meet increasingly demanding sustainability standards—investing in clean technologies, environmental certification systems, and process innovations that grant them privileged access to global contracts with firms committed to decarbonization. Third, countries and regions are intensifying competition to attract segments of these reconfigured value chains through comparative energy advantages, predictable regulation, specialized infrastructure, and fiscal incentives targeting energy-intensive industries.

This restructuring opens new opportunities for industrial upgrading, allowing economies previously positioned in low-value-added segments to move up the chain by leveraging structural environmental advantages. Regions endowed with abundant renewable energy can transition from suppliers of energy-intensive commodities to producers of high-value, low-carbon materials, specialized components, and premium finished goods. This evolution enables them to capture a larger share of global value creation, deepen productive capabilities, foster advanced technical competencies, and establish enduring commercial linkages with multinational firms leading the global transition toward sustainable production.

4.5 TECHNOLOGICAL ACCELERATION AND SYSTEMIC INNOVATION

The geographic concentration of green industries driven by the convergence of GCA and powershoring is accelerating technological progress through the formation of specialized innovation clusters that combine industrial density, proximity to advanced research institutions, and intensive collaboration among firms facing related technological challenges. These clusters operate as living laboratories where decarbonization technologies are developed, tested, and scaled at industrial levels, creating environments that transform theoretical innovation into applied solutions through rapid feedback, validation, and optimization.

Technological acceleration within these ecosystems unfolds through a set of reinforcing mechanisms. Knowledge spillovers among geographically proximate firms speed up the diffusion of innovations, technical improvements, and best practices. Formal and informal collaborations to solve shared challenges enable companies to pool resources, expertise, and innovation risks, thereby lowering R&D costs and enhancing the efficiency of technological learning. The presence of universities and specialized research centers offering programs tailored to the clusters' needs sustains a continuous flow of skilled professionals and applied research directly aligned with industrial priorities. At the same time, concentrated demand for advanced solutions attracts global equipment suppliers and technology developers to establish local operations and joint R&D initiatives, fostering rapid customization and refinement of technologies for specific industrial applications.

This intensive innovation dynamic is already producing tangible technological advances in key domains of industrial decarbonization. Electrolysis technologies for H_2V production are undergoing rapid cost declines and efficiency gains, with electrolyzers improving from conventional efficiencies of 60–70% to advanced systems reaching 80–85%. Hydrogen-based steelmaking has progressed to commercial-scale testing through demonstration projects, including a large-scale facility under construction in Sweden, building on a history of 15–30% energy efficiency gains achieved through technological upgrades. Carbon capture and utilization (CCU) technologies are also moving from pilot to early commercial implementation, though fully net-negative industrial carbon systems remain experimental (Ohman et al., 2022). In parallel, energy storage solutions are being developed specifically for industrial contexts, featuring optimized energy densities and lifespans tailored to the requirements of energy-intensive production.

Together, these developments illustrate how spatial industrial concentration under the GCA–powershoring framework generates an innovation-driven ecosystem that accelerates the technological foundations of global decarbonization while reinforcing regional competitiveness in the emerging low-carbon industrial paradigm.

4.6 GLOBAL MULTIPLICATION OF CLIMATE BENEFITS

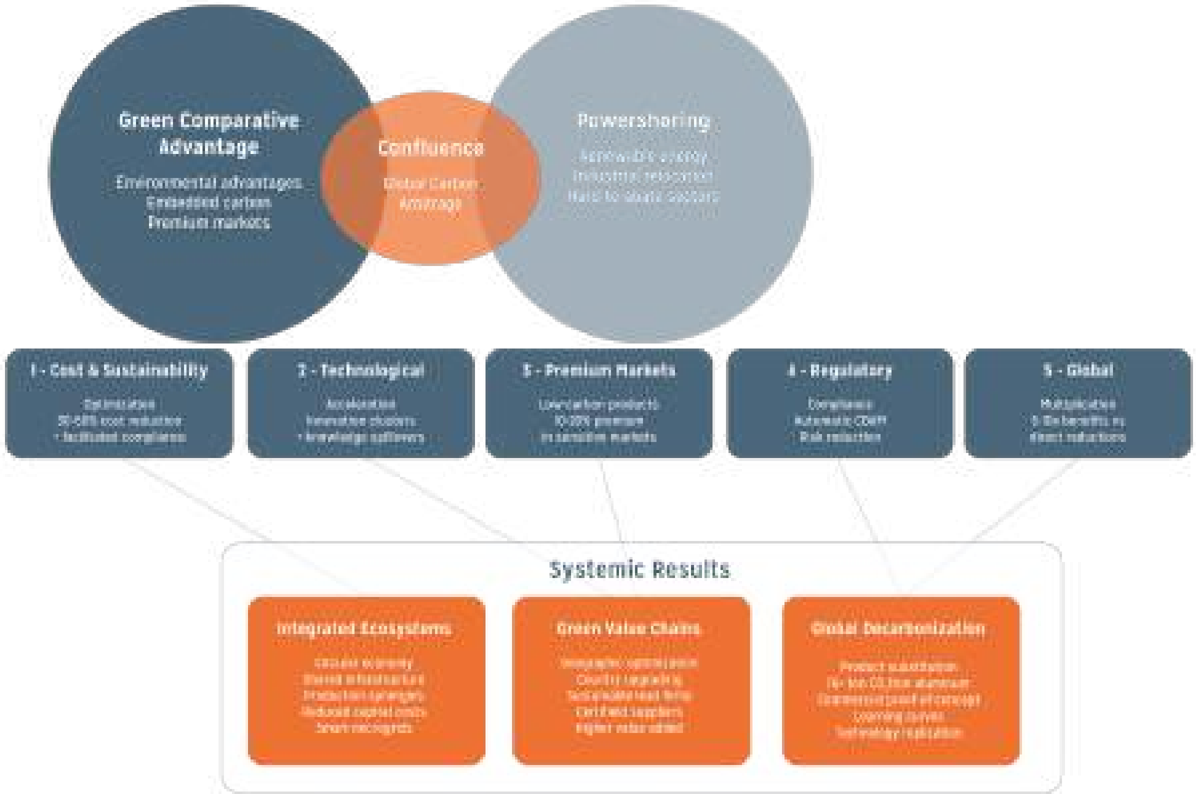
The convergence of GCA and powershoring produces multiplier effects that extend climate benefits well beyond the direct emissions reductions achieved within production regions. These effects unfold through three interconnected channels: the substitution of carbon-intensive products in global markets, the demonstration of the commercial viability of clean technologies, and the acceleration of global learning curves that drive down costs and enable widespread adoption.

The substitution channel is the most immediate and measurable. Each ton of a low-carbon product exported in place of a carbon-intensive alternative generates a net global emissions reduction equivalent to the difference in carbon intensity between the two. This effect can be considerable—for example, replacing coal-based aluminum production in China with geothermal-based production in Iceland results in an emissions saving of more than 16 tCO_2per ton of aluminum produced. Through international trade, such substitutions propagate decarbonization benefits across borders, creating a direct link between trade flows and global emissions outcomes.

The demonstration channel operates by validating the technical and commercial feasibility of clean technologies and industrial processes, thereby reducing perceived risk and uncertainty for other potential adopters. Successful large-scale implementation of H_2V, low-carbon steel, or other advanced decarbonization processes serves as proof of concept, catalyzing replication across different regions and sectors. As these technologies demonstrate profitability and operational reliability, they unlock investment and policy support elsewhere, accelerating the diffusion of clean industrial paradigms.

The learning-curve channel reinforces these dynamics by multiplying cost-reduction effects achieved through concentrated deployment, experience accumulation, and economies of scale. As production scales and technologies mature, unit costs of clean equipment and processes decline, making them more affordable globally. The resulting price reductions in renewable hydrogen technologies, electrolyzers, or carbon capture systems facilitate adoption beyond pioneering regions, spreading the benefits of technological progress worldwide. Together, these channels create a self-reinforcing cycle of innovation, cost reduction, and adoption, transforming localized powershoring initiatives into drivers of systemic global decarbonization.
The schematic figure below summarizes the structure of this convergence and its amplifying feedback loops.

Confluence: Green Comparative Advantage + Powershoring



INTERNATIONAL TRADE AS GLOBAL DECARBONIZATION OPTIMIZER

Alignment between private economic incentives and global climate objectives

5. GREEN TRADE AND ECONOMIC DEVELOPMENT

5.1 THE RETURN OF GEOGRAPHY AS A DETERMINANT OF DEVELOPMENT

Geography is reclaiming a central role in the global economy (Arbache, 2023). After losing prominence from the Industrial Revolution through the height of globalization and the dematerialization of production, territory is once again becoming a decisive determinant of competitiveness and development. Climate change, the pursuit of energy and food security, decarbonization imperatives, geopolitical fragmentation, rising global demand, and technological transitions are repositioning natural resources and natural capital as key strategic vectors in the emerging international economy

This renewed relevance of geography is redefining the classical foundations of comparative advantage. Unlike the late 20th century—when international trade was largely shaped by labor cost differentials, logistics efficiency, and global supply-chain integration—the 21st century is increasingly governed by geographic and environmental constraints. Renewable energy, arable land, critical minerals, water resources, biomass, and biodiversity are no longer peripheral inputs; they are becoming central assets that condition the competitiveness and resilience of nations.

For developing countries endowed with abundant natural capital and competitive renewable energy potential, this shift represents a historic turning point. Natural capital, long viewed as a liability associated with primary-export dependency, is now emerging as a structural advantage. This transformation mirrors the industrial integration of Asia into global manufacturing value chains in previous decades, suggesting that the current reorganization of production may create a comparable wave of opportunity for regions rich in renewable and environmental assets.

The rising value of natural and energy capital—reflected in the growing relative prices of renewable electricity, critical minerals, and environmental services—signals the emergence of new Ricardian rents. Just as Ricardo's classical theory attributed rents to differences in land productivity, the contemporary economy generates location-based rents from differences in carbon intensity, renewable resource availability, and environmental performance. These rents, however, are not automatically converted into development gains.

Their transformation into sustainable prosperity depends on the capacity of countries to capture and channel them toward industrialization, diversification, and technological upgrading. Without such conversion, these advantages risk perpetuating traditional patterns of primary specialization and dependency—the modern expression of the resource curse. The central challenge, therefore, lies in industrializing comparative advantages: turning natural endowments into dynamic assets that foster technical progress, value creation, and long-term structural transformation.

5.2 FROM ENDOWMENT TO TRANSFORMATION: INDUSTRIALIZING COMPARATIVE ADVANTAGES

The thesis of industrializing comparative advantages asserts that natural resource endowments, by themselves, do not generate development; they must be transformed into foundations for the accumulation of physical, human, and technological capital. Within the context of the global energy transition, this transformation can be catalyzed by trade in green goods and services, productive investments linked to renewable energy, and the free flow of technology, talent, and ideas, supported by the establishment of green industrial hubs capable of integrating these dynamics into coherent development strategies.
International trade can once again play a role analogous to Asia's historical export-led growth strategies—now anchored in low-carbon goods and services, constituting a form of "green export-led growth." Rather than competing primarily on labor costs, developing countries can compete on climate efficiency: the capacity to produce with lower emissions intensity, higher renewable energy content, and reduced geopolitical vulnerability. This reorientation toward climate-efficient competitiveness positions trade as a key enabler of both economic upgrading and global decarbonization.

Industrializing green comparative advantages depends on the fulfillment of three interdependent conditions. The first is the development of robust energy and institutional infrastructure capable of converting abundant renewable resources into stable and competitive productive inputs—requiring clear regulation, long-term energy contracting, and sufficient transmission capacity. The second involves strategies for domestic value addition through the processing of natural resources, such as refining critical minerals, producing sustainable fuels, or manufacturing low-carbon industrial goods. The third condition is deep integration into global flows of capital and technology through public–private partnerships, joint ventures, co-development agreements, and favorable trade regimes that ensure access to finance and innovation.

By aligning these pillars, trade becomes an instrument of structural transformation, allowing countries to move beyond the static exploitation of resource advantages toward dynamic industrialization trajectories. The combination of GCA and powershoring thus enables developing economies to translate environmental endowments into sustained competitiveness, technological learning, and long-term development grounded in the global transition to a low-carbon economy.

5.3 GREEN TRADE AS A CATALYST FOR STRUCTURAL TRANSFORMATION

The contemporary debate on trade and development, revisited by Goldberg and Ruta (2025), distinguishes between the static and dynamic effects of trade. Static effects emerge from specialization based on factor endowments, while dynamic effects result from learning, technological diffusion, innovation, and institutional change induced by trade. What is novel in the current context is that green comparative advantages can operate simultaneously across both dimensions, combining the efficiency of specialization with the transformative power of technological upgrading and institutional evolution.

While trade in traditional commodities has historically generated limited static gains and minimal technological spillovers, green trade—anchored in renewable energy and sustainable value chains—offers the potential for much greater dynamic benefits. Producing H_2V, low-carbon steel, or advanced biofuels requires mastering sophisticated technologies, adopting complex operational and management models, and adhering to technical standards and certification systems that foster local innovation and workforce qualification. These processes cultivate domestic technological capabilities and institutional maturity, transforming trade into a conduit for development rather than dependency.

Powershoring amplifies these effects by generating classical industrialization spillovers such as cluster formation, knowledge diffusion, and agglomeration economies. The combination of predictable and competitively priced renewable energy, proximity to natural resources, and regulatory stability establishes ideal conditions for the creation of new industrial complexes. When aligned with coherent industrial and trade policies, these conditions produce compounding effects on competitiveness and innovation. Integration into global green value chains reinforces these dynamics through mechanisms such as learning-by-exporting, co-development, and co-innovation—particularly in sectors governed by mutual certification, traceability, and low-carbon performance standards.

In this framework, green trade transcends its conventional role as a vehicle for resource exportation and becomes a driver of structural transformation. By reorganizing productive structures, upgrading technological capabilities, and deepening institutional sophistication, it enables developing economies to move up GVC. The strategic challenge lies in capturing the spillover effects of investment and technology while using enhanced environmental and geopolitical bargaining power to avoid the historical trap of specialization in low-value segments of international production.

5.4 FROM RESOURCE CURSE TO GREEN OPPORTUNITY: AVOIDING A NEW RESOURCE TRAP

Economic history shows that resource abundance can generate both prosperity and dependency. The so-called "resource curse" historically arose from the interplay of price volatility, Dutch disease, and institutional capture. The emergence of new forms of wealth—renewable energy, critical minerals, and biomass—carries a similar risk of a "green resource curse" if countries export clean resources without capturing value added and knowledge. This risk becomes evident when renewable energy is used primarily for activities such as powering data centers or producing H_2V for export without building local industrial linkages.

Avoiding this trap requires development strategies oriented toward productive resilience. As highlighted by Arbache (2025a), transitioning to resilient value chains reflects a growing willingness among global firms to pay premiums for stability, supply-chain security, energy reliability, and sustainability. This trend creates leverage opportunities for countries rich in natural capital—provided they can transform their endowments into industrial and technological assets through coherent policy frameworks.

The Chinese experience offers instructive, though distinct, lessons. Just as China leveraged its domestic market and low labor costs to secure strategic technologies, developing countries endowed with renewable energy and natural resources can use natural capital as a bargaining instrument—offering clean energy, biomass, biodiversity, or critical minerals in exchange for co-production, technology transfer, and long-term partnerships. The structural advantage lies in the scalability of renewable and biological resources: while domestic markets are finite, renewable energy and biomass potential can expand significantly. The challenge is to design investment and trade regimes that maximize these benefits by attracting foreign capital and promoting complementary, rather than extractive, partnerships.

Achieving this transformation requires aligning industrial, environmental, and trade policies within an integrated strategy. Green industrial policies should prioritize the creation of productive linkages and regional clusters connecting energy generation, resource transformation, and manufacturing. Trade policies need to reduce tariff and non-tariff barriers to green commerce while harmonizing sustainability standards to ensure competitive integration. Finally, innovation and education policies must drive technological upgrading and cultivate human capital suited to the energy transition and bioeconomy sectors. Only through this coherent institutional architecture can static comparative advantages be converted into dynamic competitive advantages capable of generating sustained growth, industrialization, and social inclusion.

5.5 EMERGING EVIDENCE AND IMPLICATIONS FOR PUBLIC POLICY

Recent experiences illustrate how green comparative advantages can generate dynamic and transformative development effects. Chile, for instance, is investing in hydrogen (H_2V) hubs and establishing technological partnerships with the European Union and Japan to enable local production of hydrogen derivatives. Morocco has become a global reference for integrating solar and wind energy into the chemical and fertilizer industries, turning natural endowments into a platform for technological sophistication. Indonesia, through its policy mandating domestic nickel processing, has launched an industrial learning trajectory centered on electric battery production. Brazil combines an almost entirely renewable electricity matrix, a consolidated biofuels sector, significant reserves of critical minerals, and unparalleled biodiversity—elements that together confer both temporal and competitive advantages. Properly coordinated, this combination could position Brazil as a global green production platform, capable of attracting energy-intensive industries and lowering global decarbonization costs.

Realizing this potential depends on three structural conditions. The first is governance and institutional coordination to ensure regulatory predictability and coherence across energy, trade, and development policies. The second is the development of physical and digital infrastructure compatible with green industrial hubs, including efficient logistics corridors, connectivity networks, and smart grid systems. The third condition involves strategic international integration through agreements that combine selective trade openness, co-financing mechanisms, and harmonized environmental certification standards.

These elements are fundamental for green trade to evolve from a source of low-value exports into an engine of transformative development. The core implication is that 21st-century growth will accelerate in proportion to developing countries' ability to align industrial and commercial strategies with the dynamics of the global energy transition. In an era when clean energy costs and carbon intensity increasingly determine investment decisions, climate competitiveness has become synonymous with economic competitiveness.

Industrializing comparative advantages thus defines a new development paradigm—one that merges climate efficiency with productive resilience, integrating trade, energy, and technology into a unified trajectory of progress. Just as export-oriented industrialization reshaped Asia's development during the 20th century, green industrialization anchored in sustainable trade now holds the potential to redefine the development pathways of the 21st century.

5.6 INCLUSIVE DEVELOPMENT AND GREEN PROSPERITY

Industrializing comparative advantages is not merely a production strategy—it can serve as a comprehensive social development project. Green trade has the potential to become a catalyst for poverty reduction, reduced inequality, and gender inclusion, while simultaneously enhancing competitiveness and accelerating global decarbonization. The energy transition is reshaping the international division of labor, as global demand for renewable energy and sustainable goods expands sectors that rely heavily on human capital and innovation. Producing hydrogen, biofuels, electrical equipment, batteries, and environmental services requires engineers, technicians, managers, and skilled operators, supported by networks of small and medium enterprises. These activities generate formal, stable, and higher-quality employment, in contrast to the precarious jobs typically found in extractive industries or informal urban economies. According to IRENA, the renewable energy sector employed 13.7 million people in 2022 and could reach 38 million by 2030, with a significant share of new positions in emerging economies.

Beyond quantity, the quality of green jobs is decisive: they require technical training, stimulate continuous learning, and tend to offer stronger labor protections. Powershoring can promote industrialization or reverse premature deindustrialization—as in Brazil—by creating sustainable industrial hubs that integrate SMEs and peripheral regions into GVC. By combining clean energy, innovation, and trade, developing countries can establish virtuous cycles of productivity and income generation. Each dollar exported in green goods and services tends to create greater domestic value added than traditional commodities, as it involves manufacturing, logistics, certification, and technological components. This amplifies employment multipliers and strengthens public finances. Increased formalization and tax collection provide states with the fiscal resources needed for social policies, infrastructure, and education, initiating a virtuous cycle in which green trade generates both growth and equitable distribution of benefits.

These dynamics are particularly relevant for low-income regions where renewable energy potential and natural resources are concentrated. Wind farms, solar parks, and biorefineries located in inland or semi-arid areas can create local employment, stable income, and community entrepreneurship, contributing to the reduction of territorial inequalities. The green economy also holds strong potential for empowering women and youth. The expansion of jobs in energy, the bioeconomy, and environmental services opens new opportunities in rural and peri-urban areas historically excluded from innovation and formal employment circuits. Targeted training programs and credit policies can transform the energy transition into a vehicle for social mobility.

At the macro level, green trade strengthens the fiscal and institutional foundations of development. The formalization of value chains and enforcement of ESG standards foster transparency, traceability, and better public governance. Firms integrated into global environmental and social frameworks are more likely to register employees, comply with labor standards, and pay taxes. The resulting increase in fiscal revenue expands the state's capacity to implement redistributive policies and accelerate progress toward the Sustainable Development Goals.

Green trade and powershoring thus align agendas that were long considered divergent: economic growth, social justice, and environmental sustainability. For businesses, they create new market opportunities while reducing carbon-related risks and compliance costs. For governments, they expand employment and strengthen fiscal capacity. For vulnerable populations, they open new pathways for inclusion and upward mobility. For the environment, they promote the protection and regeneration of natural capital. This convergence outlines a "new green social contract"—a vision of prosperity in which competitiveness and inclusion reinforce each other. Industrializing comparative advantages offers developing countries a chance to grow while decarbonizing, and to include while growing, integrating climate efficiency, social cohesion, and productive sovereignty into a unified framework for sustainable development.

6. EMPIRICAL EVIDENCE AND GEOECONOMIC TRANSFORMATIONS

6.1 ACCELERATED RECONFIGURATION OF GLOBAL VALUE CHAINS

The convergence of GCA and powershoring is catalyzing a restructuring of GVCs across multiple temporal and geographic dimensions, representing a systemic transformation that redefines the core determinants of international competitiveness. Industrial location timelines are being compressed as renewable energy advantages and clear economic incentives converge. The CBAM further accelerates this trend by establishing immediate, measurable incentives for industries to relocate production toward low-carbon or renewable-based regions.

Emerging evidence indicates that global industrial investment decisions are increasingly being reassessed to avoid CBAM-related costs and capture competitive advantages associated with renewable energy. This shift reflects a paradigm change in industrial location logic—from one primarily driven by labor costs, market proximity, and logistics, to one grounded in carbon intensity, renewable energy access, and environmental compliance. Much like the offshoring movements of the 1980s and 1990s, this new wave of reorganization is redefining geography's role in global production. However, instead of favoring low-cost manufacturing hubs, it now privileges regions endowed with clean, abundant, and competitively priced renewable energy, often located in countries that were previously peripheral to global industrial networks.

Multinational corporations are responding by developing vertical integration strategies that allow control over the full carbon footprint of their production—from renewable energy generation to final output. This approach minimizes regulatory exposure, enhances transparency for investors and consumers, and creates durable competitive advantages rooted in environmental performance. Although the pace of this transition varies across sectors and regions, its structural nature is unmistakable. Over time, as environmental criteria become central to trade and investment decisions, powershoring and GCA are likely to reshape GVC into a new geography of climate competitiveness—one defined less by cost minimization and more by sustainability, resilience, and long-term value creation.

6.2 EMERGENCE OF NEW INDUSTRIAL GEOGRAPHIES

Regions endowed with exceptional renewable resources are emerging as strategic centers for industrial production aimed at global markets, supported by business models grounded in comparative energy advantages. Countries such as Chile, Australia, Morocco, and Brazil are positioning themselves as future leaders in the export of energy-intensive products and (H_2), establishing a new category of international energy trade that transcends traditional commodity exports. In South America, Paraguay, Peru, Colombia, and Uruguay are also advancing strategies to participate in this emerging frontier by leveraging abundant hydropower and highly favorable solar and wind conditions. This geographic diversification of green industrial production is contributing to a more balanced global economic landscape, reducing historical concentration of industrial capacity in a few dominant regions.

Green industrial hubs are already taking shape in countries such as China and Brazil—for example, at Porto do Açu in Rio de Janeiro—demonstrating the scalability and integrative potential of this model. These complexes co-locate renewable energy generation, hydrogen production, energy-intensive industries, and manufacturing of renewable energy components, forming industrial ecosystems capable of operating with minimal carbon footprints. Looking ahead, sustainable trade corridors are expected to link these production centers to major consumer markets through dedicated low-carbon routes. Such corridors will combine optimized logistics infrastructure, digital traceability, and sustainability certification systems, facilitating the trade of green products between regions with energy advantages and environmentally demanding markets.

Several promising trade corridors are already under consideration, including Chile–Europe, Australia–Japan/Korea, Brazil–Europe, and ASEAN–China, each representing a specialized commercial infrastructure designed to connect renewable resource-rich regions with global industrial demand. According to Albertone et al. (2025), ASEAN countries are actively exploring this concept, recognizing its potential to reshape international trade patterns in the coming decades by aligning geography, energy, and sustainability within the architecture of global commerce.

6.3 IMPACTS ON THE INTERNATIONAL FINANCIAL SYSTEM

Global financial markets are rapidly developing systematic methodologies to price embedded carbon in products and services, as illustrated by mechanisms such as the CBAM. This emerging practice is transforming carbon exposure into a central category of financial risk assessment. Recent studies indicate that carbon emissions impose an average market value discount of approximately USD 79 per ton for mid-sized S&P 500 companies, while 76% of investors now explicitly incorporate corporate climate strategies into their investment decisions. By 2024, carbon pricing mechanisms covered about 28% of global emissions and mobilized over USD 100 billion (World Bank, 2025; Wang et al., 2022), establishing a financial dynamic in which banks and private equity funds systematically evaluate carbon risk when managing portfolios, assessing credit, and structuring loans.

This pricing evolution is producing measurable impacts on capital costs and access to financing. Firms with low-carbon profiles benefit from preferential interest rates and more favorable credit conditions, while carbon-intensive companies face higher financing costs or, in some cases, restricted access to capital markets. Although policy uncertainty—particularly in the United States—has introduced short-term fluctuations in climate finance, global capital markets continue to exhibit a clear structural shift toward sustainability. Financial institutions are allocating an increasing share of capital to projects and firms with verifiable green credentials, creating a long-term preference that translates into lower risk-weighted costs of capital for sustainable enterprises and enhanced portfolio resilience for lenders and investors.

Central banks are reinforcing this transformation by integrating climate considerations into monetary and prudential policy frameworks. The European Central Bank and the Bank of Japan, for instance, have begun incorporating sustainability criteria into their asset purchase programs and reserve portfolio compositions, prioritizing sovereign and corporate bonds issued by entities with credible climate commitments. The ECB has implemented climate stress tests that explicitly account for transition risks in its banking stability assessments, while the Bank for International Settlements is developing methodologies to embed climate risk factors into international banking supervision standards. These initiatives collectively signal the consolidation of climate alignment as a structural feature of global financial governance—reshaping capital flows, investment strategies, and the cost of capital in the emerging low-carbon economy.

6.4 STRUCTURAL GEOPOLITICAL TRANSFORMATIONS

The emergence of green comparative advantages is reshaping global geopolitics, redistributing economic influence and redefining international bargaining power. Countries endowed with abundant renewable resources are acquiring growing strategic relevance, while nations historically reliant on fossil fuel exports face mounting structural pressures to diversify their economies. This realignment is altering traditional patterns of dependence and competition, opening space for new forms of cooperation built around clean energy complementarities. As renewable endowments replace fossil reserves as the basis of strategic value, the incentives for geopolitical rivalry over scarce hydrocarbons diminish, fostering conditions for partnership and mutual benefit in the deployment of sustainable energy systems.

A new form of international diplomacy is gradually emerging, centered on cross-border cooperation in renewable energy generation, green technology transfer, and the coordination of climate and industrial policies. Harmonization of technical standards, certification systems, and carbon accounting frameworks is becoming an essential dimension of this evolving architecture. The notion of energy security itself is undergoing a fundamental transformation—from the control of fossil resources and supply routes to the assurance of domestic renewable capacity, technological self-reliance, and diversified low-carbon partnerships. In this new geopolitical landscape, competitiveness and security increasingly depend on the ability of nations to integrate into global networks of clean energy production and innovation, where collaboration replaces extraction as the cornerstone of international influence.

6.5 CBAM AND CARBON ADJUSTMENT MECHANISMS: CATALYSTS OF TRANSFORMATION

The European Union's CBAM exemplifies the systematic integration of embedded carbon criteria into trade policy, establishing a regulatory precedent that is already being analyzed and emulated across multiple jurisdictions. Piloted in 2023 and scheduled for full implementation in 2026, CBAM is reshaping global investment patterns and influencing industrial location decisions by internalizing the carbon content of internationally traded goods. Initially covering cement, iron and steel, aluminum, fertilizers, and electricity—sectors that account for roughly 50% of emissions from EU trade-exposed industries—the mechanism represents a structural shift in how environmental externalities are priced in global commerce.

Under CBAM, European importers must purchase certificates reflecting the embedded carbon in imported goods, calculated as the difference between the EU carbon price and that of the exporting country. This framework creates explicit financial incentives for production in regions with renewable energy resources and for the adoption of domestic carbon pricing mechanisms. Once fully operational, CBAM is expected to alter international trade flows significantly, particularly affecting exporters with high-emission production profiles in covered sectors. China, Russia, India, and Turkey are among the most exposed economies, yet they also stand to benefit if they succeed in developing competitive low-carbon industrial bases. In response, several countries are implementing adaptive measures that include accelerated carbon pricing systems, large-scale investments in industrial decarbonization, low-carbon certification initiatives, and expanded international technology cooperation.

China's policy response has been particularly vigorous. In 2024, it invested more than USD 625 billion in renewable energy—its largest annual allocation to date—as part of a strategy to sustain global competitiveness. For the first time, renewable technologies accounted for over 10% of China's total economic output. In parallel, the country is building a comprehensive carbon certification and accounting framework, having published 70 national standards by 2024 to standardize methodologies for measurement and verification, thereby facilitating trade with economies that have adopted border carbon adjustments (IEA, 2025b; ESG News, 2024). India has also advanced a broad green industrial strategy through its Production-Linked Incentive (PLI) schemes, emphasizing high-efficiency solar photovoltaic modules, electric vehicles, and green hydrogen production under the National Green Hydrogen Mission. Brazil, in turn, has approved a regulatory framework for green hydrogen and complementary legislation to establish low-carbon product certification systems, aimed specifically at maintaining export competitiveness in environmentally demanding markets.

Together, these initiatives underscore how CBAM is not merely a European regulatory instrument but a catalyst for global industrial adaptation. It is accelerating convergence between trade, energy, and climate policy, compelling countries to integrate carbon performance into their development and export strategies—thus marking a decisive step toward the emergence of a low-carbon global trade regime.

Although powershoring aligns with carbon pricing and regulatory instruments, its rationale is fundamentally economic and market-based rather than compensatory. In a context where carbon pricing mechanisms face political resistance—illustrated by the recent collapse of the International Maritime Organization's carbon tax proposal for maritime transport under pressure from the United States (GTR, 2025)—powershoring gains even greater relevance for decarbonization.

While it can be reinforced by environmental compliance policies and carbon pricing, powershoring does not directly depend on them. The International Maritime Organization episode illustrates how climate arguments based on carbon pricing and international compliance remain vulnerable to political cycles and geoeconomic disputes. Regulatory mechanisms, reliant on multilateral consensus and institutional stability, often encounter resistance amid strategic competition. By contrast, industrial attractiveness driven by clean and affordable energy is independent of political alignment, making powershoring a more resilient driver of production relocation and long-term comparative advantage.

6.6 GREEN COMPETITION AND EMERGING TRADE DYNAMICS

Countries are increasingly competing through subsidies, tax incentives, and public investments to attract green industries, generating a highly dynamic but potentially distortionary global environment. This race to lead the low-carbon economy is accelerating technological development and industrial transformation, yet it also introduces new challenges for international trade governance and market fairness. The United States, through the 2022 Inflation Reduction Act (IRA), has committed up to USD 500 billion in incentives for clean technologies during its most active implementation phase. China continues to pursue expansive industrial support policies, consolidating its dominance in manufacturing solar panels, electric vehicles, wind turbines, batteries, and other strategic green sectors. The European Union has responded with its Green Deal Industrial Plan, mobilizing around €270 billion, while Japan and South Korea have launched national programs centered on green hydrogen (H_2V) and advanced energy storage technologies.

This global competition is reshaping the geography of production and trade by accelerating industrial upgrading, fostering green technology clusters, and stimulating localized innovation ecosystems. It also underscores the growing importance of designing strategic industrial policies that balance competitiveness with international cooperation. Without careful coordination, overlapping subsidies and preferential frameworks risk provoking trade disputes, fragmenting GVC, and creating long-term market distortions that undermine efficiency and equity.

In this evolving context, the countries that successfully combine ambitious industrial policy with strategic trade engagement and technological leadership are likely to secure first-mover advantages in the emerging green economy. Those advantages will not only determine global production patterns but also shape future standards, certification systems, and governance frameworks for sustainable industries—redefining the intersection of trade, innovation, and climate policy in the decades ahead.

6.7 EU'S NEW STRATEGY TO SHAPE A CLEAN AND RESILIENT GLOBAL TRANSITION

A recent European Commission press release (15 October 2025) signals a potentially significant shift in the European Union's decarbonization strategy, proposing a more outward-oriented framework centered on international cooperation, trade, and climate diplomacy. In contrast to the previous approach—largely focused on internal regulation and the protection of domestic competitiveness—the new direction emphasizes that effective global decarbonization depends on interdependence, openness, and market integration rather than isolation. The Commission outlines the foundations of a "Clean Industrial Deal" with global scope, aimed at expanding cooperation with strategic partners and leveraging trade agreements, energy partnerships, and green alliances as key vehicles for technological diffusion and regulatory convergence.

The proposed strategy envisions Europe not only as a regulatory hub but also as an industrial powerhouse for clean technologies and climate adaptation solutions, capable of generating shared opportunities and reinforcing resilient GVC. Trade and investment are explicitly framed as instruments of collective decarbonization, marking a conceptual departure from defensive, border-oriented policies. The proposal advances cooperative carbon pricing mechanisms, greater openness to joint technological development, and coordinated use of international financial instruments to support the energy transition beyond European borders.

If implemented, this vision would represent a structural transformation in the EU's role in global climate governance—from a regional regulator primarily focused on internal market protection to a systemic architect of a cooperative and geoeconomically inclusive green transition. The approach suggests that Europe's long-term climate leadership may increasingly depend on its ability to integrate economic diplomacy, industrial policy, and global trade into a unified framework. A full evaluation of its impact will require further clarity on implementation pathways and institutional mechanisms, but the initiative already points toward a decisive reorientation of the EU's climate and industrial strategy within the global decarbonization landscape.

6.8 PROLIFERATION OF STANDARDS AND TAXONOMIES: CHALLENGE AND OPPORTUNITY

The proliferation of environmental taxonomies and sustainability standards across jurisdictions is adding growing complexity to global business operations while simultaneously creating opportunities for regulatory harmonization that could facilitate international green trade. Over the past five years, roughly 20 countries and regions have developed or initiated the development of green, social, or transition taxonomies—although most remain nonbinding. This regulatory fragmentation imposes significant compliance costs on multinational firms that must adapt to differing classification criteria, disclosure requirements, and verification methodologies across multiple markets.

In response, international initiatives have emerged to promote convergence and interoperability. The International Platform on Sustainable Finance (IPSF), for instance, is developing the Common Ground Taxonomy (CGT), a comparative framework that aligns and maps China's and the EU's taxonomies, covering approximately 80 economic activities across six sectors. The CGT illustrates the potential for technical convergence to reduce transaction costs, enhance transparency, and support the expansion of international green trade by providing a shared reference for sustainable finance and investment classification. However, the rapid multiplication of environmental standards also raises a critical policy concern: the risk of green protectionism. Strict technical or certification requirements can be used, intentionally or not, to shield domestic producers from international competition under the guise of environmental integrity. This risk underscores the need for transparent monitoring mechanisms and international arbitration frameworks capable of distinguishing legitimate environmental objectives from disguised trade barriers. Ensuring that sustainability standards remain instruments of genuine climate progress—rather than tools of exclusion—will be essential to preserving both the credibility of green finance and the integrity of open global trade.

7. TRADE BARRIERS TO GLOBAL DECARBONIZATION

Trade barriers and regulatory fragmentation have become major obstacles to global decarbonization, driving up costs for critical inputs, reducing economies of scale, and slowing the diffusion of clean technologies. Since 2020, nearly 200 new trade measures affecting low-carbon technologies have been introduced worldwide—most of them restrictive—raising transaction costs and creating uncertainty across green value chains (IEA, 2024a).

Empirical evidence confirms the magnitude of these effects. According to UNCTAD, in solar and wind energy value chains, trade defense measures have increased costs by up to 55%, with some tariffs reaching as high as 300%, substantially undermining the competitiveness of clean technologies (UNCTAD, 2024). Simulations conducted by the WTO indicate that the elimination of tariffs and non-tariff barriers on environmental goods could raise global exports by 5–14% by 2030, boost world GDP by approximately 0.8%, and reduce global emissions by around 0.6% compared with the baseline scenario (WTO, 2022).

Although these estimates remain preliminary due to methodological and data limitations, they reveal a consistent trend: trade barriers exert significant influence on international competitiveness in green sectors. The challenge is particularly acute given the narrow temporal window for global decarbonization identified by the IPCC. In this context, the broad and systematic reduction of trade barriers—combined with greater regulatory convergence—emerges as a powerful dual instrument for enhancing economic efficiency and accelerating the climate transition. By lowering costs, expanding market access, and facilitating the scaling of clean technologies, trade liberalization aligned with environmental objectives can play a decisive role in achieving a faster and more cost-effective global decarbonization pathway.

Source / Study	Scope / Method	Key Findings	Limitations
WTO – World Trade Report 2022	Global modeling of environmental goods liberalization (tariffs & non-tariff barriers)	Barrier elimination $_2$5–14% export growth by 2030; ~0.8% increase in global GDP; ~0.6% reduction in global emissions	Does not capture indirect effects (innovation, accelerated tech diffusion); modest environmental impact
Shapiro (2021), cited by WTO	Academic study on "environmental bias" in trade policies, quantitative modeling	Removing distortions $_2$+0.65% global real income; -3.6% global emissions	Model assumptions; does not cover all non-tariff barriers; global average effect
UNCTAD (2024) – Solar & Wind Chains	Empirical analysis of trade defense measures in Asian value chains	Barriers increased costs up to 55%; some tariffs reached 300%; clear negative impact on renewable competitiveness	Regional focus (Asia); does not estimate global aggregated effects
IEA (2024a, World Energy Outlook)	Monitoring of trade measures on clean tech since 2020	Nearly 200 new measures, mostly restrictive; increases costs and uncertainty; confirms regulatory fragmentation trend	Descriptive data; does not quantify macroeconomic or climate impact

7.1 BARRIERS AND TRANSITION COSTS

Tariffs on critical components for the energy transition impose direct barriers to decarbonization, artificially inflating the costs of technologies that are already competitive under open-market conditions. In the United States, tariffs range from 10% to 49% on components such as batteries and electrical systems, and reach up to 82% on lithium-ion cells, significantly increasing project costs and jeopardizing renewable deployment (FT, 2025). Yet, according to IRENA, 91% of new renewable

energy projects in 2024 were already cheaper than fossil alternatives, with solar photovoltaic energy 41% less costly and onshore wind 53% cheaper (IRENA, 2025). This creates a paradox: clean energy technologies have achieved cost leadership, but protectionist barriers erode this advantage precisely when a rapid and efficient transition is most urgent.
China currently dominates global manufacturing for renewable technologies, including polysilicon for solar panels and a wide array of other critical components. This concentration heightens the disruptive potential of trade restrictions, generating asymmetric dependencies and supply chain vulnerabilities that threaten to slow the global energy transition. Solar panels face highly variable tariff regimes across jurisdictions. In 2024, the United States raised tariffs on Chinese solar panels from 25% to 50%, with rates on finished modules set to rise to 175% in 2025 (USTR, 2024). Excluding China from global supply chains could increase international module prices by 20–30% compared to a scenario of open, competitive trade (IEA, 2023; IRENA, 2023a).

Similar dynamics affect other key sectors. Tariffs on wind turbines and energy storage systems raise implementation costs and hinder the scaling of renewable projects. In 2024, the U.S. imposed a 50% tariff on semi-finished copper products—an essential input for modernizing power grids and renewable energy infrastructure (USTR, 2024). Likewise, trade barriers on energy-efficiency equipment such as heat pumps, advanced HVAC systems, and high-efficiency electric motors increase costs and slow adoption. These measures run counter to stated decarbonization commitments, particularly in building and industrial sectors where such technologies are already economically viable in the absence of tariff distortions (IEA, 2023).
Overall, the persistence of these trade barriers reveals a critical misalignment between industrial policy and climate goals. Rather than promoting diversification and resilience, protectionist measures risk delaying global emission reductions, increasing transition costs, and undermining the very competitiveness they aim to protect.

7.2 IMPACTS OF TRADE BARRIERS

Sector-specific analyses indicate that tariffs on imported solar cells and modules have had significant economic effects in the U.S., with estimates suggesting tens of thousands of jobs not created or lost, and roughly USD 19 billion in private investment canceled or delayed due to measures implemented between 2018 and 2020 (SEIA, 2019; Reuters, 2019).

International agencies report that renewable energy performs better economically under competitive conditions. IRENA estimated that renewable capacity added in 2021 could have reduced global generation costs by approximately USD 55 billion in 2022, while in Europe, wind and solar generation helped avoid fossil fuel imports worth tens of billions of dollars from January to May 2022. These estimates illustrate that trade barriers and supply chain disruptions can erode cost savings and influence investment decisions, though the magnitude varies depending on source, period, and modeling assumptions.

Harmonizing tariff policies to facilitate flows of green technologies, goods, and services presents an immediate opportunity to accelerate decarbonization through intensified competition, expanded economies of scale, and lower costs for end consumers. This creates a virtuous cycle in which barrier reduction accelerates adoption, which in turn reduces costs via learning curves and scale effects. Non-tariff barriers are even more complex and costly, manifesting as regulatory fragmentation through diverging taxonomies, technical standards, and certification systems that generate multiple compliance costs and systemic regulatory uncertainty.

Uncoordinated proliferation of national green taxonomies imposes significant administrative and compliance costs on multinational companies, delaying investments in decarbonization technologies and creating entry barriers for smaller firms. The EU taxonomy provides a classification system defining technical criteria for economic activities aligned with a net-zero trajectory by 2050, establishing six environmental objectives and granular technical criteria that require specialized legal and technical knowledge (EC, 2020; Technical Expert Group on Sustainable Finance, 2020).

China has updated its green taxonomy to cover green bonds and loans, aiming to reduce confusion and investor/regulator costs. Initially focused on green bonds via the 2015 Green Bond Catalogue, the taxonomy now includes the Green Industries Guide and specific guidance for green lending (People's Bank of China, 2015; OECD, 2021). In the U.S., no unified federal taxonomy exists, and companies must navigate multiple sectoral and state standards with significant variations in criteria, procedures, and enforcement, adding complexity for firms operating across states (Harvard Law School Forum on Corporate Governance, 2020).

The lack of mutual recognition agreements forces multinationals to obtain multiple certifications for the same products or processes. Green technology producers often need EU certification, compliance with Chinese regulations, U.S. state requirements, and additional certifications for emerging markets—each with distinct technical criteria, bureaucratic procedures, and costs. Divergent definitions of "green," "sustainable," "low-carbon," or "renewable" create substantial confusion and barriers to entry; projects considered sustainable in one jurisdiction may be explicitly excluded from green financing in another, forcing multiple compliance strategies or geographic limitations. The EU's Guarantees of Origin (GO) system issues certificates for each megawatt-hour of renewable electricity, but these certificates are not automatically recognized outside the EU, posing further challenges for international operators (EC, 2009; AIB, 2023; Ofgem, 2023).

Regulatory complexity frequently leads to lengthy approval processes, particularly for emerging technologies such as large-scale battery storage, industrial H2V production, or hybrid solar-wind systems. Approvals may require coordination across multiple regulatory bodies, extensive environmental impact studies that may not fully consider climate benefits, and prolonged public consultations. These processes can extend the time needed to deploy new capacity, suggesting that reforms in electricity market design and political frameworks are essential to support sufficient investment in renewable generation and system flexibility solutions (IEA, 2022b; IRENA, 2023b).

7.3 RESTRICTIONS ON FOREIGN INVESTMENT

Foreign investment restrictions with sector-specific limitations are increasingly constraining the flow of international capital into energy transition projects. Many countries impose limits on foreign participation in energy sectors or require joint venture arrangements that, while intended to protect national interests, can inadvertently reduce efficiency, limit technology transfer, and discourage participation by firms with advanced technical capabilities. These measures often create financial and operational uncertainty, raising project costs and slowing the pace of global decarbonization.

China continues to enforce significant restrictions on foreign ownership across renewable energy and other strategic sectors linked to the energy transition, although some constraints have been eased for priority technologies such as advanced batteries, electric vehicles, and solar manufacturing. These partial liberalizations reflect an effort to attract foreign capital selectively while maintaining national control over critical supply chains. In the United States, foreign investment in energy infrastructure is systematically reviewed by the Committee on Foreign Investment in the United States (CFIUS), whose broad mandate to assess national security risks introduces regulatory uncertainty and often lengthens approval timelines—factors that can deter foreign investors from participating in large-scale energy projects. The European Union has similarly adopted a comprehensive framework for screening foreign direct investment, designed to safeguard strategic sectors and technological autonomy. While this approach strengthens oversight, it may also restrict the entry of much-needed international capital into renewable and clean technology ventures.

Taken together, these restrictions illustrate a growing tension between national security and global climate objectives. By limiting cross-border investment and technology partnerships in the very sectors driving the energy transition, such measures risk undermining the scale and speed of decarbonization. Achieving the necessary pace of global energy transformation will likely require balancing strategic autonomy with regulatory openness—ensuring that investment frameworks protect legitimate security interests without impeding the flow of capital and innovation essential to achieving climate goals.

7.4 ADDITIONALITY AS HIDDEN GREEN PROTECTIONISM

The European energy additionality criterion exemplifies how well-intentioned environmental standards can operate as hidden protectionism, systematically disadvantaging countries that already possess largely decarbonized electricity systems. Under EU rules for (H_2V), renewable energy used in production must come from facilities installed within 36 months of the hydrogen plant's commissioning, explicitly excluding older renewable sources such as legacy hydropower—even if fully emissions-free. This regulation penalizes nations like Brazil, Norway, and Iceland, which invested heavily in renewable infrastructure decades ago, while favoring European countries still expanding their renewable capacity. A Brazilian project using hydroelectric power from a 1980s plant—entirely emissions-free—would fail to qualify as "green," whereas a German project using newly installed, subsidized solar energy would meet the criteria automatically.

The technical rationale for this rule is that using existing renewable energy could "displace" clean electricity that would otherwise replace fossil generation elsewhere on the grid. Yet this logic collapses in countries where electricity is already predominantly renewable. In Brazil, for example, with about 90% renewable generation, industrial use of existing hydropower does not increase marginal emissions, since additional demand is met mainly by new renewable projects due to cost competitiveness and supportive regulation. The result is a conceptual distortion that turns legitimate comparative advantage into regulatory disadvantage.

By requiring “additional” renewable capacity even where grids are already clean, the EU framework effectively penalizes long-term planning and early decarbonization. It creates perverse incentives by rewarding latecomers that are still building renewable infrastructure while penalizing countries that have already achieved low-carbon energy systems. This approach undermines both economic efficiency and climate equity, revealing the tension between regional industrial policy and the broader objective of global decarbonization.

7.5 AGGREGATE IMPACT OF TRADE BARRIERS

Collectively, non-tariff barriers increase the overall costs of renewable energy and other low-carbon projects compared to hypothetical free-trade scenarios with harmonized regulatory frameworks. Despite the remarkable progress of the past decade—during which most newly commissioned renewable capacity has achieved generation costs below those of the cheapest fossil alternatives—significant structural obstacles persist. Limited access to affordable financing, complex and bureaucratic licensing procedures, supply chain bottlenecks, and rising geopolitical tensions continue to constrain the pace and scale of global deployment. These barriers interact cumulatively, raising project risk premiums and delaying investment cycles, particularly in developing countries where capital costs and institutional hurdles are highest. Removing or aligning non-tariff measures across jurisdictions, while improving regulatory predictability, would substantially reduce transaction costs and accelerate the expansion of renewable energy, reinforcing both economic efficiency and the global decarbonization trajectory.

7.6 REGULATORY FRAGMENTATION BY MAJOR JURISDICTIONS

Global regulatory fragmentation has produced a multilateral environment in which major economic powers impose unilateral standards, generating overlapping compliance requirements, higher transaction costs, and exclusionary effects that can marginalize smaller producers from green technology markets. This fragmented system also heightens the risk of trade disputes disguised as environmental policy, as competing regulatory frameworks increasingly define the conditions of market access.

The European Union represents one of the most developed and complex regulatory systems, setting high technical thresholds for global trade in green goods, services, and technologies. The EU Green Taxonomy establishes detailed and evolving technical criteria for environmentally sustainable activities, covering multiple environmental objectives with costly transition periods and gradual implementation. Corporate sustainability regulations, such as the Corporate Sustainability Due Diligence

Directive (CS3D, effective 2024), extend compliance obligations to firms with more than 1,000 employees and annual revenues exceeding €450 million—including foreign companies with equivalent EU turnover—requiring them to identify, prevent, and mitigate human rights and environmental risks throughout their value chains (EC, 2024). In parallel, eco-design standards impose stringent product-level requirements for efficiency and sustainability, compelling manufacturers to adapt production processes or develop new product lines tailored to the EU market (EC, 2023a).

In the United States, domestic content requirements embedded in the Buy American Act and Build America programs prioritize U.S.-made materials in public procurement and infrastructure projects, including steel, iron, and manufactured products (U.S. Department of Energy, 2023). Combined with the Inflation Reduction Act's tax incentives, these measures tie renewable energy credits to domestic content, influencing global investment allocation in renewable and energy-efficiency projects while introducing potential distortions in international competition.

China, in turn, is advancing its own strategic regulatory agenda through the "China Standards 2035" initiative, designed to shape global norms in emerging technologies such as artificial intelligence, 5G, and big data (China Briefing, 2023). Simultaneously, Beijing has tightened control over rare earth mining and processing, enforcing government licensing and production quotas (ABC News, 2023). China currently dominates refining for five of six critical minerals essential to the energy transition, supplying roughly 70% of rare earths used by the United States (China Briefing, 2023). Substantial state subsidies have led to overcapacity and record exports of solar panels, electric vehicles, semiconductors, and batteries (IfW Kiel, 2022). Its 2024 Negative List continues to prohibit foreign participation in strategic sectors such as rare earth mining and processing (China Briefing, 2023; WSJ, 2023).

Developing countries face structural constraints that often exclude them from the expanding global green technology marketplace. Weak certification infrastructure, limited technical expertise, a shortage of regulatory professionals, and scarce financial resources hinder their ability to comply with rapidly evolving international norms (Dechezleprêtre et al., 2023; UNCTAD, 2022). In the absence of mutual recognition agreements, certification requirements act as de facto technical barriers, forcing exporters to undergo multiple costly tests and approvals (UNCTAD, 2021). Recent EU measures, such as the Deforestation-Free Products Directive (EUDR), frequently disregard national circumstances, local legal frameworks, and existing certification systems, exacerbating compliance challenges for smaller economies (EC, 2023b).

This global regulatory landscape underscores the urgent need for differentiated compliance regimes for developing countries that account for their limited resources, access to finance, technological capabilities, and training capacities. Regulatory fragmentation—whether deliberate or systemic—creates a trade environment in which dominant economies impose unilateral standards that multiply compliance costs, marginalize less developed producers, and increase the risk of environmental protection being used as a pretext for protectionism (Van Asselt, 2022).

8. BRAZIL: A PARADIGMATIC CASE OF GREEN-ENERGY CONVERGENCE

Brazil exemplifies how natural competitive advantages, when combined with coherent public policies and strategic infrastructure investments, can position a country as a central player in the global green economy. While major industrial powers grapple with the commercial, regulatory, and geopolitical challenges discussed in previous sections, Brazil stands out for its ability to overcome structural constraints to decarbonization through a distinctive trajectory of sustainable development. Its energy matrix—one of the cleanest among large economies—is predominantly renewable, supported by decades of investment in hydropower, bioenergy, and, more recently, solar and wind capacity. Complementary policies in logistics, agriculture, and innovation have further reinforced the country's environmental competitiveness, integrating productivity gains with sustainability objectives. As a result, Brazil illustrates how early and consistent investment in natural capital, when aligned with long-term development planning, can generate durable economic and environmental advantages in the transition to a low-carbon global economy.

8.1 THE UNIQUENESS OF BRAZIL'S ELECTRICITY MATRIX

Brazil stands out globally for possessing one of the most renewable electricity matrices among major economies. In 2024, approximately 90% of the country's electricity generation originated from renewable sources—a result of decades of sustained investment and policy continuity. Hydropower remains the backbone of the system, accounting for about 56% of generation, while wind and solar energy have expanded rapidly, contributing roughly 14% and 9%, respectively. Together, these sources supply nearly one-quarter of Brazil's electricity, creating a diversified renewable mix unmatched in scale and maturity by most industrialized nations.

This predominance of renewables confers Brazil a structural competitive advantage. While renewable shares reach about 35% in China, 24% in the United States, and 47% in the European Union, Brazil's renewable system is already consolidated, supported by infrastructure built and amortized over decades. The hydropower fleet, largely developed between the 1960s and 2000s, has recovered its initial investment costs, resulting in low marginal operating expenses. In contrast to fossil-based plants exposed to volatile fuel prices and rising carbon costs, hydroelectric generation offers predictable and stable operation, minimizing exposure to carbon pricing mechanisms that increasingly shape global industrial competitiveness. This stability provides an essential foundation for long-term industrial planning—a critical advantage in an era of energy market volatility and regulatory uncertainty linked to climate and geopolitical shifts.

Brazil's untapped renewable potential is equally remarkable. The country's onshore wind capacity could reach 880 GW, of which 522 GW are considered technically viable, while offshore wind potential is estimated at 700 GW. With only 33.7 GW currently installed, Brazil exploits just about 3% of its combined wind potential. Solar energy prospects are even greater: average daily solar irradiation in the Northeast ranges from 5.5 to 6.5 kWh/m²/day—significantly higher than European photovoltaic leaders such as Germany (around 3.0 kWh/m²/day) and Spain (4.7 kWh/m²/day). The country's technical solar potential exceeds 28,500 GW, roughly 134 times its total installed generation capacity of 212.5 GW.

Another distinctive strength is the natural complementarity among Brazil's renewable resources. Periods of low rainfall coincide systematically with strong Northeast winds and high solar irradiation, allowing seasonal balancing between hydropower, wind, and solar generation. This inherent synergy reduces the need for large-scale energy storage and contributes to a more stable and efficient energy system, though prolonged droughts remain a structural vulnerability. Supporting this system is Brazil's extensive and integrated national transmission network—one of the largest in the world—which enhances system efficiency, stability, and geographic flexibility in energy distribution.

This combination of abundant, diverse, and geographically complementary renewable resources gives Brazil a unique strategic position in the global energy transition. Countries with less diversified renewable endowments face higher intermittency risks and must rely on costly investments in energy storage or fossil backup capacity to ensure supply stability. Brazil, by contrast, benefits from a naturally balanced and cost-effective renewable ecosystem, providing a durable foundation for industrial competitiveness in a decarbonizing world economy.

8.2 TEMPORAL ADVANTAGE: DECADES AHEAD OF GLOBAL COMPETITION

Brazil's competitive advantage becomes even more evident when compared with the scale of investments and time horizons required for major economies to reach similar levels of renewable penetration. Using 2024 data on installed capacity, generation composition, average technology costs, and historical implementation rates, Brazil's electricity matrix—already at roughly 90% renewables—serves as a benchmark of what others would need to replicate.

China, while leading the world in total installed renewable capacity at about 56% of its generation capacity, still produces only 35% of its electricity from renewable sources. Fossil fuels continue to supply around 62% of its generation due to grid management priorities, transmission constraints, and system inertia favoring baseload thermal generation. With an overall installed capacity of approximately 3,350 GW, including 1,878 GW of renewables, China would need to replace around 1,100 GW of fossil capacity and add an additional 1,600 GW of renewables to match Brazil's 90% renewable standard. Assuming average investment costs of US$1,000/kW for solar and US$1,300/kW for wind, the required investment would total roughly US$3.2 trillion. At an average annual addition rate of 200 GW, this transition would take between 20 and 25 years—equivalent to approximately 0.9% of China's 2024 GDP per year.

The United States faces an even steeper challenge. With only 24% renewable generation in 2022 and about 388 GW of renewable capacity out of a total 1,300 GW, the country would need to retire around 700 GW of fossil generation and install an additional 1,200 GW of renewables to achieve a 90% renewable share—an expansion of 1,900 GW. This transformation would require an estimated US$2.3 trillion over 25 to 30 years, or about 0.4% of annual GDP, not accounting for transmission upgrades and other enabling infrastructure.

The European Union, though leading among advanced economies with 47% renewable generation in 2024, still faces significant hurdles. With approximately 600 GW of renewable capacity already in place, it would need to add roughly 800 GW more to approach Brazil's level. Due to population density, complex regulatory environments, and the need to coordinate among 27 national grids, investment costs are estimated to be 20–30% higher than global averages, totaling about US$1.2 trillion over 18 to 22 years—around 0.3% of annual EU GDP.

These figures represent conservative baselines and exclude major complementary expenditures. The International Energy Agency projects that global grid modernization alone will require US$14 trillion through 2050, while energy storage systems will demand an additional US$120 billion annually. Decommissioning fossil plants, expanding transmission networks, developing renewable backup systems, and funding social transition programs would substantially increase total costs. Taken together, these estimates highlight how Brazil's existing renewable infrastructure—accumulated over decades of investment—constitutes not only an environmental achievement but also a deep source of structural economic advantage in an increasingly carbon-constrained global economy.

The table below summarizes the estimates.

Renewable Generation Gap and Investment Needs

Country / Region	Current Renewable Generation	Gap to 90%	Required Investment	Estimated Timeline	% of Annual GDP	Additional Capacity
Brazil	90%	–	–	–	–	Already Achieved
China	35%	55%	US$ 3.2 trillion	20–25 years	0.9%	2,700 GW
United States	24%	66%	US$ 2.3 trillion	25–30 years	0.4%	1,900 GW
European Union	47%	43%	US$ 1.2 trillion	18–22 years	0.3%	800 GW

This analysis underscores Brazil's structural competitive advantages, which extend far beyond technical aspects of its energy matrix. The country's temporal advantage—estimated at 18 to 30 years—creates a unique window to consolidate lasting industrial leadership in energy-intensive sectors and establish a strong position in the global green economy.

Brazil's structural cost advantage stems from the maturity and amortization of its renewable infrastructure, which allows for low, stable, and predictable electricity prices. Other major economies must incur substantial marginal costs to achieve comparable levels of decarbonization, giving Brazil a durable competitiveness edge in electricity-intensive industries such as aluminum, steel, chemicals, and (H_2V) production. This cost stability also reduces exposure to carbon pricing and fossil fuel volatility, providing a secure foundation for industrial expansion.

In addition, Brazil enjoys a significant temporal advantage for market capture. Its ability to supply low-carbon products ahead of competitors positions the country to access premium markets increasingly regulated by carbon intensity standards. Early entry enables Brazil to establish long-term commercial partnerships, shape emerging certification frameworks, and secure market shares that will be difficult for latecomers to displace.

A further advantage lies in the opportunity cost faced by other major economies. To reach Brazil's renewable share, China, the United States, and the European Union must allocate considerable portions of their GDP to energy transition investments, diverting capital from other strategic priorities. Brazil, having already completed much of this investment cycle, can channel public and private resources toward green industrialization, innovation, and export capacity building.

Finally, Brazil benefits from insulation against "green inflation." Economies still transitioning from fossil to renewable systems may experience price pressures due to infrastructure replacement and supply constraints, while Brazil's mature renewable base provides cost stability that supports industrial competitiveness and macroeconomic resilience.

This temporal advantage is inherently strategic and non-replicable. Once other economies complete their transitions, Brazil's relative advantage will narrow. The country therefore has roughly two decades to capitalize on this lead through powershoring strategies, the development of green industrial hubs, and specialization in renewable energy-intensive products. This configuration offers a historic opportunity to convert natural endowments into sustainable industrial leadership and to position Brazil as a key global supplier of green goods during the decisive phase of the world's energy transition, with substantial potential economic and social benefits.

8.3 THE NORTHEAST AS THE EPICENTER OF POWERSHORING

The Brazilian Northeast has emerged as an ideal hub for powershoring strategies due to the convergence of world-class renewable resources, robust connectivity to the national transmission grid, and access to strategic infrastructure. The region's exceptional natural conditions make it one of the most competitive areas in the world for renewable-based industrial development. Wind capacity factors regularly exceed 50%, outperforming many established wind regions globally, while solar irradiation levels are comparable to those found in leading renewable zones such as Chile's Atacama Desert and Australia's Northern Territory.

Wind and solar power in the Northeast have become increasingly competitive in government electricity auctions, with prices declining steadily over recent years. This trend reflects technological advances, economies of scale, and the region's superior renewable conditions, positioning these sources among the lowest-cost options for electricity generation. The high concentration of wind farms—complemented by a growing portfolio of solar projects—has created a solid and expanding pipeline of renewable energy investments.

The region also benefits from significant port infrastructure that underpins its industrial potential. Suape (Pernambuco), Pecém (Ceará), and Itaqui (Maranhão) already handle substantial cargo volumes, supporting logistics for energy-intensive industries and renewable exports. Additional infrastructure, such as the new port under construction in Piauí, will further enhance connectivity and facilitate green industrialization. Integration with Brazil's extensive national transmission network ensures stable year-round operations, mitigating intermittency risks and supporting continuous industrial activity—an advantage over regions with less diversified renewable sources.

Moreover, the Northeast's geographic position provides logistical advantages for international trade, reducing transit times to key export markets in Europe, North America, and Africa. This combination of renewable abundance, logistical efficiency, and established infrastructure creates a robust foundation for developing green industrial hubs and expanding Brazil's role as a global supplier of low-carbon industrial products.

8.4 STRATEGIC SECTORS FOR GLOBAL GREEN LEADERSHIP

Brazil possesses the necessary conditions to become a central player in the emerging global markets for (H_2V) and ammonia. Its combination of abundant renewable resources, internationally competitive production costs, and strategic geographic location creates strong foundations for industrial scaling and export-led growth in this sector. Multiple projects are already underway, with significant production potential expected over the coming decade.

Analyses from McKinsey (2021) and BloombergNEF (2024) indicate that Brazil can produce H_2V at costs competitive with other leading markets such as Chile and Australia. Its geographic position also provides logistical advantages for serving major export destinations—including Europe, Japan, and South Korea—while meeting growing domestic demand for industrial decarbonization. The Brazilian steel sector, one of the world's largest, offers a particularly promising avenue for adopting hydrogen-based low-carbon technologies. The combination of an almost entirely renewable electricity matrix, abundant high-quality iron ore, and competitive potential for domestic hydrogen production creates a powerful structural advantage for both domestic and export-oriented green steel (Wilmoth et al., 2025; Agora Industry, 2025). In jurisdictions with stringent environmental standards, low-carbon steel can command significant price premiums, generating additional value-added opportunities.

According to the IEA's Breakthrough Agenda Report 2024: Steel (2024b), indicative levelized production costs for near-zero-emission steel in the EU range from US$700 to US$900 per ton using hydrogen-based direct reduction and electric arc furnaces. In contrast, Brazil's low-carbon production costs are estimated between US$550 and US$750 per ton, reflecting lower electricity prices, more affordable inputs, and the absence of EU-style carbon pricing. This cost structure allows Brazil to supply steel and semi-finished products at competitive prices while fully aligned with global decarbonization pathways (IEA, 2024a).

Brazil's aluminum industry already benefits from a predominantly renewable electricity base, resulting in below-average carbon intensity compared to global peers. Expanding production—particularly through renewable-rich regions such as the Northeast—could further reinforce competitiveness in international markets increasingly valuing certified low-carbon aluminum.

The fertilizer industry presents another strategic opportunity. Green ammonia production from H_2V could reduce Brazil's heavy dependence on nitrogen fertilizer imports, which currently expose the country to supply risks amplified by geopolitical instability. Developing a domestic green ammonia industry would simultaneously enhance food and energy security while creating export opportunities aligned with global low-carbon transition goals.

Finally, structural inefficiencies in the global solar supply chain highlight an additional opening for Brazil. Although China dominates solar panel manufacturing, its upstream polysilicon production remains heavily dependent on coal-based electricity, resulting in high embedded emissions. Moreover, China imports much of its high-purity quartz, adding maritime transport emissions. Brazil, endowed with abundant quartz reserves and a renewable energy matrix, is well positioned to produce low-carbon silicon and polysilicon, offering an environmentally coherent alternative for solar supply chains (E+ Energy Transition Institute, 2025). Relocating part of global production to Brazil would lower embedded emissions in photovoltaic panels and align production processes with climate goals. Strategically situating energy-intensive industries in clean-energy geographies like Brazil thus enhances both economic efficiency and climate effectiveness.

8.5 INTEGRATED AND SYNERGISTIC COMPETITIVE ADVANTAGES

Beyond its vast renewable energy resources, Brazil's combination of natural assets amplifies its competitive position in the global green economy. The country holds the world's largest reserves of freshwater, approximately 60% of the Amazon rainforest—the richest biodiversity on the planet—and an extensive agricultural base that uses only about 7.6% of national territory, leaving enormous potential for sustainable expansion. In addition, Brazil leads globally in iron production, possesses 95% of the world's niobium reserves, ranks second in rare earth reserves, and holds significant deposits of bauxite, manganese, graphite, copper, and other strategic minerals. Yet, only about 27% of its territory has been geologically mapped, suggesting a vast reservoir of untapped mineral wealth.

This convergence of natural advantages enables the development of an integrated bioeconomy powered by renewable energy. Agricultural and forest residues can feed renewable-powered biorefineries, fostering circular, regenerative, and high-value industrial chains. Brazil's decades of experience in biofuels further reinforce this potential. The country is the world's second-largest ethanol producer—around 36 billion liters annually—and the third-largest biodiesel producer, with approximately 7.5 billion liters per year. This industrial base positions Brazil to lead the next generation of advanced sustainable fuels.
The Sustainable Aviation Fuel (SAF) market represents one of the most promising frontiers. Global demand is projected to expand sharply through 2030, supported by EU mandates targeting a 2% SAF blend by 2025 (McKinsey, 2024; ICCT, 2025). Brazilian companies such as Raízen and Acelen are investing heavily in SAF production, while Petrobras explores alternative technological routes. Leveraging degraded land for biomass cultivation and existing expertise in biofuel production could provide Brazil with a strong competitive edge in sustainable aviation and maritime fuels. By scaling these capabilities, the country can play a leading role in decarbonizing international transport while strengthening energy security and creating high-value industrial opportunities aligned with global climate goals.

8.6 POWERSHORING ALREADY UNDERWAY

Brazil is advancing rapidly in its powershoring agenda, propelled by a combination of diversified private investments and increasingly structured public policies. Federal initiatives such as Nova Indústria Brasil and the Ecological Transformation Plan embody the powershoring rationale by aligning incentives, financial mechanisms, and regulatory frameworks to convert the country's natural and competitive endowments into low-carbon industrial capacities. This institutional architecture is reinforced by a comprehensive set of recent legislative measures, including the new hydrogen legal framework, the carbon market regulation, the updated biofuels law, the National Critical Minerals Policy, and the National Circular Economy Policy. Additional mechanisms such as sectoral funds, the ECO Invest instrument—which protects foreign investors from currency fluctuations in green transition projects—and the Brazil Investment Platform, a digital hub connecting global investors with sustainable infrastructure and energy projects, collectively provide legal predictability and extend the investment horizon in strategic green sectors (Guerra et al., 2025).

Within this framework, projects in advanced biofuels, pulp and paper, fertilizers, steel, and metallurgy—based on renewable biomass and green hydrogen—are progressing through various stages of development. These initiatives attract both domestic and international capital, including sovereign wealth funds, consolidating Brazil's role as a global hub for sustainable industrial production. The growing convergence between public policy and private sector initiative illustrates a coordinated national strategy. Brazil is leveraging not only its renewable energy, arable land, biomass, and mineral wealth but also a modernized regulatory environment that fosters investment confidence. This combination positions Brazil among the first emerging economies to operationalize the powershoring concept at scale, with tangible benefits for competitiveness, industrial innovation, and sustainability.

The National Bank for Economic and Social Development (BNDES) plays a central catalytic role in this process, expanding credit lines and programs directed at the energy transition, hydrogen, bioeconomy, strategic mining, and industrial decarbonization. The bank supports feasibility studies, public-private partnerships, and the structuring of integrated value chains designed to attract foreign capital and promote collaboration between domestic and multinational enterprises in sectors such as pulp and paper, sustainable mining, and renewable energy. Through long-term financing, guarantees, and blended finance instruments, BNDES mitigates investment risks and accelerates transformative projects, reinforcing Brazil's emergence as a global powershoring destination—where competitiveness, climate alignment, and industrial modernization converge.

8.7 GREEN DIPLOMACY AND STRATEGIC SOFT POWER

Brazil stands at a pivotal moment with the opportunity to emerge as a true global green power—an actor capable of combining environmental leadership with economic influence. Its trajectory of reconciling growth with decarbonization provides a compelling model for other emerging economies, demonstrating that prosperity and climate ambition can reinforce rather than constrain each other. This positioning grants Brazil significant soft power in international climate diplomacy, enhancing its credibility as a bridge-builder in a fragmented global governance landscape.

The Brazilian presidency of the G20 in 2024 and the hosting of COP30 in Belém represent strategic platforms to consolidate this leadership. Both forums enable Brazil to shape global coalitions around key priorities such as climate justice, technology transfer, green trade, investment, and financing for the energy transition. By leveraging these platforms, Brazil can advance a development-oriented climate agenda—one that links decarbonization to growth, employment, and social inclusion.

In this context, Brazil is uniquely placed to act as a strategic bridge between developed economies, which serve as technology suppliers and markets, and developing economies, which provide resources, growth potential, and new industrial frontiers. Through innovative triangular partnerships, Brazil can encourage broader Latin American engagement in powershoring strategies, facilitating trade integration, technological cooperation, and co-financing of transformative projects.

Its consolidated expertise in renewable energy, sustainable agriculture, and the bioeconomy provides a strong foundation for exporting technical knowledge and institutional capacity. By fostering South-South and North-South cooperation based on these strengths, Brazil can help shape an inclusive and pragmatic model for the global green transition—one that integrates climate ambition, economic opportunity, and development equity.

9. THE EUROPEAN CASE: TURNING GREEN INFLATION INTO A COMPETITIVE OPPORTUNITY

9.1 STRUCTURAL CHALLENGES OF EUROPEAN GREEN INFLATION

The European Union is facing growing economic challenges arising from the escalating costs of the energy transition. Subsidies, fiscal incentives, and the vast investments required for decarbonization have generated significant upward pressure on energy tariffs and industrial competitiveness. The EU's current strategy—balancing ambitious climate neutrality targets with the imperative of energy security in the wake of geopolitical disruptions—has exposed structural tensions between environmental ambition and economic affordability for consumers and firms.

Energy prices across Europe now reflect not only the costs of energy imports and generation but also a complex web of regulatory charges, climate-related taxation, and tariff-based mechanisms designed to finance the transition. This layered cost structure has resulted in electricity prices substantially higher than in regions endowed with abundant renewable resources and simpler regulatory environments. For electricity-intensive industries, these pressures threaten global competitiveness and, in some cases, operational viability (Dechezleprêtre et al., 2025). Sectors such as steel, aluminum, and chemicals face particularly acute challenges, with rising energy costs creating incentives to relocate production to regions offering lower electricity prices and cleaner energy sources.

Emerging green industries—including hydrogen-based steel, low-carbon aluminum, (H_2), and ammonia-derived fertilizers—also face cost disadvantages relative to countries with more abundant and affordable renewable energy. This disparity creates a structural dilemma: while Europe seeks to lead in green industrial technologies, high input costs risk undermining the commercial viability of its own transition industries.

Beyond economic competitiveness, the European energy transition poses serious social equity concerns. Rising energy prices disproportionately affect small businesses and lower-income households, many of which already struggle to afford adequate energy services—a condition formally recognized as energy poverty in EU legislation (EC, 2023c). Lower-income families spend a significantly higher share of disposable income on energy compared to wealthier households, deepening inequality and limiting access to the benefits of the transition.

This economic and social dynamic carries important political implications. When environmental policies are perceived as regressive—imposing disproportionate costs on working families while benefiting higher-income groups capable of investing in cleaner technologies—they risk eroding public support for climate action. The experience of recent social movements in several European countries underscores this risk: high energy and transition costs can provoke organized public resistance, undermining long-term decarbonization goals. The EU's challenge, therefore, lies in designing and implementing climate policies that integrate distributive considerations, ensuring that the transition remains both economically viable and socially just.

9.2 TRANSFORMATIVE POTENTIAL OF STRATEGIC GREEN TRADE

Strategically leveraging green comparative advantages through international trade could fundamentally reshape the European energy transition, reducing costs via global energy arbitrage and improving overall efficiency. Rather than indefinitely subsidizing structurally expensive domestic production—an approach that strains fiscal capacity—the European Union could co-invest with its private sector in powershoring initiatives and selectively import low-carbon products from regions where production is inherently cleaner and more cost-efficient. This strategy would allow Europe to focus its resources on high-value technological innovation, advanced manufacturing, and strategic industrial and defense capabilities, while contributing to global decarbonization (Arbache & Román, 2024).

Although still at an early stage, hydrogen (H_2) exports are expected to expand significantly in the coming decades. The HyDeal Ambition project, for example, plans to import 3.6 million tons of green hydrogen from North Africa, and similar partnerships with South American producers could complement this supply. Other trade configurations—such as importing pre-processed or intermediate materials from regions rich in renewable energy—appear particularly promising. Low-carbon aluminum from Iceland or Brazil, for instance, could prove more cost-competitive than European production while maintaining equal or even lower carbon intensity. Likewise, producing green steel in regions with abundant low-cost renewable hydrogen could reduce total transition costs for European industries. Metz (2024) finds that importing green iron is often more economical than transporting hydrogen or ammonia to Europe, suggesting that international trade in intermediates can complement domestic green steel initiatives and reinforce European industrial competitiveness (Agora Industry, 2025).

Quantitative evidence supports these conclusions. Verpoort et al. (2024) show that differences in renewable energy costs across regions can dramatically affect the competitiveness of basic materials. With a €40/MWh electricity price gap between energy-rich and energy-poor regions, relocating production could cut costs by approximately 18% for steel, 32% for urea, and 38% for ethylene. These gains stem primarily from access to cheaper, cleaner electricity and locally available low-carbon inputs—benefits that more than offset transport and financing costs. The advantage is especially pronounced in electricity-intensive stages of production, such as electrolysis and the synthesis of hydrogen derivatives (direct reduced iron, ammonia, methanol). In contrast, simply importing hydrogen to sustain production in high-cost regions yields minimal savings—typically 1–2%—whereas importing processed intermediates captures nearly the full economic benefit while preserving value-added activities within Europe.

Strategic imports of green intermediates would also strengthen downstream industries, particularly in manufacturing sectors facing intense global competition, such as automotive production. Lower-cost green steel and aluminum would directly reduce production expenses for electric vehicles and industrial equipment, enhancing export competitiveness (Agora Industry, 2025). Furthermore, analyses by the European Central Bank suggest that a coordinated green import strategy could help ease inflationary pressures during the most investment-intensive phase of the transition (2025–2035). By reducing input costs and stabilizing prices, such a strategy would expand fiscal and monetary space for investment in research and development, next-generation infrastructure, and social programs that facilitate a just transition for workers and regions affected by industrial restructuring (ECB, 2025).

In sum, trade-based decarbonization through powershoring offers the EU a pragmatic pathway to maintain industrial competitiveness, achieve climate targets more efficiently, and reinforce its leadership in the global green transition—all while sharing the benefits of the energy transformation with developing regions.

9.3 FISCAL AND ECONOMIC OPTIMIZATION

Europe is mobilizing substantial financial resources to advance its green transition through multiple instruments and mechanisms. The Green Deal Industrial Plan represents a major investment commitment, while the European Hydrogen Strategy sets ambitious development targets extending to 2030. A more selective import and co-investment strategy could optimize the allocation of these resources by redirecting part of the current expenditure toward research and development, infrastructure upgrades, and workforce retraining programs aimed at equipping labor for the emerging green economy.

The CBAM could also be refined to recognize environmental differentiation among imports, distinguishing products with high and low embedded carbon. By calibrating CBAM in this way, the EU could generate additional fiscal revenues without undermining global efficiency in the allocation of sustainable production. In sectors such as automotive manufacturing, access to competitively priced low-carbon inputs would allow electric vehicles and other green technologies to reach broader market segments, making sustainable mobility more affordable.

Similarly, lower-cost sustainable construction materials could accelerate the implementation of energy-efficiency projects under initiatives like the European Renovation Wave, generating employment across construction, installation, and maintenance. Reducing input costs would also allow Europe to focus on high-value, technology-intensive segments of the green economy—advanced renewable systems, energy storage, and transition-related industrial equipment—where it already holds strong technical capabilities. Manufacturing niches such as offshore wind turbines, electrolyzers, and advanced recycling technologies stand to benefit directly from such specialization.

In the chemical industry, strategic imports of green feedstocks—such as low-carbon ammonia and methanol—could sustain competitiveness by lowering the cost of producing basic chemicals. This, in turn, would enable European firms to specialize further in high-value-added products, including specialty chemicals and pharmaceuticals, which are less energy-sensitive and yield higher profit margins.

Financial markets play a complementary role in this transformation. European green finance instruments already account for a significant share of global issuance, with strong potential for further expansion. The growth of climate risk assessment services, sustainable investment products, and environmental data analytics can create new revenue streams while enhancing transparency and resilience in the financial system. Collectively, these shifts could drive a qualitative evolution of Europe's labor market—away from energy-intensive activities and toward high-skill, innovation-driven sectors aligned with long-term sustainability and competitiveness goals.

9.4 RISK MITIGATION AND SYSTEMIC RESILIENCE

Geographic diversification of green product supply offers Europe a strategic path to reduce systemic vulnerabilities and strengthen the resilience of its energy transition. Diversifying sourcing beyond a narrow group of suppliers can mitigate risks associated with supply chain concentration, exposure to extreme weather events, and geopolitical disruptions. By relying on a broader network of trade partners endowed with abundant renewable resources, Europe can enhance the security, stability, and cost-efficiency of its green industrial transformation.

Lower input costs from geographically diversified supply chains can also generate favorable macroeconomic effects. Reduced energy and material expenses help alleviate inflationary pressures, contributing to more stable interest rates and creating conditions for long-term investment planning. Predictable import contracts for low-carbon products enhance market stability, while lower domestic energy prices reduce the need for subsidies and ease pressure on public budgets and exchange rates. In this sense, green trade diversification supports not only climate goals but also macroeconomic resilience and fiscal balance. To achieve these outcomes, Europe can deepen strategic partnerships with countries rich in renewable energy and natural capital. Such partnerships should extend beyond simple trade relations to encompass technology transfer, joint infrastructure investment, institutional capacity building, and mechanisms for mutual market access for certified low-carbon products. These cooperative frameworks would foster shared growth while aligning standards and certification systems across jurisdictions, facilitating integration into global green value chains.

Several renewable-rich nations already maintain strong economic and historical ties with Europe, offering a solid foundation for this new phase of green cooperation. Brazil, Uruguay, and Chile—among others—stand out for their extensive renewable potential, political stability, and established trade relations. Shared historical and cultural links, often reinforced by migration and longstanding bilateral engagement, create a conducive environment for expanding a mutually beneficial green trade agenda. Such partnerships can help Europe secure affordable, sustainable inputs for its industries while providing these countries with access to advanced technology, investment capital, and high-value markets—establishing a virtuous cycle of economic and environmental co-development.

9.5 POTENTIAL CONTRIBUTION TO EUROPEAN NDCs

The European Union has committed to reducing net greenhouse gas emissions by at least 55% by 2030 compared with 1990 levels. However, recent analyses suggest that current measures may be insufficient to fully meet this goal, indicating the need for additional and more efficient strategies. Investment requirements for the EU's climate transition are projected to range between 2% and 3% of annual GDP during the 2025–2030 period, underscoring the scale of financial mobilization required.

A strategically designed green trade policy could optimize these resources through two complementary mechanisms. First, by importing low-carbon materials from regions with abundant renewable resources, the EU could lower the systemic costs of its energy transition. Second, by sourcing energy-intensive products—such as steel, aluminum, and fertilizers—from countries with competitive renewable energy, Europe could reduce production costs for domestic industries while maintaining environmental integrity.

Geographic diversification of supply chains would further enhance resilience by mitigating dependence on a limited number of suppliers and lowering exposure to geopolitical and climatic risks. Access to competitively priced green inputs would create a more favorable macroeconomic environment, alleviating inflationary pressures and supporting long-term industrial investment. In this way, structured international trade would not substitute but rather complement domestic policies, contributing to the EU's climate objectives through optimized resource allocation, cost efficiency, and strengthened international cooperation for global decarbonization.

10. POLICY PROPOSALS TO FOSTER GLOBAL GREEN TRADE

The evidence presented in this article demonstrates that the intersection of GCA and powershoring provides a tangible framework for accelerating global decarbonization through international trade. This convergence can align economic efficiency with climate effectiveness, transforming trade flows into mechanisms of emissions reduction and sustainable industrial development. However, realizing this potential depends on coherent policy coordination capable of addressing systemic barriers, ensuring regulatory convergence, and mobilizing sufficient incentives for large-scale transformation.

To this end, the following section outlines policy proposals structured across three complementary levels—multilateral, national, and subnational—reflecting the need for integrated governance. At the multilateral level, reforms should strengthen international cooperation, harmonize sustainability standards, and promote green trade facilitation. National policies should focus on industrial, fiscal, and innovation strategies that leverage renewable resources and attract investment in clean industries. At the subnational level, regional planning and infrastructure development are essential to operationalize powershoring through localized industrial ecosystems and green clusters. Together, these coordinated approaches can enable the emergence of a new global economic geography based on environmental competitiveness, resilience, and shared prosperity.

10.1 MULTILATERAL POLICIES: REBUILDING THE GREEN TRADE ARCHITECTURE

The WTO must undergo substantial modernization to systematically integrate environmental criteria into its trade rules and dispute settlement mechanisms. Three structural reforms stand out as essential. First, an Expanded Environmental Goods and Services Agreement (EGSA-E) should be launched to revive and broaden the scope of the original EGA negotiations. Beyond final environmental goods, the new agreement should include manufactured inputs, environmental services, and digital technologies critical to the energy transition. By eliminating tariffs and non-tariff barriers across a wider range of sectors, this reform would accelerate the global diffusion of clean technologies.

Second, an Environmental Additionality Criterion should be established to distinguish legitimate environmental protection from disguised protectionism. This criterion would assess whether trade-restrictive measures generate measurable environmental benefits or simply protect less efficient domestic industries under the guise of sustainability.

Third, the creation of a Specialized Climate and Trade Panel is essential to arbitrate disputes involving environmental claims. Composed of experts in green technologies, carbon accounting, and life-cycle analysis, this panel would deliver faster, technically sound rulings, recognizing the urgency of the global energy transition.

Fragmented regulations also pose a major obstacle to green trade and require coordinated solutions among major economic blocs. A Global Convergent Taxonomy, building on the IPSF Common Ground Taxonomy, could provide a unified technical reference with sector-specific thresholds defining maximum carbon intensity per product category. Mutual Recognition of Green Certifications would reduce redundant compliance costs by allowing automatic recognition of accredited environmental certifications across jurisdictions. In parallel, an International Carbon Traceability System—possibly based on blockchain or equivalent technologies—could ensure transparent tracking of carbon footprints along GVC and facilitate fair border carbon adjustments.

The CBAM represents an important precedent for integrating climate policy and trade, yet global effectiveness requires multilateral coordination. A Coordinated Multilateral CBAM among developed economies, featuring harmonized carbon pricing and mutual recognition of equivalent domestic policies, would prevent trade distortions and enhance environmental effectiveness. Development-Weighted Differentiation could grant longer transition periods and technical support to developing countries, helping them build certification and monitoring capacity. Finally, allocating CBAM revenues to an international climate cooperation fund would finance technology transfer, green infrastructure, and capacity-building in developing nations—transforming what is now a unilateral adjustment tool into a true instrument of global climate solidarity.

10.2 NATIONAL POLICIES: STRATEGIES DIFFERENTIATED BY ECONOMIC PROFILE

Countries such as Brazil, Chile, Australia, and several North African nations possess exceptional opportunities in the emerging green economy, but realizing them requires coherent and targeted policy frameworks. A National Powershoring Strategy should integrate industrial, energy, and investment attraction policies within a single framework. This strategy would identify priority sectors—such as aluminum, steel, green hydrogen, and fertilizers—set measurable targets for green foreign direct investment (FDI), and coordinate infrastructure planning to ensure synchronization between energy generation, logistics, and industrial capacity.

The establishment of Integrated Green Hubs can accelerate this agenda. These hubs should combine differentiated governance, advanced infrastructure (energy, ports, logistics), and specialized services such as certification, research and development, and workforce training. Operating under simplified regulatory frameworks and accelerated environmental licensing for pre-approved projects, such hubs would provide investors with predictability and scale economies. Complementing this, Proactive Green Diplomacy is essential. Governments should prioritize bilateral and regional partnerships with key importing markets, negotiate mutual recognition of green certifications, and engage in coalitions for technology transfer and industrial cooperation, strengthening their position in global green trade negotiations.

In contrast, developed economies such as the United States, the European Union, and Japan face distinct challenges that call for differentiated approaches. A Selective Green Import Strategy should balance energy security with cost efficiency by diversifying sources of low-carbon materials and establishing long-term, stable supply partnerships while safeguarding domestic capacity in critical technologies. High-Tech Green Specialization should channel public R&D investment toward frontier technologies—such as nuclear fusion, advanced storage, and direct air capture—where these countries possess comparative advantages in human capital and innovation. Exporting technological knowledge and services would reinforce this specialization. Simultaneously, a Just Industrial Transition must ensure social cohesion through retraining programs for workers displaced from carbon-intensive industries, combined with income support and relocation incentives toward regions with emerging green opportunities.

Emerging economies such as India, Mexico, Thailand, and South Africa must balance industrial growth with environmental objectives. A Selective Green Industrialization Strategy can identify sectors where resource endowments or cost advantages enable competitiveness in green manufacturing, emphasizing those with potential for technological learning and quality employment. Substantial investment in Technical Capacity Development is also crucial—expanding technical education, establishing applied research centers, and promoting international technology transfer aligned with the needs of green industries. Finally, Integration into Global Green Value Chains requires attracting foreign investment targeted at high-value segments, with clear mechanisms for technology transfer, supplier upgrading, and progressive domestic value capture. These strategies together would enable diverse economies to align industrialization with decarbonization, fostering a more inclusive and geographically balanced global green transition.

10.3 SUBNATIONAL POLICIES: MAXIMIZING REGIONAL ADVANTAGES

Developing green hubs requires differentiated governance structures capable of overcoming traditional administrative and institutional constraints. Regional Green Development Agencies should be established with clear mandates to coordinate the development of green industrial clusters. These agencies must possess operational autonomy, the authority to coordinate across multiple levels of government, and the ability to issue accelerated environmental licenses. Functioning as "one-stop shops" for investors, they would streamline procedures and provide a single interface for companies pursuing green industrial projects.

Integrated Territorial Planning is equally critical. Comprehensive master plans should align land use, energy infrastructure, logistics corridors, and environmental protection. These plans would incorporate scenario modeling for industrial expansion and assessments of environmental carrying capacity to ensure sustainable long-term development.

Structured Public-Private Partnerships can provide the financial backbone for these initiatives. By sharing investment risks, governments and private actors can co-finance essential infrastructure, establish guarantees to attract long-term investors, and collaborate on applied research and technological innovation.

Workforce development represents a decisive factor for the success of green hubs. Specialized Technical Universities should be created or expanded to focus on renewable energy, bioeconomy, circular economy, and green industrial processes, integrating industry-partnered curricula, cutting-edge laboratories, and international exchange programs. Complementing this, Centers of Excellence in Green Technologies can act as bridges between academia and industry, developing applied solutions while training highly qualified personnel in collaboration with global universities and multinational companies. Finally, Talent Development and Attraction Programs can strengthen the human capital base through scholarships for doctoral studies abroad in strategic fields and differentiated immigration policies for professionals in green technologies. Fast-track visas, temporary tax incentives, and cultural integration programs can help attract global expertise, accelerating the buildup of knowledge ecosystems essential for powering the green industrial transformation.

10.4 FINANCIAL INSTRUMENTS AND SUPPORT

Financing the green transition at the necessary scale requires an unprecedented mobilization of public and private capital, supported by innovative financial mechanisms and strong institutional coordination. Development banks should play a central role by expanding or refining their mandates to finance green industrial projects. These institutions must offer instruments for risk mitigation, competitive interest rates, long-term credit, project structuring support, and sectoral funds for strategic areas. Additional tools such as currency hedging and digital matchmaking platforms can help attract international investors and reduce transaction costs.

Green sovereign funds can serve as long-term investment vehicles focused on acquiring strategic stakes in global green industries and projects, combining financial returns with measurable environmental outcomes. Indexed green sovereign bonds represent another promising mechanism, linking debt instruments to the achievement of verifiable environmental targets. This creates tangible incentives for effective climate policies and enhances accountability through transparent performance monitoring.

Fiscal incentives are also essential to accelerate the transition. Accelerated green depreciation would allow companies to immediately or rapidly depreciate investments in certified green technologies, lowering upfront costs and improving returns on capital. Environmental results tax credits could replace traditional expenditure-based incentives, rewarding measurable results such as emissions avoided, renewable energy generated, or green jobs created—thus maximizing environmental efficiency per fiscal unit. Finally, a carbon tax with revenue recycling can encourage innovation by channeling collected revenues back to industries demonstrating progress in decarbonization, supporting the transition without undermining competitiveness in key industrial sectors.

10.5 COORDINATION AND GOVERNANCE OF THE TRANSITION

The scale and complexity of the global green transition require governance structures capable of coordinating policies across ministries, sectors, and levels of government while maintaining transparency and social legitimacy. National Green Transition Councils should be established as interministerial bodies that include representatives from the private sector, civil society, and the scientific community. Their role would be to ensure policy coherence, reviewing sectoral initiatives for consistency with national decarbonization goals and identifying potential conflicts between industrial, environmental, and fiscal measures. National Green Certification Agencies would serve as technical institutions responsible for defining certification standards, accrediting certifying bodies, and negotiating international mutual recognition agreements. These agencies would help reduce compliance costs and facilitate participation in global green markets.

Transition Observatories should complement these institutions by systematically tracking the progress of the green transition through indicators such as carbon intensity, employment generation in green sectors, R&D investment, and export competitiveness. Regular publications of reports and policy briefs would strengthen accountability and enable evidence-based adjustments.

Social governance and transparency mechanisms are equally essential. Monitoring systems must ensure that vulnerable groups—particularly Indigenous peoples and local communities—are protected from potential adverse effects of projects and policies. Compensation and benefit-sharing mechanisms, participatory consultation processes, and transparent disclosure practices are necessary to align the green transition with principles of social justice and inclusive development.

11. FUTURE PERSPECTIVES AND THE INEVITABILITY OF TRANSFORMATION

The analyses converge on a central conclusion: restructuring international trade toward sustainability is not only a political goal but an economic inevitability. Mounting structural pressures—climate change, energy volatility, supply chain disruptions, and the search for industrial competitiveness—are making the reorganization of global trade around green comparative advantages a fundamental condition for economic resilience and survival.

The drivers of this transition are increasingly systemic. Companies and governments are moving toward energy-diversified production models as extreme climate events disrupt supply chains, volatile energy prices erode predictability, and geopolitical tensions reshape access to critical resources. In this context, resilience has replaced mere cost optimization as the primary determinant of corporate strategy. The insurance industry has already begun internalizing these risks by adjusting coverage in high-exposure regions, influencing investment decisions in infrastructure, real estate, and industrial projects. The economic impact of recent climate disasters—such as the 2021 floods in Germany and Belgium or heatwaves reducing hydropower and nuclear output in Europe—illustrates the financial rationale for diversification and decarbonization. Between 2020 and 2024, sharp fluctuations in European oil and natural gas prices further strengthened the logic for renewable energy expansion as a source of cost stability and industrial competitiveness.

These converging pressures suggest that environmental and climate agendas will continue advancing, even if intermittently slowed. Increasingly, they will be framed in terms of national security, risk management, and competitiveness rather than purely environmental concerns—a reframing that makes them more politically resilient and economically grounded (Arbache, 2025c).

Three broad scenarios can be envisioned for the evolution of global green trade.

In the Accelerated Global Cooperation (2025–2035) scenario, international coordination succeeds. Rapid technological progress combines with aligned multilateral frameworks to produce a virtuous cycle of innovation, cost reduction, and global adoption. The WTO concludes an expanded Environmental Goods and Services Agreement (EGSA), eliminating tariffs on over 600 green goods and services, while CBAM evolves into a harmonized system of mutual recognition. Resource-rich countries emerge as major industrial players in green value chains. This scenario is characterized by dynamic job creation, falling costs, expanding green trade volumes, and the emergence of well-integrated sustainable trade corridors.

In the Fragmented Progress (2025–2040) scenario, progress is gradual and uneven. Cooperation advances through regional, bilateral, or sectoral agreements, creating three to five major green trade clusters with internally harmonized standards but persistent divergences among blocs. While efficiency improves locally, global diffusion remains limited. Employment growth and cost reductions are regionally concentrated, reflecting asymmetrical progress and persistent institutional barriers.

The Green Fragmentation and Protectionism (2025–2050) scenario depicts a breakdown of coordination and the proliferation of protectionist measures disguised as environmental policy. Competition for green market dominance replaces cooperation, resulting in a green trade war. Developing countries endowed with natural capital and renewable resources face systemic exclusion from high-value markets, and global decarbonization slows dramatically.

Together, these scenarios illustrate that achieving a sustainable transformation of global trade depends on effective policy coordination, strategic investment, and innovative governance. Only by aligning economic and environmental objectives through cooperative frameworks can the world capture the full developmental and climate potential of a global green trade transition.

12. Conclusion

The analysis presented in this article establishes a clear theoretical and empirical foundation: international trade is not an obstacle to global decarbonization but rather an efficient mechanism to accelerate the energy transition through the optimization of green comparative advantages and corporate powershoring strategies. The central thesis—that the convergence of GCA and powershoring can transform international trade from a potential barrier into an effective catalyst for decarbonization—is validated by the evidence. This is not merely a theoretical proposition but an operational strategy grounded in verifiable competitive advantages and ongoing market dynamics.

Iceland exemplifies this dynamic through its leadership in green premiums. Chile is poised to capture a significant share of the global green hydrogen market. Brazil, with a temporal advantage of 18-30 years, holds a unique opportunity for industrial leadership in green sectors. The pursuit of resilient value chains, rising costs from extreme climate events, energy volatility, and the need to enhance competitiveness all create dynamics in which the reorganization of global trade is a matter of timing.

Europe provides an illustrative case of how strategic trade policies can transform structural challenges of the green transition into sustainable competitive advantages. While previous sections highlighted how trade barriers slow global decarbonization, the European case demonstrates that smart trade integration can accelerate the energy transition, reduce costs for consumers and firms, and strengthen technological leadership—lessons that are relevant for other economies facing similar dilemmas.

Countries with abundant natural capital and renewable resources can achieve leadership in green products through coordinated investments in green hubs, infrastructure, attractive regulatory frameworks, and strategic partnerships with developed economies. Developed economies can optimize transition costs through powershoring and strategic imports, freeing resources for other sectors. Emerging economies can balance domestic capacity development with integration into global green value chains. Properly structured international trade—through the systematic removal of barriers and harmonization of standards—represents a highly effective tool to accelerate decarbonization and limit global warming.

This conclusion is supported by convergent evidence: regions with exceptional natural capital and renewable resources can produce green goods at lower costs; hub-based production can reduce global costs; specialization can accelerate the transition by several years; and resource reallocation to higher value-added activities addresses broader development priorities.

Policies facilitating investment and flows of green products can simultaneously lower transition costs, democratize access to sustainable technologies, and enhance industrial competitiveness. Conversely, protectionist resistance can generate higher costs and delays. Corporations that anticipate this transformation—investing in powershoring, participating in green hubs, developing diversified green supply chains, and advancing next-generation technologies—can capture significant first-mover advantages.

The convergence of climate urgency, technological advancement, and geopolitical realignment creates a historically unique window of opportunity. This window is temporally limited: early entrants can establish scale advantages, expertise, and strategic relationships that are difficult to replicate. A successful transition could generate millions of green jobs, drive economic development along new pathways, reduce decarbonization costs, and accelerate the energy transition required for climate stability.

The article demonstrates that the combination of GCA and powershoring offers a solution that turns one of the greatest challenges of our era—the global energy transition—into a historic economic opportunity. This is not incremental optimization but a fundamental reconfiguration of the world economy based on economically decisive energy comparative advantages.

Time is critical. With the window to limit global warming rapidly closing and costs from climate events accelerating, speed of implementation becomes the decisive factor for success. Countries and companies that understand and capitalize on this convergence will not only contribute to global climate stability but also position themselves as leaders of the next industrial revolution—one founded on sustainability, efficiency, and resilience. The historic opportunity is before us, grounded in empirical evidence, measurable economic trends, and operational success stories. It demands urgency, scale, and international coordination.

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