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The Geography of Decarbonization: Distorted Relative Prices and the Misallocation of Global Green Investment

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Sumário

The Geography of Decarbonization: Distorted Relative Prices and the Misallocation of Global Green Investment

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Abstract

Decarbonization is reshaping the structure of relative prices across the global economy. As clean energy, natural capital, and location-specific assets become dominant inputs in energy-intensive industries, the relative cost of producing low-carbon goods is increasingly determined by geography. Under undistorted conditions, this structural transformation should redirect investment toward renewable-rich economies where production is cheaper and emissions intensity lower. Yet this reallocation remains incomplete. This paper argues that two systematic distortions explain the divergence. First, industrial policy interventions — subsidies, tax credits, trade barriers, and certification systems — disconnect effective prices from underlying structural costs, redirecting investment toward structurally inefficient locations. Second, institutional failures in certification, procurement, and standards create demand uncertainty that leaves otherwise competitive projects unbankable. Together, these distortions generate static misallocation, slower technological learning, higher fiscal burdens, delayed emissions reductions, and suppressed industrial opportunities in developing economies. This paper is part of a broader research agenda on powershoring and green comparative advantage, which argues that decarbonization is not only a technological transition — it is a spatial and price reorganization of global production.

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Introduction: Decarbonization as a Problem of Space, Prices, and Coordination

The global decarbonization debate is typically framed as a technological race, a financing challenge, or a problem of carbon pricing and regulatory ambition. These perspectives are important, but they remain incomplete because they understate a more fundamental transformation now underway: decarbonization is also reorganizing the geography of global production and is changing relative prices (Arbache and Esteves, 2023; Arbache, 2025a; 2026a). As energy systems change, the location of production is becoming increasingly important for both economic efficiency and emissions reduction.

This transformation is particularly visible in hard-to-abate and energy-intensive sectors such as hydrogen, aluminum, steel, fertilizers, sustainable aviation fuels, chemicals, and critical minerals processing. In these sectors, production costs depend heavily on factors that are geographically unevenly distributed, including renewable energy resources, electricity costs, biomass availability, water access, mineral endowments, logistics infrastructure, and regulatory conditions. As these factors become more important, geography is re-emerging as a central determinant of comparative advantage (Arbache, 2023; 2025a; 2026b).

Under standard economic conditions, this shift should generate a large-scale reallocation of investment toward locations where low-carbon production can occur at lower cost and lower emissions intensity, thus affecting relative prices (Arbache and Esteves, 2023; Arbache, 2025a). Yet this reallocation is occurring far more slowly than underlying fundamentals would predict. Investment often remains concentrated in structurally higher-cost locations, while many renewable-rich economies remain underinvested despite possessing significant cost advantages (Arbache, 2025b).

This paper argues that this divergence reflects a growing disconnect between structural competitiveness and effective competitiveness. Structural competitiveness reflects underlying production fundamentals such as energy costs, natural resource endowments, logistics conditions, and capital requirements. Effective competitiveness reflects the prices firms actually face after accounting for subsidies, tax incentives, trade barriers, certification systems, regulatory asymmetries, and market-access restrictions. In many sectors, policy interventions are now large enough to materially alter competitiveness rankings across countries Arbache, 2026a).

But distorted prices alone do not fully explain observed investment patterns. Even when structurally efficient projects possess substantial cost advantages, many fail to move forward because firms face uncertainty regarding future demand (Arbache, 2025b). Fragmented certification systems, weak interoperability of standards, insufficient long-term procurement arrangements, and uncertain regulatory recognition often reduce project bankability. As a result, decarbonization is increasingly constrained not only by price distortions, but also by weak institutional coordination.

The paper builds on a broader strand of recent work to which I have contributed and develops five core arguments. First, it shows how structural changes in relative prices are reshaping comparative advantage under decarbonization. Second, it explains why the physical characteristics of renewable energy systems are reinforcing the economic importance of geography. Third, it examines how industrial policy interventions increasingly distort effective prices and redirect investment toward structurally inefficient locations. Fourth, it introduces demand uncertainty and project bankability as a second major constraint on efficient global capital allocation. Fifth, it examines the broader implications of these distortions for technological learning, global value chains, development, welfare, and the future geography of industrialization.

The paper also contributes to a broader debate about the changing material foundations of the global economy. For decades, influential strands of globalization theory suggested that digitalization and the rise of intangible assets would gradually reduce the importance of geography. This paper argues that decarbonization is producing the opposite effect. The transition is generating a new phase of rematerialization in which clean energy systems, industrial minerals, land, water, logistics infrastructure, and location-specific assets are becoming more economically important (Arbache, 2026b,d).

The central argument is straightforward: decarbonization is not simply a technological transition. It is simultaneously a spatial, industrial, trade, and development transition. Whether it becomes fast, affordable, and inclusive will depend heavily on whether global institutions allow production to move toward the most efficient locations.

2. From Comparative Advantage to Distorted Competitiveness

The analytical starting point is classical trade theory. In its standard formulation, the Heckscher–Ohlin framework predicts that countries specialize according to their relative factor endowments. Traditionally, these factors include labor and capital. In a decarbonizing world, however, this representation becomes insufficient. Clean energy and natural capital must be incorporated explicitly as production factors. Electricity generated from renewable sources, water availability, land, biomass, and environmental conditions are no longer background variables; they are central inputs in a wide range of industrial processes, including hard-to-abate and most energy-intensive sectors.

Once these factors are included, the logic of comparative advantage leads to a clear prediction. Countries with abundant and low-cost renewable energy, combined with complementary natural resources, should specialize in energy-intensive low-carbon goods. This prediction does not require new theory. It follows directly from standard microeconomic reasoning. What has changed is the structure of costs.

A further clarification is necessary. The issue is not simply that relative prices are being distorted by policy intervention; it is also that the underlying structure of relative prices is itself changing. In conventional commodity markets, price volatility often reflects cyclical fluctuations in demand, supply disruptions, or financial speculation. In the current transition, however, deeper structural forces are at work. Climate policy, technological change, carbon regulation, geoeconomic fragmentation, and physical constraints associated with renewable energy systems are altering the relative value of key inputs and assets in persistent ways (Arbache and Esteves, 2023; Arbache, 2025a; 2026a; 2026d). The relative prices of fossil fuels, clean electricity, critical minerals, dispatchable low-carbon power, transmission infrastructure, and carbon-intensive industrial inputs are being fundamentally reorganized, although these structural shifts are not yet fully reflected in observed market prices.

This distinction matters because policy debates often confuse short-term commodity volatility with long-term structural revaluation. The same confusion is visible in portions of the natural capital and wealth accounting literature, which often adopt conservative assumptions about future rents in order to avoid overstating commodity booms. While such caution may be statistically prudent, it may also understate structural changes associated with decarbonization, climate risks, geopolitical fragmentation, and the rising scarcity value of certain location-specific assets. In a rapidly changing transition environment, excessive assumptions of rent stability may become analytically misleading. Short-term commodity price volatility generates statistical noise around an otherwise stable equilibrium; long-term structural revaluation reshapes comparative advantage itself. The geography of decarbonization is therefore being influenced not only by policy distortions layered onto an otherwise stable system, but by a deeper transformation in the relative scarcity of factors of production across space.

In sectors such as green hydrogen, electricity accounts for the dominant share of production costs. The IEA estimates that electricity typically represents 60–80% of the total cost of producing hydrogen via electrolysis, depending on capacity factors and financing conditions (IEA, 2019, 2023). In aluminum, electricity alone accounts for around 30–40% of total production costs, reflecting the energy intensity of smelting processes (IEA, 2021). In steel, energy inputs—including electricity and fuels—represent roughly 20–30% of total costs, with higher shares in low-carbon production routes such as hydrogen-based direct reduced iron (IEA, 2020). In basic chemicals, energy expenditures can reach up to 60% of operating costs in ammonia production, where natural gas or electricity is a key input (IRENA, 2022a; IEA, 2021).

These magnitudes are not marginal. They imply that differences in the cost of clean electricity translate directly into large differences in total production costs. Given that renewable electricity costs vary across countries by factors of two to four in harmonized estimates (OECD/NEA, 2020), the resulting cost differentials are sufficient to determine industrial location. Under undistorted conditions, production would therefore shift toward regions where clean energy is structurally cheaper.

Yet this reallocation has not occurred at the scale that fundamentals would suggest. The reason is that firms do not make decisions based on structural costs alone. They respond to effective costs, which incorporate policy-induced distortions. These distortions arise from multiple sources: production subsidies, tax credits, local-content requirements, trade barriers, certification rules, and regulatory asymmetries across jurisdictions.

To clarify the role of policy, it is useful to distinguish between two broad categories of intervention. Corrective (or efficiency-enhancing) policies address market failures, internalize externalities, reduce coordination costs, and build the institutional infrastructure required for markets to function (e.g., harmonized certification, long-term procurement frameworks, carbon pricing, R&D support for infant technologies). Distortive (or compensatory) policies, by contrast, permanently offset structural disadvantages through sustained fiscal transfers, local-content mandates, or trade barriers that override comparative advantage. While both types coexist in practice, their economic implications differ markedly: the former can accelerate movement toward structurally efficient production, whereas the latter tends to lock capital into higher-cost locations and generate persistent allocative inefficiencies (Arbache, 2025c; 2026e).

The relevant decision variable can therefore be expressed as an effective cost function, in which structural costs are adjusted by policy wedges. When these wedges are large, effective competitiveness can diverge substantially from underlying comparative advantage. In extreme cases, high-cost locations become more attractive than structurally efficient ones. This is not a theoretical curiosity. It is a defining feature of the current policy landscape.

The implication is that the observed geography of green industrial investment does not necessarily reflect the true economics of decarbonization. Instead, it reflects the interaction between structural conditions and policy-induced distortions. As long as these distortions persist, capital will not flow to the most efficient locations, and the reorganization of production will remain incomplete.

This raises a deeper question: why are these structural shifts in relative prices reshaping comparative advantage with such persistence? Part of the answer lies in policy distortions, which are examined in subsequent sections. But part of it lies in something more fundamental — the changing physical characteristics of the energy system itself. Unlike fossil fuels, renewable energy introduces new spatial constraints related to transportability, intermittency, storage, and infrastructure requirements. These physical characteristics help explain why geography is re-emerging as a central economic variable, and why the reorganization of production under decarbonization is not simply a policy problem but also a spatial one.

3. Energy Density and the Structural Return of Geography

The reemergence of geography as a central economic variable is rooted in a physical transformation of the energy system (Arbache, 2026c,d). Fossil fuels are characterized by high energy density and well-developed logistics. These properties allowed energy production and industrial activity to be geographically separated. Oil, gas, and coal could be transported over long distances at relatively low cost, enabling industries to locate near markets, labor, or technological clusters rather than near energy sources.

Renewable energy systems operate under fundamentally different conditions. Wind and solar resources are spatially uneven and require large-scale infrastructure for generation, transmission, and storage. Even when generation costs are low, the system cost of delivering energy to distant locations can be substantial. Electricity transmission involves high capital expenditure, long permitting processes, and physical constraints. Storage technologies remain costly for many applications. Hydrogen, often presented as a transportable energy carrier, introduces additional layers of complexity. Its low volumetric energy density requires compression, liquefaction, or conversion into derivatives, all of which involve significant costs and efficiency losses.

These physical constraints translate directly into economic outcomes. For industrial users, what matters is not the cost of generating electricity at the source, but the marginal cost of energy at the point of use. When this cost becomes strongly location-dependent, the spatial organization of production must adjust accordingly. Energy-intensive industries have strong incentives to locate where clean energy is abundant, reliable, and inexpensive.

This logic defines powershoring (Arbache, 2022; Arbache and Esteves, 2023). Powershoring is not simply a policy strategy. It is also an economically efficient response to the physics of the energy transition. By relocating production to energy-rich regions, it reduces system costs, avoids transmission losses, and accelerates the deployment of low-carbon industrial capacity.

However, this adjustment mechanism depends critically on the functioning of relative prices. If prices reflect underlying scarcities, production will move toward efficient locations. If prices are distorted, the adjustment will be delayed or blocked. The current global landscape suggests that the latter condition dominates.

3.1 Cross-country differences in renewable electricity costs

A key premise of this paper is that the geography of clean energy matters because the cost of producing renewable electricity differs substantially across locations. Strictly speaking, the short-run operating marginal cost of solar and wind generation is often close to zero once plants are built. For investment, industrial location, and trade decisions, however, the relevant metric is the cost of producing electricity on a comparable project basis. For that reason, the most appropriate internationally harmonized indicator is the levelized cost of electricity (LCOE), rather than short-run marginal operating cost.

To document these differences using a consistent methodology, Table 1 reports harmonized LCOE estimates from the IEA/OECD-NEA Projected Costs of Generating Electricity 2020 and its official supporting data workbook. The advantage of this source is methodological comparability: country submissions are processed under a common analytical framework, allowing like-for-like comparisons across technologies and jurisdictions. The table focuses on utility-scale solar PV and onshore wind at a 7% discount rate, which is the central case in the workbook. Solar PV and onshore wind are used because they offer the broadest and most comparable country coverage. The results show large differences in clean electricity costs across countries, with important implications for industrial location and powershoring.

Table 1. Harmonized renewable electricity costs across selected countries
LCOE of new projects, USD/MWh *(7% discount rate, central case, selected countries)*

Group	Country	Solar PV (USD/MWh)	Onshore Wind (USD/MWh)
Renewable-resource-abundant economies	India	35.5	35.8
	Australia	37.1	43.0
	Brazil	46.0	33.6
Cost-competitive in at least one technology	France	33.9	56.1
	Denmark	–	29.2
	Netherlands	80.0	41.2

Group	Country	Solar PV (USD/MWh)	Onshore Wind (USD/MWh)
Structurally higher-cost industrial economies	Belgium	90.2	67.2
	Italy	60.5	67.9
	Austria	–	76.4
	Japan	172.1	140.2
	Korea	96.6	113.3
Reference large market	United States	43.7	61.3

Source*:* Author's compilation from the official supporting workbook to IEA/OECD-NEA, Projected Costs of Generating Electricity 2020. The publication states that a "uniform, consistent method of analysis produces comparable, levelized costs of electricity," and the workbook provides the underlying country-technology entries.
Notes*:* We use LCOE instead of marginal operating cost because for variable renewables the short-run marginal operating cost is often close to zero; what matters for investment and location decisions is the project-level cost of delivered electricity. We do not include hydropower in the table because hydropower entries in the harmonized workbook are fewer and more heterogeneous project-by-project, making solar PV and onshore wind a cleaner cross-country comparison set. Values are expressed in USD/MWh, representing the average cost of generating one megawatt-hour of electricity over the lifetime of the project. The LCOE includes capital expenditures (CAPEX), operating and maintenance costs (OPEX), and the cost of capital. If hydropower were fully accounted for, average LCOE levels in countries with abundant hydro resources—such as Brazil, Norway, and Canada—would be significantly lower. This effect is particularly strong in systems like Brazil's, where a large share of hydropower capacity consists of mature assets with capital costs already amortized, implying lower effective generation costs than those reflected in standard LCOE estimates for new projects. Country groupings are based on the overall cost profile across technologies, not on a single metric. France and Denmark are grouped separately to reflect that certain advanced economies remain competitive in specific renewable technologies despite generally higher industrial energy costs — a heterogeneity that reinforces the paper's central argument that what matters is the geography of delivered clean

electricity costs at the point of industrial use, not broad regional classifications. Denmark's onshore wind LCOE (USD 29.2/MWh) is drawn from the same IEA/OECD-NEA 2020 dataset; solar PV data for Denmark is not reported in the harmonized workbook. All other notes from the original table apply.

The dispersion is economically significant. In utility-scale solar PV, the gap between India (USD 35.5/MWh) and Belgium (USD 90.2/MWh) is roughly 2.5 times; the gap between India and Japan (USD 172.1/MWh) is far larger still. In onshore wind, Brazil (USD 33.6/MWh) sits far below Japan (USD 140.2/MWh) and Korea (USD 113.3/MWh). These are not marginal differences. They are large enough to alter the economics of hydrogen, green steel, aluminum, ammonia, fertilizers, and other electricity-intensive activities.

Two points follow. First, clean electricity costs are not merely different across countries; they are different by multiples, not by small percentages. Second, the dispersion is not reducible to a simple Europe-versus-rest dichotomy. There is substantial heterogeneity within advanced economies themselves. Some European locations remain relatively competitive in specific technologies, while others are structurally expensive. This nuance actually strengthens the core argument of the paper: what matters is not broad regional labels, but the geography of delivered clean electricity costs at the point of industrial use.

This evidence reinforces the central logic of powershoring. If clean electricity is a dominant input in hard-to-abate sectors, then countries combining abundant renewable resources with comparatively low electricity costs should enjoy a structural advantage in attracting energy-intensive green production. Under undistorted relative prices, this would imply a much stronger relocation of industrial investment toward such jurisdictions. The fact that this relocation remains limited suggests that the observed geography of investment is being shaped not only by structural costs, but also by policy-induced wedges that alter effective competitiveness.

4. Distorted Prices and the Architecture of Green Industrial Policy

The present phase of the energy transition is characterized by an unprecedented level of policy intervention. Governments are deploying a wide range of instruments to promote domestic green industries, including subsidies, tax credits, public procurement, regulatory mandates, and trade measures. These interventions are often justified by concerns related to industrial policy, energy security, employment, strategic autonomy, and geopolitical competition (IMF, 2023; OECD, 2024; WTO and World Bank, 2023).

While such objectives may be legitimate, their economic effects must be carefully assessed. By altering effective prices, these policies can sustain production in locations that are structurally inefficient. Subsidies reduce production costs directly. Local-content requirements restrict sourcing options. Certification systems and regulatory definitions determine which products qualify as "green," often in ways that favor domestic producers. Border measures can raise the cost of imports, even when those imports are more efficient from a global perspective.

The cumulative effect of these interventions is to reshape the price system faced by firms. Instead of reflecting underlying cost conditions, prices become the outcome of policy interactions. In this environment, investment decisions are guided not by comparative advantage, but by policy incentives. This has two major consequences. First, it leads to a misallocation of capital. Resources are directed toward projects that are viable only under continued policy support, rather than toward projects that are structurally competitive. Second, it increases the global cost of decarbonization. Producing low-carbon goods in high-cost locations requires either higher prices for consumers or sustained fiscal transfers. In both cases, the economic burden of the transition rises.

Moreover, these distortions interact with the organization of global value chains. Industrial production is not a collection of isolated plants, but a network of interconnected stages. Costs incurred at upstream stages propagate downstream, affecting the competitiveness of entire sectors. Protecting high-cost upstream production can therefore weaken downstream industries that depend on these inputs. This dynamic is particularly relevant in advanced economies with strong manufacturing ecosystems.

The tension between protecting domestic industries and maintaining global efficiency is not new. What is new is its interaction with the physics of the energy transition. In a world where energy costs are increasingly location-specific, attempting to override comparative advantage becomes more expensive and less sustainable over time.

The issue, therefore, is not whether governments should intervene. Governments have legitimate reasons to do so: learning externalities, coordination failures, resilience concerns, national security considerations, and political constraints are all real. The relevant question is whether intervention accelerates movement toward structurally efficient production or merely compensates indefinitely for structural disadvantages. Policies that lower long-run costs and expand efficient global supply are fundamentally different from policies that permanently suppress underlying comparative advantages.

4.1 Policy Interventions, Effective Prices, and the Fragmentation of Demand

The distortions discussed above are no longer theoretical possibilities. They are increasingly embedded in the policy architecture of major economies and are already shaping global investment decisions in low-carbon industries. What is emerging is not a coherent global market for decarbonization, but a fragmented system in which governments simultaneously subsidize domestic production, restrict external competition, and selectively create demand under nationally defined regulatory frameworks.

The United States provides one of the clearest examples of direct price intervention. The Inflation Reduction Act introduced one of the largest clean industrial policy packages in modern economic history, with estimates of total fiscal commitments rising substantially above initial projections as private-sector responses accelerated (Bistline et al., 2023; Goldman Sachs, 2023). In hydrogen, the Section 45V production tax credit is particularly significant because it can provide up to USD 3 per kilogram for qualifying projects over a ten-year period. This subsidy is economically meaningful because it can be comparable to—or in some cases exceed—the structural cost advantage enjoyed by renewable-rich producers in developing economies. In practical terms, this means that a producer operating in a structurally high-cost energy system may become more competitive than a producer located in a naturally lower-cost renewable environment purely because policy intervention alters effective prices (Internal Revenue Service, 2024; U.S. Department of Energy, 2024). Similar mechanisms are emerging in sustainable aviation fuels and other sectors where fiscal incentives materially alter production economics.

In Europe, intervention operates through a somewhat different institutional architecture but often generates similar allocative consequences. Rather than relying primarily on large production tax credits, European policy increasingly combines direct subsidies, demand mandates, certification systems, and regulatory screening mechanisms. The European Hydrogen Bank, for example, reduces revenue uncertainty and improves project bankability through direct auction-based subsidies. ReFuelEU creates future demand for sustainable aviation fuels through mandatory blending targets. At the same time, regulatory frameworks governing certification, additionality requirements, temporal correlation rules, and emissions accounting often increase compliance costs for external suppliers and create uncertainty regarding long-term market access (European Commission, 2024a,b; Bruegel, 2024).

Carbon border measures add another layer of complexity. The European Union's Carbon Border Adjustment Mechanism, which entered full implementation in January 2026 following a transitional reporting phase that began in October 2023, prices carbon differentials more explicitly and may over time create stronger incentives for emissions reductions in exporting countries. In practice, however, it also increases compliance and administrative costs for exporters, creates regulatory uncertainty in jurisdictions where carbon accounting methodologies differ from EU standards, and contributes to market fragmentation when similar instruments diverge across major economies. These effects are particularly significant for developing-country exporters attempting to establish themselves in emerging low-carbon industrial markets, where certification and traceability requirements impose costs that disproportionately affect producers with limited institutional capacity (European Union, 2023; European Parliament, 2024). Whether CBAM ultimately accelerates global decarbonization or primarily redirects trade flows without reducing aggregate emissions will depend critically on whether its implementation is accompanied by complementary international coordination mechanisms.

Similar interventions are expanding elsewhere. Canada, Australia, Japan, China, and several Middle Eastern economies are increasingly deploying industrial subsidies, concessional finance, tax incentives, long-term contracts, and strategic investment programs to accelerate domestic green industrialization. While the instruments differ across countries, the broader pattern is increasingly global: governments are actively reshaping relative prices in strategic sectors rather than allowing structural cost conditions to determine investment allocation (IEA, 2024; IRENA, 2022b; OECD, 2024).

The cumulative effect is a growing divergence between structural competitiveness and observed investment outcomes. Firms are no longer responding primarily to underlying production costs. They are increasingly responding to policy-adjusted effective prices shaped by subsidies, regulatory eligibility rules, compliance costs, and expected access to final markets.

But the problem extends beyond excessive intervention. In many cases, distortions also emerge from the absence of complementary institutions necessary for efficient global allocation. Fragmented certification systems, weak interoperability of standards, underdeveloped long-term procurement frameworks, insufficient cross-border infrastructure, and high financing costs in developing economies all reduce the probability that structurally efficient projects secure stable demand. The World Bank, IEA, and industry studies increasingly highlight these coordination failures as major constraints on scaling global clean industrial investment (Arbache and Esteves, 2023; World Bank, 2023; IEA, 2023; Hydrogen Council, 2024).

This distinction is important. Some policies distort prices directly by artificially lowering costs in structurally inefficient locations. Other policy failures emerge because governments have not built the institutional architecture required for efficient prices to translate into investment at scale. The first distorts production decisions. The second prevents efficient projects from becoming bankable. Together, these mechanisms help explain why the geography of decarbonization is adjusting far more slowly than underlying economic fundamentals would predict.

A summary of some of the major policy instruments currently shaping effective prices, market access, and demand formation across jurisdictions is presented in Appendix Table A1.

5. A Simple Analytical Framework: Relative Prices, Policy Wedges, and Location Decisions

To formalize the argument, consider a stylized global economy with multiple potential production locations indexed by i, each characterized by distinct structural cost conditions and policy environments. Firms choose production locations by minimizing expected costs while accounting for market access and financing constraints.

This framework departs from conventional asset-accounting approaches in an important respect. Many wealth-accounting frameworks intentionally avoid making strong assumptions about future commodity prices and future rents in order to preserve statistical neutrality. While such caution may be appropriate for long-term accounting exercises, it is less useful for understanding investment behavior in rapidly changing transition sectors. In emerging green industries, expected rents are increasingly shaped by climate policy credibility, expected carbon prices, certification systems, technological learning, trade policy, and geopolitical risks. Investors are therefore responding not to static expectations, but to dynamic expectations regarding the future evolution of relative prices.

Let the structural unit cost of producing a low-carbon good in location i be defined as:

$$C_i^S = \alpha E_i + \beta V_i + \gamma K_i$$

where i indexes potential production locations. C_i^Srepresents the structural unit cost of producing the good in location i under undistorted market conditions. E_i denotes the cost of clean energy delivered at the point of industrial use in location i. V_i captures other variable production inputs, including labor, feedstocks, logistics, and intermediate goods. K_i represents capital-related costs, including financing costs, infrastructure requirements, and fixed investment expenditures. The parameters α, β, and γrepresent the cost-share weights of each input category, normalized such that $\alpha + \beta + \gamma = 1$. In many hard-to-abate sectors, α is relatively large because energy costs account for a substantial share of total production costs.

Under standard competitive conditions, firms would allocate production toward locations that minimize C_i^S, reinforcing comparative advantages based on clean energy abundance, natural resource endowments, and other structural cost advantages.

However, firms do not respond to structural costs alone. They respond to effective costs that incorporate policy distortions associated with both production and market access:

$$C_{id}^{eff} = C_i^S - \sigma_i + \tau_{id} + \rho_{id}$$

where d indexes destination markets. C_{id}^{eff}represents the effective cost of producing in location i and selling into destination market d. σ_i captures domestic subsidies, tax credits, and other policy incentives that reduce production costs in location i. τ_{id} represents tariffs, trade barriers, and transport-related costs associated with exporting from location i to destination market d. ρ_{id} captures regulatory compliance costs, certification requirements, and other market-access frictions that vary across jurisdictions.

Firms therefore choose production locations according to:

$$i^* = \arg\min{}_i \, C_{id}^{eff}$$

where i^* represents the cost-minimizing production location. In other words, firms choose the location that minimizes effective production costs after accounting for both structural cost conditions and policy distortions.

This formulation captures the central mechanism of the paper: location decisions are increasingly driven by policy-adjusted effective prices rather than underlying structural costs. When subsidies, trade barriers, and regulatory frictions become sufficiently large, observed competitiveness can diverge sharply from comparative advantage. In extreme cases, structurally high-cost locations may become more attractive than naturally efficient ones. This divergence helps explain why the observed geography of green industrial investment frequently differs from what underlying cost fundamentals would predict.

6. Demand Uncertainty and the Bankability Constraint

Cost distortions alone do not fully explain slow investment reallocation. Even when structurally efficient producers possess substantial cost advantages, projects frequently fail to move forward because firms face uncertainty regarding future demand. Emerging green industries often operate in markets characterized by uncertain regulatory frameworks, fragmented certification systems, evolving emissions standards, and weak long-term purchasing commitments. Producers may therefore be highly competitive from a production-cost perspective while still facing considerable uncertainty about whether their output will be recognized, certified, and purchased in final destination markets.

To capture this second constraint, let P_d denote the expected market price that producers receive in destination market d. Let π_{id} represent the probability that output produced in location i will successfully secure market access in destination market d. This probability reflects factors such as certification recognition, regulatory approval, long-term offtake agreements, trade rules, and broader policy credibility. A value of $\pi_{id} = 1$ implies full certainty of market access, while lower values reflect greater uncertainty regarding future demand realization.

Projects become financially viable only when expected revenues are sufficient to cover operating costs and generate the minimum return required by investors. Let C_{id}^{op} denote the effective operating cost of production in location i selling to market

id

d — that is, the variable cost component of C^{eff}, excluding upfront capital expenditure. Projects move to financial close only when:

$$\pi_{id} \cdot P_d \geq C_{id}^{op} + r \cdot K_i$$

where C_{id}^{op} represents effective variable production costs (energy, labor, feedstocks, logistics, and policy-related compliance costs, net of operating subsidies), r denotes the minimum rate of return required by investors, and K_i represents the upfront capital investment required in location i. The left-hand side captures expected revenue after discounting for market-access uncertainty; the right-hand side captures total cost recovery requirements, combining operating costs and the capital return threshold. This formulation is consistent with the structural cost framework in the previous section: K_i enters both C_i^S (as the capital cost component determining structural competitiveness) and the bankability constraint (as the investment scale that must generate adequate return). The bankability condition adds a distinct element: even when structural and effective costs are competitive, projects remain unbankable if π_{id} is sufficiently low — that is, if market-access uncertainty prevents expected revenues from covering financing requirements.

This framework introduces a second distortion channel. Even when structural production costs are low, projects may fail because uncertainty surrounding certification recognition, long-term procurement arrangements, trade rules, or policy stability reduces the probability of securing demand. In such cases, projects fail not because they are structurally uncompetitive, but because they remain unbankable.

The problem is further compounded by institutional gaps. Many governments have focused heavily on supply-side subsidies while underinvesting in the institutional architecture necessary for global market formation. Fragmented certification systems, weak interoperability of standards, inadequate transmission infrastructure, limited cross-border financing mechanisms, and insufficient long-term procurement frameworks all reduce project bankability.

It is also important to acknowledge that structural advantages in renewable-rich economies can be partially offset by domestic institutional and supply-side risks. Regulatory unpredictability, land and water governance constraints, currency volatility, and limited execution capacity can raise the effective cost of capital and reduce π_{id} even in locations with excellent physical fundamentals. Addressing these domestic institutional gaps is therefore a necessary complement to international coordination efforts.

The policy problem is therefore twofold. Some governments distort prices too aggressively through subsidies, tax credits, and trade barriers that lower effective costs in structurally inefficient locations. Others fail to create the institutional conditions required for efficient prices to translate into investment at scale — leaving structurally competitive producers unable to secure bankable demand. Together, these distortions significantly slow the geographic reallocation of production.

Importantly, the two mechanisms are not fully independent. Policy interventions that subsidize domestic production in destination markets (increasing σ_i for producers in d) often also reduce π_{id} for external producers by creating regulatory eligibility barriers, certification complexity, and uncertainty about long-term market access — particularly when domestic subsidy programs are accompanied by local-content preferences or standards that implicitly favor domestic supply. Conversely, institutional failures that reduce π_{id} can amplify the relative attractiveness of subsidized domestic production in destination market d, reinforcing misallocation even when the price distortions alone would be insufficient to reverse location decisions. The interaction between these two channels implies that the true cost of current policy fragmentation may be larger than the sum of its parts: price distortions and institutional gaps can compound each other, making the geography of decarbonization less efficient, less inclusive, and more costly than either mechanism in isolation would suggest. The following section calibrates the magnitudes of these distortions using sectoral evidence, before turning to their aggregate implications.

7. Calibration: Orders of Magnitude and Policy Distortions

The objective of the following examples is not econometric identification, but disciplined calibration of the mechanisms described above using observable sectoral evidence. The analytical mechanisms described in the previous sections are only economically meaningful if the magnitude of policy distortions is sufficiently large relative to underlying structural cost differentials. If policy interventions were small compared to differences in production costs across countries, their impact on global investment allocation would be limited. Existing evidence suggests that this is often not the case. In several sectors that are central to industrial decarbonization, current policy interventions are large enough to materially alter competitiveness rankings across locations and redirect investment toward structurally less efficient jurisdictions.

Green hydrogen illustrates the mechanism most clearly. As documented above, LCOH varies widely across jurisdictions — from roughly USD 1.5–2.5/kg in renewable-rich economies such as Brazil, Chile, and Australia by 2030 (BloombergNEF, 2024) to USD 4–6/kg or more in structurally higher-cost locations in Europe, Japan, and Korea (IEA, 2023). Under normal market conditions, these differentials would concentrate large-scale production in lower-cost geographies. The key question for calibration is whether current policy interventions are large enough to offset these structural advantages. The evidence suggests they often are. In the United States, the IRA's Section 45V Clean Hydrogen Production Tax Credit provides up to USD 3/kg for qualifying projects over ten years (U.S. IRS, 2024; U.S. DoE, 2024) — a wedge that can approach or exceed the entire structural cost advantage of the most competitive renewable-rich exporters. In Europe, the first European Hydrogen Bank auction awarded subsidies of approximately €0.37–0.48/kg, while H2Global relies on long-term contracts to reduce revenue uncertainty and improve project bankability (EC, 2024a,b; H2Global Foundation, 2024). These interventions do not eliminate the structural advantages of lower-cost producers, but they can materially narrow differentials and redirect investment toward structurally less efficient locations.

A similar pattern is visible in sustainable aviation fuels, where structural production costs vary significantly across regions due to differences in feedstock availability, agricultural productivity, renewable energy costs, and existing industrial capabilities. According to the IEA (2023, 2024), SAF currently remains substantially more expensive than conventional jet fuel, with production costs typically ranging from approximately USD 1,200 to more than USD 3,500 per ton depending on the technological pathway and feedstock used. Countries such as Brazil benefit from relatively low-cost sugarcane ethanol, large-scale biomass availability, established biofuel infrastructure, and accumulated technological experience. McKinsey (2024) estimates that Brazil could emerge among the lowest-cost global producers of alcohol-to-jet SAF due to its sugarcane-based ethanol platform and lower feedstock costs. As ICAO (2024) and ICCT (2025) document, feedstock costs often represent the largest share of total SAF production costs, particularly in HEFA and Alcohol-to-Jet pathways — creating cross-country cost differentials that can reach several hundred dollars per ton depending on biomass type, agricultural productivity, and local processing infrastructure.

Under normal market conditions, these structural advantages would encourage greater production expansion in lower-cost geographies. However, policy interventions increasingly reshape effective competitiveness. In the United States, the IRA created a SAF blender's tax credit of USD 1.25 per gallon, rising to USD 1.75 per gallon depending on lifecycle emissions reductions, materially improving the economics of domestic production (U.S. IRS, 2024). In Europe, European Union's ReFuelEU Aviation regulation establishes mandatory SAF blending targets—2% in 2025, 6% in 2030, and progressively higher thereafter—while imposing certification and traceability requirements that may increase compliance costs for foreign producers (EC, 2024a,b; EUR-Lex, Regulation (EU) 2023/2405). As a result, producers located in structurally efficient regions may still face considerable uncertainty regarding whether their fuels will secure regulatory recognition and long-term market access in major importing economies.

The aluminum sector adds a further dimension to this argument, because electricity systems simultaneously shape both production costs and emissions intensity — making location decisions consequential for competitiveness and climate outcomes at once. Primary aluminum production typically requires approximately 13–15 MWh of electricity per ton of output, making it one of the most electricity-intensive industrial products in the global economy (IEA, 2024; IAI, 2023). Electricity frequently accounts for roughly 30–40 percent of total smelting costs, meaning that differences in power prices directly affect competitiveness across locations. At the same time, emissions intensity varies dramatically depending on the electricity source. According to the IAI (2021), primary aluminum produced in hydro-based systems such as Canada, Norway, Iceland, and Brazil often generates roughly 4–6 tons of CO_2 per ton of aluminum, while coal-intensive production systems can generate approximately 16–20 tons per ton, and in some cases more depending on grid carbon intensity. This dispersion is economically significant because International Aluminium Institute data show that China currently accounts for roughly 60 percent of global primary aluminum production, much of it historically concentrated in coal-intensive regions, although some capacity has gradually migrated toward hydropower-rich provinces such as Yunnan. The IEA also projects growing demand for aluminum in electricity grids, electric vehicles, renewable infrastructure, and broader clean energy technologies. Even partial relocation of future incremental production toward low-carbon electricity systems could therefore generate substantial emissions reductions at relatively low cost. Yet such relocation remains limited because investment decisions continue to be shaped by legacy industrial structures, trade barriers, long-term contracts, and policy distortions.

These examples illustrate a broader point. Policy distortions do not need to be large relative to total production costs in order to alter global investment decisions.

They only need to exceed the underlying structural cost differentials between competing locations. In many green industrial sectors, those cost differentials are often measured in tens rather than hundreds of percentage points. This places them well within the range of existing subsidies, tax incentives, regulatory barriers, and market-access restrictions currently observed across major economies. This helps explain why distorted relative prices have become such a powerful determinant of the emerging geography of decarbonization.

8. Misallocation and Static Inefficiency: From Micro Distortions to Aggregate Losses

The analytical framework developed in previous sections implies that distorted relative prices can redirect investment toward structurally inefficient locations. This section provides a simple quantitative illustration of that mechanism. The objective is not precise forecasting, but to demonstrate how relatively small policy distortions can alter marginal investment decisions and generate large aggregate inefficiencies when repeated across sectors expected to scale rapidly under decarbonization.

The section proceeds in two steps. First, it illustrates how policy wedges can reverse location decisions at the project level. Second, it shows how repeated micro-level distortions can scale into large aggregate losses when applied to major industrial sectors.

8.1 Micro-level investment distortions

Consider a stylized setting with two regions. Region A represents a renewable-rich economy with low structural production costs. Region B represents a higher-cost industrial economy. Under normal market conditions, firms allocate production to the location with lower structural costs. However, subsidies, trade barriers, and regulatory frictions can alter effective costs and reverse this decision. Table 2 presents stylized scenarios based on cost differentials commonly observed in energy-intensive sectors such as hydrogen, low-carbon metals, and sustainable fuels.

Table 2. Stylized project-level distortions and investment allocation

Scenario	C^S_A	C^S_B	Policy Wedge in A	Policy Wedge in B	C^{eff}_A	C^{eff}_B	Location	Ineff.
Baseline (no distortion)	100	150	0	0	100	150	A	0
Moderate subsidy in B	100	150	0	−40	100	110	A	0
Strong subsidy in B	100	150	0	−60	100	90	B	50
Subsidy in B + trade barrier on A exports	100	150	+20	−60	120	90	B	50
Regulatory penalty on A + subsidy in B	100	150	+20	−50	120	100	B	50

Notes: Policy Wedge in A captures costs imposed on Region A producers — including tariffs, trade barriers, and regulatory compliance costs (ρ_{id}) when accessing destination market d. Policy Wedge in B captures subsidies and tax incentives (σ_i) that reduce effective costs in Region B. Negative values represent cost reductions; positive values represent additional costs imposed. Inefficiency is measured as the excess structural cost incurred by producing in B rather than A: $C^S_B - C^S_A = 50$ in all distorted scenarios.

The baseline scenario reflects efficient allocation: production occurs in Region A because structural costs are lower. As policy support in Region B increases, the effective cost gap narrows. Once policy wedges exceed underlying structural cost differences, investment is redirected toward Region B despite its higher structural costs.

The resulting inefficiency equals the difference between the structural cost of production in the chosen location and the lowest-cost alternative. In this example, producing in Region B instead of Region A increases costs by USD 50 per unit. This gap must ultimately be absorbed through higher consumer prices, fiscal transfers, lower corporate margins, or slower deployment.

The key implication is straightforward: distortions do not need to be large relative to total production costs to alter outcomes. They only need to exceed cross-country cost differentials.

8.2 Aggregate implications of repeated misallocation

Project-level distortions become far more consequential when repeated across sectors expected to expand rapidly during decarbonization. Even modest inefficiencies can generate large aggregate losses when applied to very large industrial markets.

To illustrate this scaling effect, consider three sectors expected to expand substantially under deep decarbonization scenarios: green hydrogen, sustainable aviation fuels, and low-carbon aluminum. Assume that renewable-rich producers possess structural cost advantages due to lower electricity costs, better renewable resources, cleaner energy systems, or lower feedstock costs. Assume further that policy interventions partially offset these advantages through subsidies, tax incentives, regulatory preferences, or trade barriers. Table 3 presents stylized aggregate scenarios.

Table 3. Illustrative aggregate cost implications of repeated misallocation (projected mid-2030s scenarios)

Sector	Projected annual output value (mid-2030s, USD bn)	Illustrative cost penalty from misallocation (%)	Estimated annual additional global cost (USD bn)
Green hydrogen	300	15	45
Sustainable aviation fuels	150	20	30
Low-carbon aluminum	250	10	25

Notes: Projected market sizes reflect mid-2030s expansion scenarios drawn from IEA World Energy Outlook 2023, IRENA World Energy Transitions Outlook 2022, ICAO 2050 Net Zero roadmap, and sectoral industry assessments. These projections assume substantial but not maximal policy ambition and represent order-of-magnitude reference values rather than point estimates. The cost penalty percentages represent the additional production cost incurred by misallocated investment relative to a counterfactual in which the same output is produced in structurally lower-cost locations; they are applied to projected output value as a proportional proxy for production costs, and are calibrated to be consistent with the policy wedge magnitudes documented in Section 7. These estimates should be interpreted as illustrative of the direction and scale of misallocation costs, not as forecasts. They do not capture slower technological learning, persistent fiscal burdens, downstream inflationary pressures, delayed emissions reductions, or lost industrial development opportunities in structurally competitive emerging economies — channels that are addressed qualitatively in Section 9.

Under these stylized assumptions, annual inefficiencies could plausibly reach tens of billions of dollars—and potentially more as these sectors scale. These estimates should not be interpreted as forecasts. Their purpose is simply to illustrate how repeated micro-level distortions can produce large macroeconomic consequences.

The broader implication is that small distortions applied repeatedly across large sectors can generate substantial global inefficiencies. The current geography of decarbonization may therefore be considerably more expensive than necessary—not because clean technologies are inherently too costly, but because distorted relative prices continue to redirect investment away from structurally efficient locations.

9. Dynamic Inefficiencies and Long-Term Structural Consequences

The static inefficiencies discussed in the previous section likely understate the full economic consequences of distorted investment allocation. The largest costs may emerge dynamically over time through technological lock-in, slower learning effects, persistent fiscal burdens, supply chain rigidities, delayed emissions reductions, and weaker development outcomes. These effects are particularly important because industrial investments in infrastructure-intensive sectors often generate path dependence. Once production facilities, logistics systems, supplier networks, regulatory frameworks, and technological ecosystems become concentrated in particular locations, relocation becomes significantly more difficult. Early distortions may therefore shape industrial geography for decades through mechanisms widely studied in the literature on increasing returns and technological lock-in (Arthur, 1989; David, 1985).

Learning effects represent one of the most important channels through which early distortions can generate long-term costs. In many clean technologies, costs decline through cumulative deployment, scale economies, operational experience, and supply chain maturation. The economics literature has long documented the role of learning-by-doing in reducing production costs over time (Arrow, 1962; Wright, 1936). More recent work shows that accelerated deployment can substantially reduce long-term clean technology costs through endogenous learning effects (Nemet, 2019; Way et al., 2022). It is important to acknowledge that, in certain contexts, subsidizing deployment in initially higher-cost locations can accelerate global learning if it rapidly increases cumulative production volumes. However, this dynamic benefit is bounded: when investment is systematically locked into structurally inefficient locations, the baseline cost curve remains elevated, learning occurs at a higher starting point, and the long-run slope of cost reduction tends to flatten relative to a scenario where scale expands in naturally efficient environments. The result may be slower cost declines and delayed diffusion of low-carbon technologies.

Fiscal costs represent a second dynamic distortion. Sustained reliance on subsidies, tax incentives, and other forms of industrial support can create significant long-term fiscal burdens. While temporary support may be justified in the presence of market failures or infant industry dynamics, persistent subsidy competition can become increasingly expensive and politically difficult to sustain. Recent OECD work highlights both the growing scale of green industrial policy interventions and the risks associated with poorly coordinated subsidy competition across jurisdictions (OECD, 2023, 2024). Similar concerns have been raised in the context of geoeconomic fragmentation and growing industrial policy competition (IMF, 2023).

These distortions may also propagate through value chains. Many low-carbon sectors supply critical inputs for downstream industries. Aluminum affects transportation, construction, transmission systems, and renewable infrastructure. Green hydrogen affects fertilizers, steel, chemicals, and shipping fuels. Sustainable aviation fuels affect airlines and logistics systems. When upstream inputs are produced in artificially high-cost locations, these costs can cascade across downstream sectors, increasing broader decarbonization costs and weakening competitiveness in industries that rely on these inputs. This problem becomes particularly important when industrial policy focuses excessively on individual plants rather than broader production networks (IEA, 2023; OECD, 2024; Arbache, 2026e).

Climate outcomes may also worsen. Higher production costs slow deployment, delay emissions reductions, and may increase political resistance to decarbonization by raising consumer prices and industrial adjustment costs. The

IEA has repeatedly emphasized that speed of deployment is central to achieving net-zero targets (IEA, 2023). If distorted allocation slows investment in structurally efficient locations, decarbonization may become both slower and more expensive than necessary. This reinforces the argument that trade can function as a mechanism of climate efficiency by allowing production to expand where emissions reductions are cheapest and fastest (Arbache, 2025d).

These distortions may also generate unintended geopolitical consequences. Many current industrial policies are justified on resilience grounds. Governments increasingly seek to reduce dependence on concentrated suppliers and improve national supply security. These concerns are legitimate, particularly after disruptions associated with the pandemic, geopolitical tensions, and rising supply chain vulnerabilities. However, the relationship between domestic production concentration and resilience is more complex than industrial policy narratives often suggest. Excessive reshoring or full duplication of supply chains can reduce efficiency and increase costs without necessarily improving supply security — particularly when domestic production depends on imported inputs or when the risk being managed is technological rather than geographic. Diversified international production networks can, in some configurations, provide greater resilience than full domestic concentration by distributing exposure across multiple suppliers and geographies (IMF, 2023; OECD, 2025; Arbache, 2025c). That said, the optimal degree of geographic diversification depends on the specific risk profile of each sector: supply chains exposed to geopolitical disruption, export restrictions, or highly concentrated upstream inputs may justify a higher degree of domestic capacity than sectors characterized by competitive, multi-polar global supply. The policy implication is therefore not that resilience concerns are illegitimate, but that they should be assessed sector-specifically and with explicit recognition of the efficiency costs of each resilience strategy.

The developmental implications are equally important. Many emerging economies possess abundant renewable resources, critical minerals, land, water, and biomass that could support industrial upgrading. If current policy distortions continue to suppress investment in structurally efficient regions, developing economies may remain concentrated in lower-value segments of global trade while higher-value industrial activities remain concentrated elsewhere. This would replicate familiar patterns of uneven industrial development documented in the trade and development literature (World Bank, 2020; UNCTAD, 2023; Arbache and Esteves, 2023; Arbache, 2025a).

Finally, climate change itself may amplify these inefficiencies over time. Physical climate risks are increasingly affecting water availability, agricultural productivity, infrastructure resilience, and energy systems. These dynamics may further alter the relative prices of geographically fixed assets in ways that existing investment strategies still fail to fully incorporate.

Taken together, these dynamic effects suggest that current distortions generate far more than short-term inefficiencies. They may shape the future geography of industrial production, technological leadership, fiscal sustainability, global development, and the speed of decarbonization itself. The costs of getting location decisions wrong today may persist for decades.

10. Value Chains, Rematerialization, and the Return of Geography

Much of the public debate surrounding industrial relocation implicitly assumes that entire industries move across borders as integrated units. This assumption is increasingly inconsistent with how global production is organized. Modern production systems are structured through fragmented global value chains in which different stages of production are distributed across multiple jurisdictions according to cost structures, technological capabilities, logistics conditions, regulatory environments, and market access considerations (Gereffi et al, 2005; Baldwin, 2016; World Bank, 2020).

This distinction is particularly important in the context of industrial decarbonization. In many sectors, the economically relevant question is not whether entire industries relocate, but whether specific energy-intensive upstream stages of production move toward locations with lower structural costs. Downstream activities may remain close to consumer markets, technological ecosystems, or final demand centers, while upstream production increasingly shifts toward regions with abundant renewable energy, lower emissions intensity, and favorable natural resource conditions. This logic is particularly visible in aluminum, fertilizers, hydrogen derivatives, chemicals, and sustainable fuels, where energy-intensive intermediate inputs account for a large share of total costs (IEA, 2023; Energy Transitions Commission, 2023).

A low-carbon aluminum producer, for example, may relocate smelting operations to regions with abundant hydropower while maintaining downstream fabrication facilities near major manufacturing hubs. Sustainable aviation fuel supply chains may combine agricultural production, refining, logistics, certification systems, and final demand across multiple jurisdictions. These patterns suggest that decarbonization may produce a more geographically distributed industrial architecture rather than simple reshoring or full industrial relocation. This perspective also helps explain why many current policy debates remain incomplete. Much of the reshoring debate assumes that resilience requires the domestic replication of complete supply chains. In reality, resilience may often be better achieved through diversified international specialization rather than excessive domestic concentration (IMF, 2023; Arbache, 2025a,c).

These dynamics also challenge an influential strand of late twentieth-century economic thought that predicted the declining importance of geography. The "weightless economy" thesis argued that digitalization, services expansion, declining transport costs, and the growing role of intangible assets would progressively reduce the importance of physical geography in economic organization (Quah, 1999). Similar arguments emerged in broader globalization literature that emphasized the declining importance of distance and physical location.

These arguments captured important structural changes in advanced economies, particularly the rising importance of services, intangible capital, digital platforms, and knowledge-intensive sectors. However, they underestimated the continued material foundations of the global economy and failed to anticipate the large-scale rematerialization associated with decarbonization (Arbache, 2026b).

The clean energy transition is extraordinarily material-intensive. Electrification requires vast quantities of copper, aluminum, steel, cement, lithium, nickel, rare earths, transmission infrastructure, land, water, and renewable generation assets. The IEA projects major increases in demand for critical minerals and industrial materials under net-zero scenarios, while the Energy Transitions Commission has similarly emphasized the scale of material requirements embedded in clean infrastructure expansion (IEA, 2023; Energy Transitions Commission, 2023).

What is emerging is not a dematerialized economy, but a differently material economy. The transition reduces dependence on fossil fuel extraction while increasing dependence on geographically specific renewable resources, industrial minerals, infrastructure systems, and natural capital. Geography is therefore not disappearing—it is returning in a different form.

This helps explain why decarbonization is simultaneously a climate transition, an industrial transition, and a spatial reorganization of global production. Countries endowed with favorable combinations of renewable energy, natural capital, logistics infrastructure, and industrial capabilities may occupy increasingly strategic positions in future value chains. The geography of development opportunities may therefore broaden—but only if global policy frameworks allow efficient specialization to emerge.

11. Policy Implications: From Protection to Coordination

The analysis developed in this paper does not imply that governments should withdraw from industrial policy or abandon intervention in strategic sectors. Such a conclusion would be both unrealistic and analytically weak. Governments face legitimate concerns related to learning externalities, national security, resilience, political feasibility, coordination failures, and technological uncertainty. In many cases, temporary intervention may be necessary to accelerate early-stage deployment, support innovation, and reduce dependence on highly concentrated supply chains. The problem identified in this paper is not intervention per se, but the growing divergence between industrial policy objectives and global allocative efficiency.

A central distinction must therefore be made between policies that accelerate movement toward structurally efficient production and policies that indefinitely compensate for structural disadvantages. The former can reduce long-run global costs, accelerate technological diffusion, and expand supply. The latter may preserve domestic production in the short run, but often at the cost of higher fiscal expenditures, slower global deployment, and higher input prices across value chains. Operationalizing this distinction requires transparent sunset clauses, performance-based support tied to cost-reduction milestones, and regular independent assessments of whether subsidies are converging toward structural efficiency or merely entrenching higher-cost baselines. This distinction becomes particularly important in sectors where geography plays a central role in cost structures. In renewable-intensive industries, the objective of maintaining every stage of production domestically may become increasingly expensive as differences in delivered clean energy costs widen across countries. Attempting to override these structural realities indefinitely may generate growing fiscal burdens and weaken downstream competitiveness.

A more efficient approach would combine domestic strategic capabilities with greater international specialization. Rather than attempting to replicate complete supply chains in every major economy, policymakers could focus on securing resilience through diversification. This would involve allowing upstream production to expand in structurally efficient renewable-rich locations while preserving downstream industrial capabilities closer to consumer markets. This is precisely the logic of powershoring: rather than reshoring entire industries, advanced economies could anchor downstream value-added activities domestically while allowing energy-intensive upstream stages to relocate toward regions where clean energy is structurally cheaper and more abundant. Powershoring thus offers a framework for reconciling industrial policy, resilience, and allocative efficiency — not by eliminating specialization, but by aligning it with the new geography of clean energy costs.

Such an approach would require new forms of international coordination. Harmonized certification systems, interoperable carbon accounting methodologies, long-term procurement frameworks, trade agreements for low-carbon goods, and financing mechanisms for projects in developing economies would all help reduce current inefficiencies. The absence of such coordination is increasingly costly. Fragmented regulatory systems create uncertainty for investors and reduce the probability that structurally efficient projects reach financial closure. In many sectors, the challenge is no longer technological feasibility. It is institutional coordination. A more efficient decarbonization architecture would therefore rely less on permanent protection and more on international coordination mechanisms that allow comparative advantage to operate within climate-compatible rules. The argument here is therefore not against industrial policy. It is an argument for better-targeted industrial policy operating under global efficiency constraints.

12. Development Implications: The Geography of New Industrial Opportunities

The developmental implications of current investment distortions are potentially profound. Many emerging and developing economies possess structural advantages that could position them as major participants in low-carbon industrialization. Abundant renewable energy resources, critical minerals, land availability, biomass potential, water resources, and relatively low production costs create favorable conditions for a new generation of energy-intensive industries. These structural advantages are becoming increasingly important as decarbonization reshapes global production patterns and alters the geography of comparative advantage.

These opportunities are increasingly visible in specific sectors and geographies. Brazil possesses structural advantages in sustainable aviation fuels, green ammonia, low-carbon aluminum, fertilizers, and green chemicals due to abundant biomass resources, a mature ethanol industry, and a relatively clean electricity matrix. Chile has emerged as a major candidate for green hydrogen and ammonia production due to exceptional solar resources. Countries such as Saudi Arabia, Oman, and the United Arab Emirates are investing heavily in hydrogen and synthetic fuels by combining low-cost renewable energy with large-scale infrastructure. In Africa, countries such as Namibia, Mauritania, Morocco, and Egypt are increasingly attracting investment in hydrogen derivatives and green industrial hubs. Indonesia has sought to leverage its nickel reserves to move into battery value chains, while Australia is expanding its role in hydrogen and critical mineral processing (IEA, 2023; IRENA, 2022b; UNCTAD, 2023).

The developmental significance of these sectors extends well beyond commodity exports. Green ammonia can support domestic fertilizer industries and broader chemical upgrading. Low-carbon aluminum and green steel can anchor more sophisticated manufacturing chains. Sustainable aviation fuels create opportunities that combine agriculture, industrial processing, logistics, certification systems, and export infrastructure. Critical minerals processing creates opportunities to move beyond raw extraction toward refining, precursor materials, and advanced manufacturing. In many cases, the relevant opportunity is not the relocation of entire industries, but the relocation of higher-value upstream stages of production that were historically concentrated elsewhere. This logic aligns with broader literature on global value chains, upgrading, and industrial diversification (Gereffi et al., 2005; World Bank, 2020).

For many developing economies, this may represent one of the largest industrial opportunities in decades. Compared to previous waves of industrialization — where latecomers often faced high technological barriers, dominant incumbents, and sharply shrinking opportunities in labor-intensive manufacturing — several energy-intensive low-carbon sectors retain a degree of geographic openness that creates meaningful entry possibilities for resource-rich economies. This is most evident in sectors where structural cost advantages linked to renewable energy, biomass, or mineral endowments are large enough to offset technological learning gaps — green hydrogen, ammonia, sustainable aviation fuels, low-carbon aluminum, and certain stages of critical mineral processing among them. In these activities, the global geography of production has not yet fully consolidated, and new comparative advantages linked to renewable resources and natural capital are actively shaping investment allocation.

It is important, however, to distinguish this from a claim that low-carbon sectors are uniformly open to late entry. Several upstream technology segments — electrolyzer manufacturing, battery cell production, power electronics, and solar PV module fabrication — already exhibit significant geographic concentration, substantial first-mover advantages, and technological barriers that limit rapid entry by countries without prior industrial capabilities. The development opportunity is therefore not symmetrically distributed across all green sectors: it is most accessible in energy-intensive processing stages where structural resource advantages are large, and more limited in technology-intensive manufacturing stages where learning curves and incumbent concentration dominate (Hausmann et al., 2007; Rodrik, 2013; UNCTAD, 2023).

Even where these entry opportunities are structurally accessible, however, their realization is far from guaranteed. If current policy distortions continue to suppress investment in structurally efficient locations, existing industrial concentration patterns may become even more entrenched. Advanced economies may attract large volumes of investment, but at significantly higher global costs and with reduced opportunities for broader developmental diffusion. This would replicate a familiar historical pattern in which developing economies remain concentrated in lower-value segments of global trade while higher-value industrial activities remain concentrated elsewhere (Prebisch, 1950; Baldwin, 2016).

The irony is that the current transition creates unusually favorable conditions for breaking this pattern. The growing importance of renewable energy, natural capital, and geographically specific productive assets potentially broadens the set of countries capable of participating in industrial upgrading. But realizing that opportunity requires institutional frameworks that allow efficient cross-border specialization rather than systematically suppressing it. Trade, investment coordination, certification harmonization, infrastructure development, and financial de-risking mechanisms will be central to this process.

The stakes therefore extend beyond climate efficiency. They concern the future geography of industrial development itself. A decarbonization strategy that ignores comparative advantage may not only be more expensive and slower; it may also become significantly less inclusive. The alternative is a model of green industrialization that combines decarbonization, trade, and development more effectively by allowing structurally efficient regions to play a larger role in global production networks.

13. Welfare Implications: The Cost of Distorted Geography

The distortions examined throughout this paper ultimately generate welfare losses because production increasingly occurs in locations where costs exceed those that would prevail under an allocation guided by structural comparative advantage. These losses are distributed across three distinct channels, each operating at a different time horizon.

The first and most directly measurable channel is the static production cost gap. When output Q is produced at observed cost C_{obs} rather than at the structurally optimal cost C_{opt}, total global expenditure rises by:

$$\mathrm{WL} = (\mathrm{C_{obs}} - \mathrm{C_{opt}}) \cdot \mathrm{Q}$$

The calibrated scenarios in Section 8 provide an order-of-magnitude estimate of this component: across green hydrogen, sustainable aviation fuels, and low-carbon aluminum alone, static misallocation could generate excess annual costs on the order of USD 100 billion or more under mid-2030s market scale assumptions, even under conservative cost-penalty assumptions.

The second channel operates through slower technological learning. When deployment is systematically concentrated in higher-cost locations, the global cost curve for clean technologies declines more slowly. Following the learning-by-doing literature (Arrow, 1962; Wright, 1936; Way et al., 2022), if learning rates are approximately constant per unit of cumulative output, then the relevant question is not whether deployment is occurring, but where it is occurring and at what cost basis. Deployment at structurally higher cost implies that each unit of learning is purchased at greater expense, delaying the point at which technologies become self-sustaining without policy support. The dynamic welfare loss from this channel can be represented as the discounted value of the difference between the cost trajectories under efficient versus distorted allocation — a gap that compounds over time and is particularly important for technologies still early on their learning curves.

The third channel concerns distribution. The cost of distorted allocation does not fall uniformly. In advanced economies, it is absorbed partly through fiscal transfers (subsidies and tax expenditures) and partly through higher consumer prices for low-carbon goods. In structurally efficient economies — typically developing and emerging markets — it manifests as foregone industrial investment, lower export revenues, and delayed participation in higher-value global value chains. This distributional dimension has received limited attention in the green industrial policy literature, but it may prove economically and politically important: if current distortions persist, structurally competitive economies face the perverse outcome of paying more for their own decarbonization while simultaneously losing the industrial opportunities that their resource endowments should generate.

Taken together, these three channels suggest that the welfare cost of the current geography of decarbonization is substantially larger than static estimates imply, more persistent than transitory policy interventions would justify, and more unequally distributed than is commonly acknowledged in mainstream policy debates

14. Conclusion

This paper has argued that the global decarbonization challenge is frequently misunderstood because it is often treated primarily as a technological problem. While technological innovation remains essential, the transition is equally a problem of economic geography, relative prices, institutional coordination, and global production reallocation.

As clean energy, natural capital, and location-specific productive assets become increasingly central to industrial competitiveness, geography is re-emerging as a major determinant of comparative advantage. In many energy-intensive sectors, renewable-rich economies possess substantial structural cost advantages that should attract significantly larger shares of global investment. Yet this reallocation remains incomplete.

The paper identifies two major distortions that help explain this outcome. The first is the growing divergence between structural costs and effective prices created by subsidies, tax incentives, trade barriers, certification systems, and regulatory fragmentation. These distortions often redirect investment toward structurally inefficient locations. The second is demand uncertainty. Even when production costs are highly competitive, projects frequently fail because firms face uncertainty regarding certification recognition, long-term procurement arrangements, and future market access.

Together, these distortions generate much broader consequences than static inefficiency alone. They slow technological learning, increase fiscal burdens, raise costs across value chains, delay emissions reductions, reinforce industrial concentration, and suppress development opportunities in renewable-rich emerging economies.

The paper also argues that decarbonization is accelerating a broader rematerialization of the global economy. Contrary to earlier predictions that geography would become less important in an increasingly digital world, the transition is increasing dependence on physically immobile assets such as renewable resources, minerals, land, water, transmission systems, and industrial infrastructure. Geography is not disappearing. It is returning in new forms — and doing so in ways that create structural incentives for production to relocate toward regions endowed with abundant clean energy and natural capital. Powershoring captures this logic: as the energy-intensity of industrial production interacts with the spatial fixity of renewable resources, the efficient organization of global production increasingly requires upstream activities to follow energy geography rather than market proximity. Whether this reorganization occurs at scale will depend on whether global policy frameworks allow it — or continue to suppress it through sustained price distortions and institutional fragmentation.

This transformation creates both risks and opportunities. If current policy distortions intensify, the global economy may pursue a decarbonization pathway that is slower, more expensive, more concentrated, and less inclusive than necessary. If policy frameworks evolve toward greater coordination, interoperability, and efficient international specialization, decarbonization could become faster, cheaper, and more development-friendly.

he central policy challenge is therefore not whether governments should intervene. Governments inevitably will. The more important challenge is whether intervention helps align climate goals, economic efficiency, resilience, and broader development opportunities in a world where the geography of production is being fundamentally reorganized. In that sense, the future of decarbonization may depend less on whether the world can invent enough clean technologies—and more on whether it can allow those technologies to be deployed where economics, geography, and physics suggest they should be.

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Annex

Table A1: Selected policy interventions affecting effective costs, market access, and demand in green industrial sectors

Jurisdiction	Instrument / measure	What it does in practice	Main distortion channel	Why it matters for powershoring	Official / recognized source
United States	IRA Section 45V – Clean Hydrogen Production Tax Credit	Provides a 10-year production tax credit for qualified clean hydrogen of up to USD 3/kg, with value tied to lifecycle emissions and labor conditions.	Lowers σ_i directly by reducing effective domestic production cost.	Can offset or even exceed structural cost advantages of renewable-rich exporters.	IRS; U.S. DOE
United States	IRA domestic content bonus credit	Offers a bonus credit when qualified facilities/projects meet thresholds for U.S.-made steel, iron, and manufactured products.	Raises the attractiveness of domestic sourcing; acts as a local-content preference.	Pushes investment toward U.S.-embedded supply chains even when upstream production may be cheaper elsewhere.	IRS; U.S. Treasury
United States	SAF credit (Section 40B / 6426(k))	Provides a tax credit of USD 1.25/gallon, plus up to USD 0.50/gallon extra	Subsidizes domestic or eligible SAF supply; changes	Narrows or reverses cost gaps between U.S.	IRS

Jurisdiction	Instrument / measure	What it does in practice	Main distortion channel	Why it matters for powershoring	Official / recognized source
		depending on lifecycle GHG reduction.	effective producer price.	production and lower-cost foreign producers.	
European Union	European Hydrogen Bank auctions	Awards a fixed premium per kg of certified renewable hydrogen for up to 10 years through competitive auctions.	Direct production support; lowers effective cost and reduces revenue risk.	Supports EU-based renewable hydrogen and helps projects reach FID in higher-cost jurisdictions.	European Commission; CINEA; IEA
European Union	RFNBO rules (additionality; temporal and geographic correlation)	Define when hydrogen can count as renewable under EU rules; require matching of renewable electricity in time and place, subject to specific criteria.	Raises ρ_{id} through compliance complexity and regulatory risk.	Can make cross-border hydrogen projects more costly or uncertain, especially for exporters.	European Commission; European Parliament briefing
European Union	ReFuelEU Aviation	Establishes a rising SAF mandate in aviation: the Commission	Creates demand, but only for fuels that meet EU eligibility and	Important because it creates offtake, but market	EUR-Lex; European Commission Transport

Jurisdiction	Instrument / measure	What it does in practice	Main distortion channel	Why it matters for powershoring	Official / recognized source
		notes the sector is on track for 2% in 2025 and 6% in 2030.	traceability rules.	access depends on regulatory recognition.	
European Union	CBAM	During the transitional phase (1 Oct 2023–31 Dec 2025) importers report embedded emissions; full implementation begins 1 Jan 2026. Covers sectors including fertilisers, iron and steel, aluminium and hydrogen.	Raises τ_{id} and compliance costs for imports into the EU.	Directly affects the tradability of low-carbon industrial goods from third countries.	EUR-Lex; European Parliament; Commission guidance
European Union	Net-Zero Industry Act (NZIA)	Sets the objective that EU strategic net-zero manufacturing capacity should approach or reach 40% of annual deployment needs by 2030.	Industrial-policy signal favoring EU manufacturing capacity and project acceleration.	Not a classic tariff, but a strong “produce in Europe” signal shaping expectations and	European Commission; Council / Parliament briefings

Jurisdiction	Instrument / measure	What it does in practice	Main distortion channel	Why it matters for powershoring	Official / recognized source
				location choices.	
Germany / EU-linked	H2Global	Uses long-term purchase contracts (typically 10 years) to give producers price, market, and legal certainty; designed to improve bankability. Some tenders target production outside the EU/EFTA.	Acts mainly on $\pi_{id}$and revenue certainty rather than only on production cost.	Especially relevant to your paper because it shows that demand support can unlock investment when offtake risk is the binding constraint.	H2Global / Hintco; BMWK
Canada	Clean Hydrogen Investment Tax Credit	Refundable investment tax credit of 15% to 40% of eligible capital cost, depending on the carbon intensity of the hydrogen produced.	Reduces capital cost; lowers effective cost via CAPEX support rather than output support.	Illustrates that hydrogen support is not only U.S./EU-driven and that policy wedges can arise through different	Government of Canada / CRA / NRCan

Jurisdiction	Instrument / measure	What it does in practice	Main distortion channel	Why it matters for powershoring	Official / recognized source
				instruments.	
Australia	Hydrogen Headstart	Provides revenue support through competitive hydrogen production contracts for large-scale renewable hydrogen projects; the National Hydrogen Strategy 2024 also states a USD 2/kg Hydrogen Production Tax Incentive.	Mix of revenue support and tax-based production support.	Another example of governments closing the gap between production cost and sale price through public intervention.	Australian Government

Notes*:* The table summarizes selected policy instruments in major economies that affect investment decisions in low-carbon industrial sectors. The focus is on mechanisms that alter effective production costs, restrict or shape market access, or support demand formation. “Effective costs” refer to production costs as perceived by firms after accounting for subsidies, tax credits, trade barriers, and regulatory compliance requirements. Policy instruments operate through distinct channels: (i) direct cost reductions (e.g., production or investment subsidies), (ii) trade-related measures (e.g., tariffs, local-content rules), and (iii) regulatory and certification frameworks that affect eligibility and compliance costs. Demand-side instruments include mandates, auctions, and long-term contracting schemes that improve revenue certainty and project bankability, thereby affecting investment decisions independently of production costs. The table is illustrative rather than exhaustive and focuses on policies with material economic impact as documented in official sources (e.g., IEA, European Commission, U.S. Treasury, national policy frameworks).

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