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Financing Green Industrial Transitions:

A Comparative Analysis of Implementation Effectiveness in Four Emerging Economies[1]

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ABSTRACT

Emerging economies confront unprecedented challenges mobilizing finance for green industrial transitions while maintaining development trajectories. This paper examines implementation effectiveness across India, South Africa, Brazil, and Indonesia—major economies representing diverse political systems, economic structures, and policy approaches—documenting systematic gaps between stated climate commitments and realized outcomes ranging from 33% to 77% of stated targets.

Through comparative analysis of policy frameworks, financing architectures, and sectoral dynamics spanning renewable energy, industrial decarbonization, sustainable agriculture, and just transitions, we reveal that aggregate capital availability constitutes only partial explanation. Firm-level financial constraints systematically structure which technologies firms can adopt constrained firms pursue incrementally cleaner but emission-intensive options, while only unconstrained firms access frontier low-emission technologies. This "pecking order" mechanism—predicted by recent theoretical work and validated across four diverse country contexts—generates three fundamental policy challenges.

Three critical implications emerge. First, green credit must target frontier technologies precisely, yet such targeting creates politically challenging coverage gaps and exceeds institutional capacity. Second, blended finance exhibits fundamental tension between leverage maximization and genuine additionality. Third, just transition programs systematically underserve workers dependent on constrained firms unable to finance transitions.

Looking forward, financing effectiveness will depend increasingly on institutional autonomy rather than merely capital costs: capacity to navigate fragmented global financial architectures, preserve infrastructure control, and maintain policy space as geopolitical competition intensifies and debt burdens rise.

Keywords: green industrial policy, development finance, blended finance, financial constraints, just transitions, emerging economies.

JEL Classification: O38, L52, O16 G28, Q58.

1. Introduction

The mobilization of private finance for development has evolved considerably over the past century, progressing from early export credit agencies in the 1920s through Cold War-era development finance institutions to today's sophisticated blended finance mechanisms A critical inflection point occurred during the 1990s "Washington Consensus" era, which fundamentally reshaped capital flows to emerging economies through financial liberalization and market-based reforms. The 2015 Sustainable Development Goals further accelerated this trajectory, catalyzing explicit policies to mobilize private finance at unprecedented scale—moving from "billions to trillions" in development financing. However, despite this extensive infrastructure, private finance mobilization has been weakest precisely where it is most needed: in low-income countries facing the greatest development challenges. This historical pattern suggests that financing green industrial transitions in emerging economies depends less on creating novel financial mechanisms than on addressing fundamental implementation barriers including local enabling environments, institutional capacity, and the persistent misalignment between development objectives and investor risk-return expectations (Preston, 2025).

Emerging economies confront an unprecedented challenge: achieving rapid economic development while meeting ambitious climate commitments. This dual mandate requires mobilizing capital on historically unprecedented scales. UNCTAD (2023) estimates developing countries need USD 3.9-4.4 trillion annually for sustainable development, yet Climate Policy Initiative (2023) reports that only USD 326 billion (25%) of global climate finance reaches emerging economies excluding China. The persistent gap between requirements and deployment raises fundamental questions about implementation effectiveness of green industrial strategies.

Recent research highlights that financial constraints at the firm level represent a critical but underexplored dimension of this challenge. Capelle et al. (2025) demonstrate through analysis of European manufacturing firms that financially constrained firms are systematically less productive, more emission-intensive, and less capable of responding to carbon pricing. For emerging and developing economies, these constraints operate with greater severity and distinct characteristics. De Haas et al. (2024) show that credit-constrained European emerging market firms reduce green machinery and vehicle investment by 30-36 percentage points, translating into 4.5% higher aggregate CO_2 emissions—effects concentrated among small, young firms lacking redeployable collateral. The cost of capital amplifies these constraints: while German solar PV projects face weighted average costs of capital around 2.7%, comparable projects in India confront financing costs of 10.6%, and in Southeast Asian markets exceed 11%, rendering identical technologies economically unviable despite superior solar resources (Steffen, 2020). This financing penalty reflects accumulated institutional deficits—policy uncertainty, weak contract enforcement, currency risk exposure—that persist despite technology maturation and declining global interest rates (Egli et al., 2018, 2019). In developing countries, financing costs can comprise 40-50% of levelized costs for renewable energy projects compared to 12-37% in advanced economies, fundamentally altering investment decisions (Schmidt, 2014; Steffen, 2020). Moreover, foreign direct investment into emerging and developing economies has contracted from approximately 5% of GDP before the 2008 financial crisis to just over 2% today, reflecting deeper transitions in which control over capital structures has become central to economic sovereignty. Infrastructure finance increasingly relies on layered capital stacks combining policy guarantees, concessional tranches, and embedded project-level control rights, shifting core policy challenges from managing rollover risk to preserving infrastructure optionality (Gallagher, 2016; Xu & Yao, 2015). These micro-level constraints aggregate into macro-level implementation barriers that standard policy frameworks often overlook. Understanding how firm-level financial frictions interact with national policy frameworks and country-specific financing cost structures is essential for designing effective green transitions in emerging economies, where the binding constraint may be institutional autonomy rather than technology availability (Mazzucato & Semieniuk, 2018; Polzin et al., 2019).

Green industrial policy has emerged as the dominant policy paradigm, emphasizing active state roles in shaping markets toward sustainability outcomes while maintaining economic dynamism (Rodrik, 2014; Mazzucato, 2021). Unlike traditional industrial policy focused on correcting market failures, contemporary approaches involve creating new industries, transforming high-emissions sectors, and managing complex political economy dynamics (Meckling & Allan, 2020). However, scholarly attention has concentrated on policy design and theoretical justifications rather than implementation effectiveness and the financing constraints—both at macro and micro levels—that determine whether ambitious plans translate into realized outcomes.

This paper addresses three research questions through systematic comparison of India, South Africa, Brazil, and Indonesia—major emerging economies that have articulated explicit green industrial strategies but pursue markedly different approaches. **First**, what explains variation in implementation effectiveness across countries with different policy approaches and institutional contexts? **Second**, what common bottlenecks, including firm-level financial constraints, constrain green finance mobilization despite diverse national frameworks? **Third**, how effectively do blended finance mechanisms and green credit policies support transitions when firm heterogeneity in financial constraints shapes adoption of frontier technologies?

We contribute to three scholarly debates. First, we extend green industrial policy literature (Mazzucato, 2015, 2021; Rodrik, 2014; Schmitz, 2015) by systematically examining financial implementation mechanisms at both macro and micro levels, demonstrating that financing architecture—including how it addresses heterogeneous firm constraints—represents critical enabling conditions rather than secondary details. Recent theoretical work (Capelle et al., 2025; Lanteri & Rampini, 2025) shows that financially constrained firms face a fundamental trade-off between scaling capital stock and upgrading to greener vintages, creating a "pecking order" where only unconstrained firms adopt frontier technologies. This micro-level mechanism has profound implications for aggregate green transition effectiveness. Second, we engage development finance scholarship (Gabor, 2021; Griffith-Jones & Ocampo, 2018) by assessing whether the "Wall Street Consensus" emphasizing private capital mobilization through de-risking delivers promised results when firm-level heterogeneity in financial constraints is considered. Third, we contribute to just transition literature (McCauley & Heffron, 2018; Newell & Mulvaney, 2013) by documenting systematic bias in financing mechanisms toward commercially viable infrastructure versus social equity programs and smaller, more constrained firms.

2.1 Global Transition Finance Landscape

Global energy transition investment dynamics provide essential context for understanding country-level implementation challenges. Climate finance flows reached USD 1.9 trillion in 2023, with early data indicating flows exceeded USD 2 trillion for the first time in 2024 (CPI, 2025). While this represents substantial growth from USD 674 billion in 2018, a further fivefold increase is required to reach the USD 7.4 trillion needed annually through 2030 to achieve the 1.5°C scenario (CPI, 2024). Geographic concentration persists with alarming clarity: emerging markets and developing economies excluding China need USD 2.4 trillion annually by 2030 for climate and nature-related investments, yet aside from China where 98% of climate finance flows domestically, many EMDEs struggle to mobilize domestic climate finance. Regional disparities are stark: between 2020 and 2022, climate finance to sub-Saharan Africa increased from USD 10 billion to USD 19 billion, while South Asia saw growth from USD 26 billion to USD 41 billion, representing progress but remaining vastly insufficient relative to needs and population.

Sectoral allocation reveals critical gaps beyond renewable energy deployment. While renewables dominate clean energy investment at approximately 75% of total flows (IRENA and CPI, 2025), the AFOLU, industry, and water/wastewater sectors—despite large mitigation potential—have remained at low investment levels from 2018 to 2022. Adaptation finance continues to lag mitigation efforts, with only 16% of domestic and international climate finance in EMDEs channelled for adaptation, and 98% of this small share comprised of public resources or official financing (World Bank, 2024). The adaptation financing gap of USD 194-366 billion annually in developing countries underscores the systematic underfunding of resilience measures relative to emissions reduction.

The composition of finance varies dramatically across country income levels, reflecting fundamental differences in financial sector capacity and institutional frameworks. For the first time in 2023, private climate finance contributions exceeded USD 1 trillion, outpacing public investment. However, this private sector expansion remains geographically concentrated: high-income countries access predominantly private capital (approximately 85% of flows), while low and lower-middle income countries rely heavily on public and concessional finance (60-70% of flows) (IRENA and CPI, 2025). In almost 60% of banks in emerging markets and developing economies, lending for climate-related investment accounts for less than 5% of overall portfolios, with more than one-quarter offering no climate financing at all (World Bank, 2024). This domestic financial sector weakness creates structural dependence on external finance precisely where local currency financing and institutional ownership matter most for sustainable transitions.

Blended finance has emerged as a critical mechanism for mobilizing private capital in higher-risk contexts, though scale remains limited relative to needs. The climate blended finance market reached its highest ever annual total in 2023, growing 120% to USD 18.3 billion from USD 8 billion in 2022, with private sector investment increasing nearly 200% (Convergence, 2024). However, climate adaptation remains severely underfunded with only 32 adaptation blended finance transactions totalling USD 3.5 billion between 2021-2023, compared to 132 mitigation transactions totalling USD 26 billion. The catalytic potential of concessional capital is substantial: if deployed strategically, catalytic capital could mobilize USD 286 billion in private capital, seven times current mobilization levels by the entire development and climate finance systems (Convergence, 2024). Philanthropic capital plays an increasingly important but still undersized role, providing 10% of all concessional capital commitments to climate blended finance between 2017-2022, suggesting substantial unrealized potential for expansion.

The cost of capital for renewable energy projects exhibits substantial heterogeneity across technologies, countries, and institutional contexts, fundamentally shaping the pace and geography of green transitions. Steffen (2020) documents weighted average costs of capital (WACC) ranging from 2.5% for solar photovoltaic projects in advanced economies to over 12% in peripheral emerging markets—a spread large enough to reverse the economic viability of identical technologies across borders. This variance reflects not merely macroeconomic conditions but the accumulation of project-specific risk factors: policy uncertainty, grid integration challenges, currency exposure, and institutional capacity for contract enforcement (Egli et al., 2018). For the four economies examined here, these financing cost differentials translate directly into deployment constraints. India faces solar PV financing costs averaging 8.8% above

LIBOR despite competitive module prices and abundant solar resources, while Brazil confronts similar premiums despite substantial hydroelectric infrastructure (Steffen, 2020, Table 2). The rank ordering of technologies by financing cost—solar PV lowest, onshore wind intermediate, offshore wind highest—remains globally consistent, suggesting systematic differences in perceived operational and revenue risk that persist despite technology maturation (Egli et al., 2019).

These cost patterns have proven remarkably sticky over time. While general interest rate declines following the 2008 financial crisis reduced absolute WACC levels, country-specific risk premiums above benchmark rates remain elevated and change slowly even as technologies mature and deployment experience accumulates (Steffen, 2020). This persistence indicates that financing constraints operate through channels distinct from technology learning curves—reflecting instead the institutional determinants of investment risk identified in comparative political economy literature (Schmidt, 2014; Mazzucato & Semieniuk, 2018). Current climate finance represents only 1% of global GDP, while some estimates suggest specific EMDEs might have to allocate around 6.5% of their GDP by 2030 to meet climate goals—a fiscal burden that underscores the necessity of mobilizing private capital at scale.

A troubling counter trend threatens transition momentum: between 2020 and 2022, advanced economies increased fossil fuel investments by 28% and tripled fossil fuel subsidies for consumers, while in EMDEs fossil fuel investments increased 9% and consumer subsidies increased fivefold to over USD 1.2 trillion. Fossil fuel investment continued to increase globally throughout 2023 and 2024, estimated to reach USD 1 trillion, matching the scale of clean energy investments. This persistent fossil fuel financing—often enjoying lower cost of capital due to established infrastructure and proven cash flows—creates competitive disadvantages for clean alternatives and locks in emissions trajectories incompatible with climate targets.

The implication for green industrial policy is that technology cost reductions alone prove insufficient to equalize deployment opportunities. Without deliberate policy interventions addressing country-specific risk premia through guaranteed mechanisms, currency hedging facilities, or strengthened regulatory frameworks, financing cost disparities will continue to concentrate green investment in already-advantaged contexts regardless of technical potential or emission reduction needs. The evidence suggests that the binding constraint is increasingly institutional capacity to structure bankable projects, de-risk investments through credible policy frameworks, and mobilize domestic financial sectors—challenges that require coordinated interventions across industrial, financial, and regulatory domains rather than technology policy alone.

2.2 Green Industrial Policy

Green industrial policy represents theoretical evolution beyond traditional approaches centered on correcting market failures (Chang, 2002; Rodrik, 2004). Contemporary frameworks emphasize active state roles in *shaping* markets toward sustainability outcomes (Mazzucato, 2015, 2021; Rodrik, 2014). However, a critical dimension often overlooked is how firm-level financial constraints fundamentally shape policy implementation effectiveness.

Recent research by Capelle et al. (2025) provides crucial theoretical insights. In a heterogeneous-firm general equilibrium model with endogenous adoption of cleaner capital vintages under financial constraints, they demonstrate that firms face a fundamental trade-off between investing in more efficient (greener and more productive) capital vintages and scaling up their capital stock. More efficient vintages are more expensive, forcing financially constrained firms to choose between quality and quantity. This generates a "pecking order of vintages" where:

1. Constrained firms (young firms with low net worth) operate below optimal scale and choose less efficient, dirtier vintages to maintain larger capital stocks
2. Growing firms progressively upgrade to better vintages as they accumulate net worth and relax financial constraints
3. Unconstrained firms operate at optimal scale with frontier (greenest and most productive) vintages

This pecking order has profound policy implications. First, it explains why aggregate productivity and environmental performance correlate with financial system development—not just through capital availability but through enabling frontier technology adoption. Second, it suggests that untargeted credit policies expanding overall borrowing capacity may increase emissions by enabling capital-intensive expansion without necessarily upgrading technology. Third, it implies that effective green credit policies must specifically target frontier vintages to avoid subsidizing adoption of intermediate technologies that constrained firms would have adopted anyway.

Quantitatively, Capelle et al. (2025) show that completely removing financial constraints in a calibrated model increases aggregate emissions by 34% despite reducing emissions per unit of energy by 2.5%. The mechanism: GDP expands by 32% and capital intensity increases, dominating the emissions-intensity improvement from vintage upgrading. However, appropriately targeted green credit policies—relaxing constraints only for frontier vintage adoption—can reduce emissions by 2% while raising GDP by 4%. Critically, "appropriately targeted" means coverage limited to the greenest vintage in use by unconstrained firms; extending coverage even one vintage below the frontier generates emission increases rather than decreases.

Recent empirical evidence from emerging European economies provides strong validation of these theoretical mechanisms while revealing an important nuance. De Haas et al. (2024), analysing 10,776 firms across 22 countries, demonstrate that credit constraints reduce investment in greener machinery and equipment by 30-36 percentage points—precisely the types of frontier vintage technologies that Capelle et al. (2025) predict constrained firms cannot afford. Critically, however, they find no significant effect of credit constraints on firm-specific pollution abatement measures such as on-site green energy generation or waste management systems. This asymmetry reflects differences in asset redeploy ability: standard machinery and vehicles can serve as collateral and access bank finance, whereas site-specific environmental infrastructure cannot. This finding has profound implications for understanding which dimensions of green industrial policy are most sensitive to financial sector development."

These financing hierarchy challenges operate through the cost of capital mechanism. The weighted average cost of capital (WACC) comprises a risk-free base rate and a risk premium reflecting firm, sector and project-specific uncertainties (Montague et al., 2024). For emerging market firms pursuing green investments, both components are elevated. Base rates reflect sovereign risk and macroeconomic volatility, while risk premiums incorporate uncertainties around technology performance, revenue stability, and collateral enforceability. The capital-intensive nature of green technologies magnifies these costs: financing represents 25-50% of levelized costs for solar PV and up to 50% for wind power, compared to 15-25% for fossil alternatives. Consequently, WACC increases disproportionately affect green investment viability—a shift from 5% to 9% WACC (comparable to moving from advanced to emerging market conditions) raises renewable energy costs 29-34%, versus 10-11% for fossil fuels (Montague et al., 2024). This differential sensitivity means credit constraints bind particularly severely for green investments, a pattern we examine empirically below.

Beyond firm-level financial constraints, the institutional capacity of emerging market financial sectors constitutes a distinct barrier to green transition financing. In almost 60% of banks in EMDEs, lending for climate-related investment accounts for less than 5% of overall portfolios, with more than one-quarter offering no climate financing at all (World Bank, 2024). This weakness reflects not merely risk aversion but systematic capacity deficits in project appraisal, green technology assessment, and long-term lending infrastructure. The adoption of green and sustainable taxonomies—classification systems identifying activities and investments aligned with environmental targets—covers only 10% of EMDEs compared to 76% of advanced economies, limiting banks' ability to systematically direct capital toward sustainable investments (World Bank, 2024). Moreover, EMDE financial sectors often lack diversification beyond banking: capital markets, institutional investors, and insurance sectors remain underdeveloped relative to advanced economies, constraining the availability of long-term equity and project finance essential for capital-intensive green infrastructure. The Sustainable Banking and Finance Network, comprising 91 financial sector regulators representing 70 countries and USD 68 trillion (92%) of EMDE banking assets, has documented over 400 sustainable finance policies launched by member countries—a 107% increase since 2021—yet implementation capacity remains heterogeneous, with many jurisdictions lacking the technical expertise, data infrastructure, and supervisory frameworks to operationalize these policies effectively (IFC, 2024).

Multilateral Development Banks (MDBs) and development finance institutions (DFIs) play essential but evolving roles in addressing these financing gaps through both direct investment and market catalysis. IFC committed a record USD 56 billion in fiscal year 2024 to private companies and financial institutions in developing countries, while broader MDB/DFI climate finance has shifted from project-level lending toward systemic market-building interventions (IFC, 2024). These include first-loss guarantees that subordinate official capital to protect commercial lenders, synthetic securitizations that transfer credit risk from local banks' green loan portfolios, technical assistance for financial sector regulatory development, and co-investment platforms that demonstrate bankability of novel technologies or business models. However, MDB/DFI resources remain vastly insufficient relative to needs: their annual mobilization of private capital averages USD 40-50 billion, compared to the USD 2.4 trillion annually required by EMDEs excluding China by 2030. Moreover, catalytic effectiveness varies substantially across instruments and contexts. Partial credit guarantees, for instance, typically provide only one to two notch credit rating upgrades, insufficient to bring sub-investment grade projects within fiduciary mandates of most institutional investors. More effective de-risking requires layered capital structures combining junior tranches (absorbing first losses), mezzanine tranches (providing mid-risk returns), and senior tranches (achieving investment-grade ratings)—structures requiring coordinated deployment of scarce concessional capital (Convergence, 2024).

Foreign direct investment in green technologies presents distinct opportunities and constraints beyond portfolio finance. Green FDI to EMDEs has surged in renewable energy sectors, driven by declining technology costs and climate policy commitments, yet remains concentrated in larger emerging markets with established institutional frameworks. Econometric analysis indicates that closing the climate policy gap between the average EMDE and average advanced economy would triple the green FDI inflow-to-GDP ratio, potentially closing 30-50% of the private renewable investment gap in EMDEs excluding China (Jaumotte et al., 2024). However, green FDI effectiveness depends critically on complementary factors: external sector openness, rule of law, human capital availability, and technological absorption capacity (Jaumotte et al., 2024). Countries lacking these preconditions often receive FDI in extractive or low-value segments of green value chains rather than technology-intensive activities. Moreover, green FDI frequently embodies proprietary technologies protected by intellectual property regimes, limiting knowledge spillovers and local innovation capabilities. Effective industrial policies must therefore address not just financing availability but technology transfer modalities, co-innovation partnerships, and domestic R&D capacity—dimensions requiring coordination beyond financial sector interventions alone. Recent initiatives such as debt-for-climate swaps (redirecting debt service toward green investments), co-innovation funds, and joint venture platforms between advanced and emerging economy firms represent attempts to align financing with technology diffusion, though scale remains limited (SEI, 2025).

The green transition also generates systemic risks for financial sectors through stranded asset exposure, climate-physical risks, and transition-related repricing. EMDE banks maintain substantial exposure to fossil fuel sectors, both directly through lending and indirectly through firms dependent on energy-intensive processes. Abrupt repricing of fossil asset values—triggered by policy shifts, technology disruption, or physical climate impacts—can propagate losses through financial system interconnections, threatening stability precisely when financing for alternatives is most needed (IMF, 2024). Event studies indicate that climate-related disasters reduce bank stock returns by 1.7% over three-week windows, with effects concentrated in institutions with weaker capital buffers—a particular concern given that 30% of EMDEs face high financial sector risks in coming years while lacking adequate institutional capacity for crisis management (IMF, 2024). Paradoxically, financial sector fragility can both impede green investment (through credit rationing and risk aversion) and result from delayed green transitions (through stranded asset realization and physical damage). This two-way causality underscores the necessity of integrating financial stability considerations with climate policy design, including phased fossil asset retirement schedules, enhanced disclosure of climate exposures, and stress testing of transition scenarios—policy domains requiring coordination across financial regulators, environmental authorities, and industrial ministries rarely achieved in practice.

2.3 Development Finance Architecture

Traditional development finance analysis focuses on aggregate capital scarcity and country-level risk premiums. Incorporating firm heterogeneity reveals additional constraints. Domestic financial systems in emerging economies exhibit limited depth with banking sectors dominating capital allocation (Beck et al., 2005). However, the binding constraint often involves inability to finance specifically the frontier technology investments that drive green transitions.

Capelle et al. (2025) demonstrate that financially constrained firms respond significantly less to carbon pricing than unconstrained peers. Using exogenous carbon price shocks (Känzig, 2023), they show firms with higher net worth (interpreted as less constrained) cut emissions by an additional 1.5 percentage points three years after a 13% carbon price increase compared to lower net-worth firms within the same narrow industry. This differential response reflects constrained firms' inability to finance the more expensive frontier technologies that enable deep emissions reductions.

This finding has critical implications for development finance architecture. Traditional approaches emphasizing risk-adjusted returns and financial sustainability may systematically disadvantage frontier technology adoption by favouring incremental improvements. Constrained firms facing the pecking order can achieve modest greening through moderately better vintages, but frontier adoption requires either significant net worth accumulation (time-intensive) or targeted financial support specifically for expensive frontier technologies.

The "Wall Street Consensus" (Gabor, 2021) emphasizing private capital mobilization through de-risking may prove particularly problematic in this context. Private investors typically require shorter payback periods and higher hurdle rates than frontier technology economics can support. De-risking structures that make projects attractive to private capital may inadvertently select for less ambitious technology upgrades—those with quicker returns—rather than frontier adoptions with longer paybacks but larger environmental benefits.

Financial constraints for green transition are geographically concentrated, often coinciding with regions most affected by employment displacement. WACC for green projects can range from 3-5% in capital regions of advanced economies to 15-30% in peripheral regions of emerging markets (Montague et al., 2024; CPI, 2023). In India's coal belt states, South Africa's Mpumalanga province, or Indonesia's coal-dependent regions, this financing penalty renders technically viable green alternatives economically uncompetitive precisely where employment impacts are most severe. The De Haas et al. (2024) finding that small and young firms face more binding credit constraints compounds this geographic disadvantage—transition-affected regions typically have higher concentrations of such firms. This creates multiplicative disadvantage: a small firm in a peripheral, coal-dependent region may face financing costs 20-30 percentage points higher than a large firm in a capital region, severely constraining its adjustment capacity. Just transition policies must therefore address not only employment support but also the systematic financing disadvantages that slow economic transformation in transition-affected regions.

2.4 Blended Finance

Blended finance—"strategic use of development finance to mobilize additional finance toward sustainable development" (OECD, 2018)—dominates current development paradigms. However, firm heterogeneity in financial constraints creates systematic tensions between blended finance's dual objectives: achieving high leverage ratios and ensuring genuine additionality.

Capelle et al. (2025) show theoretically and quantitatively that these tensions are fundamental rather than merely implementation challenges. High leverage occurs precisely where additionality is questionable—for mature technologies that moderately constrained firms would have adopted anyway in their progression through the pecking order. Low leverage characterizes genuinely additional frontier adoptions that only occur with substantial public capital absorption of expense differentials.

Empirical evidence from blended finance performance confirms these theoretical predictions. Convergence (2023) tracking 743 global transactions reports median leverage of 3.7:1, with least developed countries achieving only 2.1:1 versus 4.8:1 in upper middle-income countries. This inverse relationship—lowest leverage where catalytic finance most needed—reflects the pecking order mechanism: countries (and firms within countries) furthest from frontier technology adoption require largest public subsidies per dollar of private capital mobilized.

Geographic and sectoral concentration further reveals these dynamics. Blended finance flows 58% to upper middle-income countries with only

12% to low-income countries, and 62% to energy and financial services where commercial capital already deploys readily (Convergence, 2023). Through the firm heterogeneity lens, this pattern reflects blended finance gravitating toward contexts where moderately constrained firms undertake incremental technology upgrades (high leverage, questionable additionality) rather than contexts requiring frontier adoptions (low leverage, high additionality).

2.5 Just Transitions

Just transition frameworks emphasizing worker protection and community support (ILO, 2015; McCauley & Heffron, 2018) typically overlook firm-level heterogeneity dimensions. However, the pecking order mechanism implies that transition burdens fall disproportionately on workers and communities dependent on constrained firms unable to finance technology upgrades.

Larger, unconstrained firms can smooth transitions by financing gradual technology adoption while maintaining employment. Smaller, constrained firms face starker choices: continue with dirty technologies until forced to exit or undertake technology investments that push them toward insolvency. Geographic and sectoral concentration of employment in constrained firms—often characteristic of coal-dependent regions—amplifies these dynamics.

Moreover, the pecking order suggests that broad credit policies (including green credit policies covering intermediate technologies) may inadvertently worsen distributional outcomes. Such policies enable constrained firms to expand capital intensity and energy consumption without achieving frontier technology adoption, potentially locking in employment in emission-intensive activities longer than narrow but deeper frontier-focused support that accelerates complete transitions.

The intersection of firm-level financial constraints and just transition imperatives creates particularly acute challenges. De Haas et al. (2024) demonstrate that smaller and younger firms—precisely those most likely to be concentrated in coal-dependent regions and informal economies—face systematically higher credit constraints. Their analysis reveals that while larger, financially unconstrained firms can finance gradual technology transitions while maintaining employment, smaller constrained firms face stark binary choices between continuing with polluting technologies until forced exit or undertaking technology investments that risk insolvency. This heterogeneity implies that just transition financing mechanisms cannot treat all firms uniformly; rather, they must provide differentiated support calibrated to firm financial capacity and regional employment concentration."

3. Research Design

We employ structured comparative case analysis examining policy frameworks, financing architectures, sectoral dynamics, and implementation outcomes across four countries, with particular attention to how policies address (or fail to address) firm-level financial constraints. This methodology allows systematic examination of how different institutional contexts and policy choices shape results while identifying common patterns (Ragin, 1987).

Country selection provides variation in financial system depth, firm size distributions, and approaches to addressing firm-level constraints. India brings relatively developed capital markets but substantial presence of constrained small and medium enterprises. South Africa offers thick financial sector relative to development level but concentrated within large firms. Brazil provides sophisticated state development bank capable of differentiated firm-level interventions. Indonesia illustrates resource-based industrialization with heterogeneous firm participation.

Analysis draws on policy documents, financing data (development bank reports, Climate Policy Initiative, Climate Bonds Initiative), multilateral institution reports, and academic literature. We structure comparison across consistent dimensions: policy frameworks, financing architectures, sectoral dynamics, and implementation effectiveness measured through quantitative indicators and qualitative assessment. Finally, we assess whether policies incorporate recognition of firm heterogeneity in financial constraints and whether green credit policies target frontier versus intermediate technologies. Following Capelle et al. (2025), we interpret implementation challenges through the lens of firm-level adoption constraints rather than solely aggregate capital scarcity.

Our Analysis -at this stage- relies primarily on aggregate data and policy documents without firm-level implementation data across all four countries. While, for example, Capelle et al. (2025) provide firm-level evidence for European manufacturing and Larsen (2025) offers detailed analysis of India's solar sector, comparable granular data for Brazil and Indonesia would strengthen conclusions. Additionally, optimal policy design with firm heterogeneity requires detailed cost-benefit analysis incorporating implementation costs (monitoring, verification, moral hazard) that our analysis does not attempt.

4. Comparative Analysis of Policy Frameworks

4.1 India: Mission-Driven Approach with Financial Constraint Recognition

India's mission-driven approach through programs like the National Green Hydrogen Mission (targeting 5 million tons annual production and 125 GW renewable capacity by 2030, allocating USD 2.4 billion in incentives) demonstrates sophisticated understanding of technology targeting. Production-linked incentive schemes for Advanced Chemistry Cell batteries (USD 2.2 billion for 50 GWh) and solar photovoltaics (USD 2.9 billion for 10 GW) explicitly aim to develop frontier manufacturing capacity rather than subsidizing incremental improvements.

Recent research reveals a distinctive Indian approach that challenges conventional assumptions about financing requirements for green industrial policy. Larsen (2025) characterizes India's model as "state-organized financing with limited fiscal expenditure." Despite annual fiscal expenditure on renewable energy of only USD 1.8 billion from the central government budget—negligible by global standards—India became the world's second-largest solar manufacturer and installer, with manufacturing capacity growing from 15 GW in 2020 to 74 GW by March 2025.

This success reflects strategic deployment of non-fiscal financing mechanisms. State-owned enterprises invest approximately USD 1.5 billion annually in solar generation, with cumulative commitments of 187.5 GW by 2030 providing stable demand signals for manufacturing expansion (Larsen, 2025). State-owned financial institutions—with India's banking sector 70% state-owned—provided USD 10.1-14.6 billion in 2023, increasing to USD 295.25 billion committed by 2030. The Indian Renewable Energy Development Agency (IREDA) alone scaled lending from USD 3.6 billion (2021) to USD 6.1 billion (2023), with 2030 targets recently increased from USD 16 billion to USD 59 billion. State-owned distribution companies provide financial de-risking through 25-year power purchase agreements, "must run" status for renewables, and Renewable Purchase Obligations mandating gradual renewable procurement increases. Direct fiscal spending remains strategically narrow—the Production Linked Incentive scheme commits USD 2.5 billion for solar manufacturing, disbursed only when facilities achieve sales targets.

IRENA and CPI (2025) document India as third-largest clean energy investment recipient among developing countries, with USD 14-16 billion annually (1.0% of GDP)—double the developing country average. However, approximately 75% targets utility-scale renewable electricity (mature technologies), with only 8-10% supporting industrial decarbonization, green hydrogen, and advanced storage (frontier technologies). Small and medium enterprises account for 45% of manufacturing emissions but receive less than 10% of climate finance (IRENA & CPI, 2025), exemplifying the "missing middle" created by firm-level constraints.

India's intentional domestic financing prioritization reflects strategic risk assessment. Government officials expressed reluctance toward international capital inflows citing debt distress observed in neighbouring countries (Larsen, 2025). Foreign direct investment increased to USD 3.76 billion (2023-24) but represents only 15% of total clean energy investment, with 85% domestically sourced.

However, firm-level constraints persist. Mid-cap projects (under USD 10 million) face 11-13% interest rates versus 8-9% for larger projects, with 300-500 basis point premiums reflecting bank perceptions that constrained firms cannot afford frontier technologies (CEEW-CEF, 2022; Larsen, 2025). India's USD 200 billion in private sector pledges concentrates among large conglomerates (Reliance, Adani, Tata) capable of frontier adoption. Mid-cap firms accounting for substantial emissions lack participation capacity, while green hydrogen investments—genuinely frontier technology—attracted only marginal deployment despite policy support.

Despite strong aggregate flows, India faces USD 34 billion annual gaps between USD 50-60 billion needed for 2030 targets and current USD 16 billion deployment (CEEW, 2022). This reflects insufficient frontier technology investment and inadequate mid-cap firm support rather than solely aggregate capital scarcity.

Larsen (2025) argues India's experience suggests "green industrial policy may be feasible for more global South countries than current literature anticipates," challenging assumptions that fiscal capacity or international capital inflows are prerequisites. However, India benefits from unique characteristics limiting extrapolation: a domestic market of 1.4 billion providing demand scale unavailable to smaller economies, and strategic focus on solar power rather than diversified sectoral coverage necessitated by resource constraints. Whether India's non-fiscal approach scales to sectors where firm constraints bind more severely (industrial decarbonization, sustainable agriculture) remains uncertain.

4.2 South Africa: Just Transition Framework Confronting Firm Heterogeneity

South Africa's Just Energy Transition Investment Plan (USD 98.7 billion needs over 2023-2027) explicitly addresses distributional concerns but less systematically incorporates firm-level financial constraint considerations. The JETP's USD 8.5 billion commitment (7.6% disbursed by September 2023) targets primarily large infrastructure rather than differentiated firm-level support enabling technology adoption across heterogeneous capabilities.

IRENA and CPI (2025) document South Africa's USD 4-6 billion annual clean energy investment falling dramatically short of the USD 19.7 billion annual requirement—representing one of the largest relative financing gaps among upper-middle income countries at 65-70% shortfall. This underperformance reflects Eskom's financial fragility creating severe counterparty risk, policy uncertainty following years of REIPPPP program interruptions, and limited domestic institutional investor capacity despite nominally deep financial sector.

Notably, South Africa's pension fund assets exceed 80% of GDP (among highest globally), yet less than 3% allocates to domestic infrastructure including clean energy, reflecting risk perceptions and regulatory constraints. IRENA and CPI (2025) classify this as illustrative of broader challenges where financial sector depth does not automatically translate to transition finance deployment when institutional barriers and risk perceptions constrain allocation.

Eskom's fragility (USD 23 billion debt) creates extreme counterparty risk affecting all firm financial positions. However, impact concentrates disproportionately on smaller, more constrained firms unable to self-finance alternatives through distributed generation. CSIR (2023) documents 332 days of load-shedding in 2023, but larger firms increasingly bypass Eskom through captive generation (5.2 GW registered under construction by March 2024), while smaller firms remain Eskom-dependent.

This creates the two-tiered system Presidential Climate Commission (2023) warns against, with firm-level financial constraints determining access to reliable energy infrastructure. DBSA's Climate Finance Facility achieved only USD 230 million disbursements versus USD 820 million target, constrained by limited bankable pipeline—reflecting that most firms in the economy lack financial capacity to structure frontier technology projects meeting facility criteria.

According to IRENA and CPI (2025), South Africa's experience demonstrates that instability within the utility sector can impose financial constraints across the entire economy by undermining investor confidence in power sector projects and limiting firms' ability to finance alternative solutions. Therefore, this has led to capital outflows rather than capital reallocation, with South African clean energy investment decreasing by 15% in 2023 compared to 2022, despite an increase in global investment levels.

4.3 Brazil: Development Bank Addressing Financial constraints Heterogeneity

BNDES's evolution toward catalytic blended finance reflects explicit recognition of firm heterogeneity challenges. The Chamada de Clima (USD 1 billion public capital targeting 5:1 leverage) structures first-loss tranches specifically to enable frontier technology adoption by firms that would otherwise face prohibitive financing costs. This approach directly addresses the pecking order mechanism by subsidizing the price premium of frontier vintages rather than overall capital costs.

IRENA and CPI (2025) document Brazil's USD 10-12 billion annual clean energy investment reflecting sophisticated financial architecture centered on BNDES, but persistent sectoral imbalances limit effectiveness. Of this total, approximately 55% targets renewable electricity (particularly hydro, wind, bioenergy), 25% sustainable transport, 12% energy efficiency, and only 8% agriculture and nature-based solutions despite these causing 72% of national emissions.

IRENA and CPI (2025) classify BNDES's Chamada structure as among most sophisticated blended finance approaches globally, noting that design appropriately recognizes trade-offs between leverage and additionality. However, ultimate effectiveness depends on whether coverage remains restricted to frontier technologies. If extended to intermediate technologies where constrained firms would progress incrementally anyway, leverage would increase but additionality decrease—precisely the tension Capelle et al. (2025) identify theoretically.

Sectoral imbalances reveal broader challenges. Agriculture causing 72% of emissions receives only 11% of climate finance (creating 75-80% sectoral shortfall). This reflects not just sector neglect but the challenge that agricultural emissions reductions often require frontier technology adoption (precision agriculture, emissions monitoring, alternative inputs) by highly constrained smallholder firms lacking balance sheet capacity for expensive upgrades. BNDES's ABC+ credit line (USD 1.8 billion over 2021-2023) represents only 3% of estimated need precisely because enabling frontier adoption by constrained agricultural firms requires grant-equivalent support that credit lines cannot provide.

IRENA and CPI (2025) document that Brazilian agriculture and forestry receive approximately USD 1.5-2 billion annual climate finance versus estimated USD 15-18 billion needed for ABC+ Plan implementation and zero deforestation by 2030—an 85-90% gap that IRENA and CPI classify as most severe sectoral finance mismatch among major emerging economies.

4.4 Indonesia: Downstreaming Without Firm-Level Financial Differentiation

Indonesia's export restrictions forcing domestic nickel processing successfully attracted USD 30 billion FDI over 2014-2023, creating battery supply chain foundations. However, this approach bypasses firm-level financial constraint issues through large-scale foreign direct investment rather than enabling domestic firm capability building across heterogeneous financial positions.

IRENA and CPI (2025) document Indonesia's USD 5-7 billion annual clean energy investment concentrated in geothermal and increasingly solar, but with implementation challenges reflected in low disbursement rates for committed international finance. The USD 20 billion JETP announced November 2021 represented largest climate finance commitment to any developing country except China, yet only USD 320 million (1.6%) had been disbursed by December 2023.

IRENA and CPI (2025) attribute this implementation gap to severe project pipeline deficits. IIF (2023) assessment found only 35% of proposed renewable projects exceeding 10 MW met minimum bankability standards—lacking feasibility studies, credible sponsors, or financial structures aligned with revenue profiles. This reflects that most Indonesian manufacturing firms lack net worth and financial sophistication to structure complex infrastructure projects meeting international lender requirements.

The JETP's USD 20 billion commitment (only USD 320 million or 1.6% disbursed by December 2023) struggled precisely because it aimed to finance domestic firm transitions. Environmental and social trade-offs from rapid nickel processing expansion (60-80 kg CO_2 per kg nickel, 90-120 million tons CO_2 annually) partly reflect inadequate technology targeting. Firms adopted whatever processing technologies they could finance rather than frontier low-emission approaches. Worker safety violations at 73% of inspected facilities (Indonesian Ombudsman, 2023) similarly reflect corner-cutting by constrained firms unable to afford best-practice investments.

Geothermal sector illustrates technology-specific barriers. Indonesia possesses world's largest geothermal resources (24 GW potential) but developed only 2.4 GW (10% utilization) by 2024. IRENA and CPI (2025) note that despite excellent geothermal conditions and policy frameworks, deployment lags due to high upfront exploration costs, long development timelines (5-7 years), and geological risks that constrained firms and even many large developers cannot absorb without substantial public risk-sharing mechanisms currently unavailable at scale.

5. Financial Challenges for Green Transition

5.1 Financing Gaps

Table 1: Annual Green Investment Requirements and Mobilized Finance

Country	Annual Need (USD bn)	Current Mobilization (USD bn)	Gap (USD bn)	Gap (%)
India	60-70	16	44-54	63-77%
South Africa	19.7	5	14.7	75%
Brazil	80	11	69	86%
Indonesia	12-14	6	6-8	50-57%

Sources: India—CEEW (2022), IRENA & CPI (2025); South Africa—Presidential Climate Commission (2022), IRENA & CPI (2025); Brazil—MDIC (2023), IRENA & CPI (2025); Indonesia—Government of Indonesia (2022), IRENA & CPI (2025)

Interpreting these gaps through firm heterogeneity lens reveals additional dimensions. Aggregate gaps partly reflect inability of constrained firms to finance frontier technologies even when capital is notionally "available." India's USD 200 billion in private sector pledges concentrates among large conglomerates (Reliance, Adani, Tata) capable of frontier technology adoption (Larsen, 2025). Mid-cap firms accounting for substantial emissions lack financial capacity to participate, creating a "missing middle" in technology adoption.

Brazil's experience with BNDES offers parallel lessons on non-fiscal financing approaches. BNDES's PROINFA program combined feed-in tariffs with mandatory local content requirements, successfully catalyzing domestic wind turbine manufacturing (particularly by companies like WEG) without direct budget transfers. Critically, Brazil demonstrated the importance of **transition from state-led to market-led mechanisms:** as wind energy achieved cost competitiveness by 2011, the program shifted from fixed feed-in tariffs to competitive reverse auctions, reducing subsidy dependency while maintaining growth momentum (Bayer, 2018). This transition pathway—initial state support creating economies of scale, followed by market-based mechanisms—offers a template for middle-income countries designing green credit policies with eventual subsidy phase-out.

South Africa's 75% gap reflects not just aggregate capital scarcity but that most firms in emission-intensive sectors lack net worth to finance technology transitions. REIPPPP attracted adequate capital for utility-scale renewable generation (relatively mature technology), but industrial decarbonization requiring frontier process technology adoption remains severely underfunded because constrained firms cannot participate and unconstrained firms are few.

5.2 The Pecking Order in Practice: Evidence from Country Cases

Capelle et al. (2025) demonstrate that financially constrained firms adopt less efficient vintages, are less productive, and have higher emission intensities. Country evidence confirms these patterns operating at scale:

India: Green bond market (USD 56 billion cumulative issuance) concentrated among large corporates. CEEW-CEF (2022) documents that projects under USD 10 million—typically by more constrained firms—face 300-500 basis point interest rate premiums versus larger projects. This premium directly reflects banks pricing the risk that constrained firms cannot afford frontier technologies and may adopt cheaper, less efficient alternatives with uncertain performance. Larsen (2025) documents that while India's large conglomerates successfully scaled solar manufacturing, mid-cap firms remain largely excluded from participation despite accounting for substantial emissions.

South Africa: Distributed generation expansion (5.2 GW registered) overwhelmingly by large commercial/industrial users financing expensive high-efficiency solar-battery systems. Smaller firms and households face Eskom-dependence and load-shedding precisely because they lack financial capacity for distributed generation investments, despite these often-having superior economics over project lifetimes.

Brazil: BNDES (2023) data shows average agricultural ABC+ loan of USD 160,000, sufficient for incremental efficiency improvements but insufficient for frontier technology adoption (precision agriculture systems, emissions monitoring, alternative input adoption) requiring USD 500,000-1,000,000+ investments. Constrained smallholders improve incrementally along their pecking order while large agribusiness adopts frontier technologies.

Indonesia: Nickel processing concentration among large Chinese-financed facilities reflects that Indonesian firms lack financial capacity for capital-intensive metallurgical technology. Attempts to broaden participation through IIF's Green Finance Facility achieved only 35% bankable project rate, indicating most firms cannot structure frontier technology investments meeting lender requirements.

5.3 Blended Finance Effectiveness

Table 2: Blended Finance Performance and Technology Targeting

Country	Facility	Target Leverage	Achieved	Technology Coverage	Additionality Assessment
India	IREDA refinancing	6-8:1	6.5-8.0:1	Mature renewables	Low (incremental)
India	WB climate facility	4:1	2.8-3.2:1	Mixed technologies	Medium
South Africa	REPP	5:1	2.4:1	Frontier + mature	Medium-High
Brazil	BNDES Chamada	5:1	TBD	Frontier targeted	Medium (structure-dependent)
Indonesia	WB facility	4.3:1	4.3:1	Mature (guarantees required)	Medium

Sources: IREDA (2023), World Bank (2023a), REPP (2023), BNDES (2023), World Bank (2023d)

Interpreting leverage ratios through technology targeting reveals systematic patterns predicted by Capelle et al. (2025). High leverage (6.5-8:1) occurs for mature technologies where constrained firms progress through pecking order—high private capital participation because investments are incremental rather than frontier. Low leverage (2.4:1) occurs where policies target frontier technologies requiring substantial public subsidy of expensive vintage premium.

India's IREDA refinancing achieving 6.5-8:1 leverage finances mature utility-scale solar that constrained firms increasingly access commercially (Larsen, 2025). Additionality is questionable—these projects likely proceed without IREDA given improving commercial viability. However, World Bank climate facility achieving only 2.8-3.2:1 leverage includes frontier technology components (early-stage hydrogen, novel storage) where private capital requires substantial public risk absorption.

South Africa's REPP achieving 2.4:1 leverage faces genuinely frontier context—utility counterparty risk and regulatory uncertainty create fundamental barriers that constrained firms cannot navigate without substantial public support. Brazil's BNDES Chamada structure explicitly recognizing this tension through first-loss tranches represents sophisticated response to firm heterogeneity, though ultimate leverage depends on whether coverage remains restricted to frontier or extends to intermediate technologies where leverage would be higher but additionality lower.

5.4 Just Transition

Table 3: Just Transition Resource Allocation and Firm Size Distribution

Country	Social Program Needs (annual, USD bn)	Allocated (USD bn)	Allocation (%)	Concentrated in Constrained Firms?
India	Not quantified	0.3-0.5	-	Coal sector SMEs underserved
South Africa	1.6	0.08	5.3%	Yes - smaller firms in coal value chain
Indonesia	1.7	0.03	1.5%	Coal mining concentrated but suppliers diffuse
Brazil	Embedded	Not tracked	-	Agricultural smallholders severely constrained

Firm heterogeneity fundamentally shapes just transition challenges. Large firms (Coal India Limited, Eskom, Vale) can finance gradual technology transitions while maintaining employment through cross-subsidization.

Smaller firms in supply chains and dependent communities lack this capacity.

South Africa's Komati closure illustrates these dynamics. The facility itself (Eskom-owned) received structured support for repurposing. However, 430 direct workers and thousands in ancillary employment at small local firms faced starkest impacts. Retraining achieving only 31% employment placement within 12 months reflects that alternative employment is predominantly with constrained firms unable to offer comparable wages or stability.

Brazil's agricultural transition challenges concentrate among smallholders operating at subsistence scale. Large agribusiness can finance frontier sustainable agriculture technology, accessing premium markets. Smallholders face the pecking order: incremental improvements affordable but insufficient to access premium markets, while frontier adoption financially impossible without grant-equivalent support. Result: continued deforestation pressure as financially constrained smallholders pursue agricultural expansion rather than sustainable intensification.

Cross-Country Comparison of Non-Fiscal Financing Models: India, Brazil, and Indonesia demonstrate distinct approaches to mobilizing green finance with limited fiscal resources. India leverages state ownership of financial institutions (70% of banking sector) to direct lending through mandates; Brazil utilized development bank financing (BNDES) with planned transitions to market mechanisms; Indonesia attempts blended finance through state-owned enterprises but faces **execution gaps**—the Indonesia Infrastructure Finance facility remains undercapitalized relative to Just Energy Transition Partnership commitments. A critical success factor across cases is **policy coherence**: Brazil's wind energy success required alignment between energy auctions (demand creation), BNDES financing (supply-side capital), and local content requirements (industrial development). Indonesia's fragmented approach—with responsibilities split between multiple ministries and weak coordination—illustrates the risks of misalignment (Indonesia document, p. 4-5)

6. Comparative Analysis of Adjustment Trajectories

6.1 Financial Constraints as First-Order Implementation Barrier

Our comparative analysis reveals that firm-level financial constraints represent first-order rather than second-order barriers to green transition implementation. This finding extends beyond aggregate capital scarcity to fundamental questions about technology adoption patterns when firms face the pecking order mechanism.

Capelle et al. (2025) demonstrate quantitatively that removing financial constraints in a calibrated model increases aggregate emissions by 34% despite enabling frontier vintage adoption by previously constrained firms. The mechanism: GDP expands 32% and capital intensity increases, dominating emissions-intensity improvements. This finding challenges conventional wisdom that alleviating financial constraints necessarily supports environmental goals. However, their work also shows that appropriately targeted green credit policies—relaxing constraints specifically for frontier vintage adoption—can reduce emissions by 2% while raising GDP by 4%. The critical qualifier "appropriately targeted" means coverage limited to genuinely frontier technologies. Extending coverage to intermediate technologies generates emission increases rather than decreases because it enables constrained firms to scale up with moderately improved but still emission-intensive technologies.

Country evidence confirms this theoretical prediction. India's approach demonstrates that significant green industrial policy implementation is possible without large-scale fiscal expenditure or international capital inflows through strategic deployment of state-organized financing (Larsen, 2025). However, even India's relatively successful model leaves mid-cap firms constrained, with financing concentrating among large conglomerates capable of frontier adoption. Brazil's BNDES Chamada attempting explicit frontier targeting through first-loss structures represents more sophisticated response, though ultimate effectiveness depends on maintaining coverage restriction as carbon prices and frontier technologies evolve.

6.2 Policy Coherence and Sectoral Financial Architecture

Policy coherence traditionally emphasizes consistency across sectoral policies (fossil fuel subsidies, renewable energy support, carbon pricing).

Our analysis suggests coherence must also address sectoral financial frameworks.

Brazil's bioethanol experience underscores another coherence dimension: regulatory stability and credible phase-out paths**.** The ProÁlcool program succeeded partly because producers had clear, predictable subsidy schedules enabling long-term investment decisions. When subsidies ended abruptly in the 1980s without market-based alternatives, the E100 vehicle market collapsed, requiring costly recovery through flex-fuel technology introduction in 2003 (Brazil document, p. 6). This historical lesson emphasizes that green credit policies require not just initial support, but pre-announced, credible transition mechanisms to market-based financing—a dimension absent in many current emerging economy programs that focus on subsidy provision without specifying phase-out criteria."

India's renewable purchase obligations and payment delays (5.3 months average) exemplify incoherence: regulations mandate renewable procurement while financial constraints prevent timely payment. Smaller, constrained developers suffer disproportionately because they lack working capital to bridge payment delays, while larger, unconstrained developers manage through balance sheet strength (Larsen, 2025). Result: systematic disadvantage to constrained firms in what should be technology-neutral competitive procurement.

South Africa's Eskom fragility creates extreme incoherence. Carbon pricing signals transition, but utility counterparty risk elevates financing costs precisely for constrained firms most needing support. Large firms increasingly bypass Eskom through self-generation (creating the two-tiered system), while constrained firms remain dependent. Policy coherence requires either Eskom stabilization enabling all firm categories to access alternative supplies on reasonable terms, or differentiated support compensating constrained firms for elevated risks they cannot diversify.

6.3 Green Credit Policy Targeting and Implementation

Both theoretical work and country-specific evidence demonstrate that green credit policy effectiveness depends critically on technology targeting precision, institutional capacity, and dynamic policy adjustment. Three fundamental findings emerge from the comparative analysis.

6.3.1 Frontier Targeting Requirements and Challenges

First, frontier targeting is essential but administratively and politically demanding. Policies must restrict coverage to genuinely frontier technologies—those adopted only by unconstrained firms under baseline conditions. Capelle et al. (2025) demonstrate that extending coverage even one vintage below the frontier generates emission increases rather than reductions, as subsidies enable constrained firms to expand capital-intensive production without proportional technology upgrades. Yet identifying what constitutes "frontier" dynamically as technologies mature and relative prices shift poses substantial information requirements. India's experience illustrates both possibilities and limitations. The country's Priority Sector Lending framework mandates commercial banks to allocate 40% of net credit to designated sectors, including renewable energy, with differential treatment for solar (classified as priority) versus other renewables (Chakravarty et al., 2024). India's approach leverages state-owned financial institutions—particularly the Indian Renewable Energy Development Agency (IREDA), Power Finance Corporation (PFC), and Rural Electrification Corporation (REC)—to channel concessional finance specifically toward solar PV and wind projects meeting capacity and technology standards. PFC and REC collectively hold loan books exceeding USD 57 billion as of March 2024, with mandates to expand renewable energy portfolios from 9% to 30% by 2030 (Deutsche Bank, 2024). However, the effectiveness of this targeting approach depends critically on technical capacity to assess technology frontiers. CPI (2024) documents that India's green finance flows reached record levels in FY 2021/22, but 83% remained domestically sourced, reflecting persistent challenges in attracting international capital for technologies perceived as non-frontier. The absence of operational green finance taxonomy until 2024 limited systematic differentiation between frontier and incremental technologies, potentially subsidizing commercial investments that would have proceeded without support.

Brazil's experience with the ABC (Low-Carbon Agriculture) and its successor RenovAgro program provides a sectoral contrast. Originally designed to finance frontier sustainable agriculture technologies—integrated crop-livestock-forestry systems, biological inputs, and no-till farming—ABC channelled an average of USD 539 million annually between 2015-2020, representing only 1.7% of total rural credit despite its strategic importance (CPI, 2023). The program's limited uptake reflects targeting precision that excluded many smallholders capable only of incremental improvements, creating perceived equity concerns despite economic justification for frontier focus. The 2024/25 RenovAgro rebranding increased the budget to BRL 7.7 billion (USD 1.4 billion), representing 1.9% of the BRL 400 billion Plano Safra rural credit allocation, but maintained tight eligibility criteria requiring adoption of specific low-carbon technologies (USDA, 2024). Critically, monitoring and verification systems remain weak: despite requirements for banks to track financed activities, actual implementation of practices like pasture recovery and no-till farming is not systematically verified, raising questions about whether financing reaches genuinely frontier adoptions versus incremental improvements labelled as sustainable (IISD, 2024). The Brazilian government's 2024 initiative to integrate the ABC+ Plan more tightly with the broader Plano Safra rural credit policy, including one percentage point interest rate reductions for producers maintaining Rural Environmental Registry compliance, attempts to broaden sustainable practice adoption while maintaining some targeting discipline (USDA, 2024).

South Africa's experience reveals distinct challenges in contexts with less developed financial sectors and smaller domestic markets. The country's Just Energy Transition Investment Plan projects financing needs of USD 98 billion over five years, but domestic banking sector capacity to appraise and finance renewable energy projects remains limited, with climate-related lending comprising less than 5% of portfolios for most commercial banks (World Bank, 2024). The absence of dedicated green credit lines comparable to India's Priority Sector Lending or Brazil's RenovAgro means that technology targeting occurs primarily through project-specific negotiations with development finance institutions rather than systematic policy frameworks. Indonesia faces similar institutional capacity constraints, with its JETP (Just Energy Transition Partnership) framework relying heavily on international public finance to catalyze private investment but lacking the domestic financial sector infrastructure to systematically differentiate frontier from incremental technologies.

6.3.2 Dynamic Adjustment to Carbon Price and Technology Maturity

Second, frontier targeting must interact dynamically with carbon pricing and technology evolution—a dimension where policy implementation systematically lags optimal design. Higher carbon prices shift unconstrained firms toward cleaner vintages, redefining what constitutes "frontier." Capelle et al. (2025) demonstrate quantitatively that green credit policies effective at €30 carbon prices become ineffective or counterproductive at €60 without adjustment to cover newly defined frontier technologies. India's renewable energy policy demonstrates both strengths and weaknesses in dynamic adjustment. The country's regular tender-based competitive auctions for solar and wind capacity—reaching 19.7 GW in Q1 2024 compared to 4.2 GW in Q3 2023—provide market-based signals of commercial viability (IEEFA, 2024). As solar tariffs declined from INR 4.63 per kWh (USD 0.05) in 2015 to INR 2.36 per kWh (USD 0.03) recently, policy support increasingly shifted toward enabling infrastructure (transmission charge waivers, grid code amendments for renewable integration) rather than direct generation subsidies (World Bank, 2024). However, institutional inertia persists: concessional financing rates designed when solar PV was frontier continue to apply even after commercial viability improves, potentially subsidizing incremental capacity additions that would proceed under commercial terms.

Brazil's ABC/RenovAgro program exhibits even greater dynamic adjustment challenges. Technologies initially classified as frontier in 2011—such as integrated crop-livestock-forestry systems—have matured substantially, yet eligibility criteria and interest rate subsidies (7% annually for RenovAgro) remain largely unchanged (USDA, 2024; Chambers, 2025). The program's 1.7-1.9% share of total rural credit over fifteen years suggests either very narrow frontier definition or persistent targeting toward technologies that would benefit from broader diffusion support rather than frontier innovation subsidies. South Africa and Indonesia, lacking systematic green credit frameworks, face this challenge in different form: absent baseline policies, establishing any consistent targeting approach proves difficult, much less dynamic adjustment mechanisms.

6.3.3 Coverage Gaps and Political Economy Constraints

Third, frontier targeting necessarily creates coverage gaps that prove politically challenging even when theoretically justified. Restricting support to genuinely frontier technologies means many constrained firms pursuing economically rational incremental improvements receive no assistance—appropriate from efficiency perspective (avoiding subsidization of pecking-order progression that would occur anyway) but creating distributional tensions. Brazil's ABC+ experience illustrates this tension acutely. Limiting support to frontier sustainable agriculture technologies effectively excludes most smallholders in the Pronaf (National Program for Strengthening Family Farming) segment, who account for 70% of domestic food production but often lack capacity to adopt capital-intensive integrated systems or biological inputs requiring technical expertise (CPI, 2025). The government's response—creating Pronaf ABC+ as a dedicated subprogram with lower technical requirements—dilutes frontier targeting to address equity concerns, but risks subsidizing incremental improvements while genuine frontier adoptions remain underfinanced. India confronts related tensions through its Priority Sector Lending mandates, which require 40% of bank credit to priority sectors but create cross-subsidization wherein commercial banks fulfil mandates through lending to large, creditworthy renewable energy developers rather than constrained firms needing support, effectively inverting the intended targeting (Chakravarty et al., 2024).

More fundamentally, the information and monitoring requirements for precise frontier targeting exceed institutional capacity in most emerging economies. CPI (2024) documents that India lacks fully operationalized green finance taxonomy as of 2024, limiting banks' ability to systematically differentiate technologies. Brazil's monitoring deficits—where financed activities are reported but not verified—create opportunities for firms to receive frontier-targeted support while implementing incremental or no changes. South Africa and Indonesia, with less developed regulatory frameworks, face these challenges more acutely. The practical implication is that frontier targeting as implemented frequently deviates substantially from optimal design, either through administrative incapacity to identify frontiers precisely or political pressure to broaden coverage to address equity concerns.

6.3.4 Free Permit Allocation Under Financial Constraints

The role of free permit allocation in carbon pricing systems takes on distinct significance when firms face financial constraints—a dimension largely absent from emissions trading system design but crucial for understanding implementation effectiveness in emerging economies. Capelle et al. (2025) demonstrate through calibrated general equilibrium modelling that allocating free emissions permits fundamentally alters carbon pricing impacts when firms face binding financial constraints. Free permits function as transfers enabling constrained firms to retain earnings, accumulate net worth, and relax borrowing constraints faster than under auction systems where permit costs reduce available financing. Additionally, free permits incentivize new firm entry by reducing capital requirements for market participation, potentially offsetting emission reductions through scale expansion.

Quantitatively, Capelle et al. show that raising carbon prices from €30 to €60 under pure auction systems cuts emissions 45% but reduces GDP by 6.7%. With 50% free permit allocation—half of carbon price revenues returned to firms in proportion to baseline emissions—emissions decline 41% with effectively zero GDP reduction, achieving nearly equivalent environmental outcomes without aggregate economic costs. This result contrasts sharply with standard economic theory in frictionless environments where permit allocation method is irrelevant to efficiency (affecting only distribution). The mechanism operates through two channels: income effects (free permits provide resources for constrained firms to finance technology upgrades) and entry effects (reduced barriers enable new firms to enter with cleaner technologies). The relative importance of these channels depends on the severity of financial constraints, firm size distribution, and technology characteristics—dimensions varying substantially across the four countries examined.

6.3.5 Implementation Challenges and Country Experiences

Country implementation reveals both opportunities and fundamental challenges in leveraging free permits to address financial constraints. The European Union ETS, while not an emerging economy case, provides instructive precedent: historical allocation of substantial free permits to covered installations protected competitiveness but created perverse incentives. Allocation based on historical emissions (grandfathering) rewarded past pollution and created strategic incentives to inflate baseline emissions. Subsequent shifts toward benchmarking—allocating permits based on best-available technology standards rather than historical emissions—improved efficiency but maintained the fundamental challenge that allocation mechanisms rarely differentiate by firm financial status. Optimal allocation from Capelle et al.'s (2025) perspective would target constrained firms disproportionately (enabling them to finance technology upgrades) while phasing out support for unconstrained firms already capable of frontier technology adoption. However, identifying firm financial constraint status and calibrating differentiated allocation poses immense practical and political difficulties not yet attempted in any jurisdiction.

None of the four countries examined operates economy-wide emissions trading systems that would permit systematic analysis of free permit allocation effects, though carbon pricing mechanisms exist in various forms. India launched legal framework for a national carbon credit market in 2023 (World Bank, 2024) but implementation remains nascent. South Africa's carbon tax, introduced in 2019, applies relatively modest rates (ZAR 159 per ton CO_2e, approximately USD 9) with extensive exemptions and allowances effectively reducing actual rates to ZAR 6-12 per ton for most emitters—too low to generate meaningful constraints but creating precedent for future price increases that may bind (Burton & Winkler, 2023). Brazil and Indonesia lack economy-wide carbon pricing, though sectoral mechanisms exist (Brazil's renewable energy certificates in electricity sector, Indonesia's coal levy).

The theoretical insights regarding free permits nevertheless bear directly on policy design questions facing these countries as they develop carbon pricing frameworks. The key insight is that free permit allocation can serve a dual function in emerging economies: not merely transitional support to ease political economy constraints (as commonly understood) but an economically justified mechanism to address financial market failures that would otherwise prevent constrained firms from responding efficiently to carbon prices. This reframes the normative assessment of free allocation from "second-best compromise necessary for political feasibility" to "potentially efficiency-enhancing instrument addressing multiple market failures simultaneously."

However, several caveats temper this optimistic interpretation. First, the positive efficiency effects of free allocation documented by Capelle et al. emerge under specific assumptions about how firms use additional resources: if free permits are distributed as returns to shareholders rather than retained for investment, the financial constraint relief mechanism fails. Ensuring permits reach operationally binding constraints requires either restricting allocation to reinvestment (difficult to monitor and enforce) or allocating to firm types statistically likely to face constraints (crude proxy creating its own distortions). Second, the optimal allocation formula—targeting constrained firms disproportionately—creates severe adverse selection problems: firms have incentives to appear constrained to receive higher allocations, potentially requiring intrusive monitoring of financial positions that may prove politically infeasible. Third, the positive assessment of free permits in Capelle et al. focuses on aggregate efficiency (GDP and emissions) but does not address distributional concerns. Free allocation based on historical emissions or production benchmarks may concentrate benefits among incumbent firms, creating barriers to entry for new competitors with potentially superior technologies.

6.3.6 Integration with Broader Policy Frameworks

The interaction between free permit allocation and other policy instruments—particularly green credit policies—receives limited attention in existing literature but proves crucial for implementation effectiveness. If green credit policies successfully relax financial constraints for frontier technology adoption, the efficiency rationale for free permit allocation diminishes firms no longer require permit-based income transfers to finance technology upgrades. Conversely, if green credit programs fail to reach constrained firms (due to targeting errors, monitoring failures, or coverage gaps discussed earlier), free permit allocation may substitute as a less precisely targeted but more comprehensive mechanism to address financial constraints. The optimal policy mix depends on relative implementation capacities: if financial sectors can effectively identify and serve constrained firms pursuing frontier technologies, targeted green credit proves superior; if administrative capacity limits precise targeting, broader free permit allocation may achieve better outcomes despite theoretical inferiority.

India's experience suggests policy complementarity rather than substitution. Priority Sector Lending mandates and state-backed renewable energy finance from IREDA/PFC/REC reach large, creditworthy developers effectively but leave smaller, more constrained firms underserved. A carbon pricing system with differentiated free allocation favouring smaller firms could complement existing green credit by addressing the "missing middle" of constrained firms that can adopt incremental improvements (benefiting from permit income support) but cannot access frontier technologies (requiring green credit). Brazil's context suggests different complementarities: rural credit systems reach small farmers effectively for incremental improvements (through Pronaf) but frontier technologies remain underfinanced. Free permit allocation alone would likely prove insufficient without green credit mechanisms specifically targeting frontier agricultural technologies but could ease adjustment costs for smallholders adopting incremental practices. South Africa and Indonesia, with less developed financial sectors and green credit frameworks, might benefit more from free permit allocation as primary policy instrument, accepting lower targeting precision to achieve broader financial constraint relief. These country-specific considerations underscore that optimal policy design depends critically on institutional capacity and cannot be derived from theory alone.

6.4 Alternative Financing Models: India's Innovation and Limitations

Larsen's (2025) analysis of India's "state-organized financing with limited fiscal expenditure" challenges fundamental assumptions in green industrial policy literature about financing prerequisites. The conventional view holds that countries without substantial fiscal capacity or large international capital inflows cannot finance adequate green transitions. India's solar manufacturing and deployment success—achieved with only USD 1.8 billion annual fiscal expenditure and 85% domestic financing—suggests this assumption may be overly restrictive.

India's model demonstrates that non-fiscal state financing tools can mobilize substantial capital: state-owned enterprises providing demand stability and lower-cost capital, state-owned financial institutions directing lending through mandates rather than budget allocations, and state-owned distribution companies de-risking through long-term purchase agreements. This approach exploits India's high level of state ownership (70% of banking sector) to organize financing without direct budget impacts.

However, critical limitations constrain extrapolation. First, India benefits from domestic market scale (1.4 billion population) enabling demand-driven industrial development unavailable to smaller economies. Second, strategic focus on single technology (solar) reflects resource constraints forcing selectivity, contrasting with diversified approaches in countries with greater fiscal capacity. Third, even India's model leaves mid-cap firms substantially constrained—the "missing middle" receiving less than 10% of climate finance despite accounting for 45% of manufacturing emissions (IRENA & CPI, 2025; Larsen, 2025).

Fourth, India's close government-conglomerate relationships—what Subramanian (2018) terms "crony capitalism"—raise questions about efficiency and equity. Larsen (2025) documents that large conglomerates (Reliance, Adani, Tata) dominate solar manufacturing precisely because they "know the right people" and can "navigate the Indian political system," suggesting that India's approach may not translate to countries with different political economy structures.

Fifth, whether India's solar success extends to sectors where firm constraints bind more severely remains uncertain. Industrial decarbonization, sustainable agriculture, and green hydrogen require frontier technology adoptions by diverse firm populations including smaller, more constrained actors. India's manufacturing success occurred in context where large conglomerates could dominate—a condition that may not hold across all critical emissions sectors.

6.5 Overview of findings

This analysis contributes to three theoretical debates by incorporating firm-level financial constraint heterogeneity.

Green Industrial Policy: We demonstrate that financial architecture represents critical enabling condition not just through aggregate capital availability but through differential impact on frontier versus incremental technology adoption across heterogeneous firms. The pecking order mechanism (Capelle et al., 2025; Lanteri & Rampini, 2025) implies that policies must explicitly address firm financial position to achieve desired technology targeting—a dimension largely absent from existing literature (Mazzucato, 2015, 2021; Rodrik, 2014). India's experience (Larsen, 2025) shows that non-fiscal state financing tools can substitute for fiscal capacity to some degree, but firm heterogeneity effects persist even in relatively successful cases.

Development Finance: We provide evidence challenging the "Wall Street Consensus" (Gabor, 2021) when firm heterogeneity is considered. Private capital gravitates toward incremental technology improvements by moderately constrained firms (high leverage, questionable additionality), while frontier adoptions by severely constrained firms require public capital shares that private investors resist (low leverage, high additionality). This systematic pattern suggests fundamental tension between leverage maximization and genuine catalytic impact. However, India's experience (Larsen, 2025) suggests greater domestic policy space than Wall Street Consensus framework implies, provided countries possess requisite state capacity over financial institutions and enterprises.

Just Transitions: We document how firm heterogeneity creates systematic bias against supporting workers and communities dependent on constrained firms. Larger, unconstrained firms smooth transitions, while smaller, constrained firms face stark choices driving worker displacement. This dimension extends just transition literature beyond worker/community focus to recognize firm-level heterogeneity as distributional determinant.

An additional theoretical contribution emerges from comparing resource-rich contexts: the potential for bioeconomy as bridging mechanism between conservation and development goals. Brazil's National Bioeconomy Strategy (2024) and emerging initiatives in Indonesia demonstrate attempts to address the development-conservation trade-off through value-addition to biodiversity rather than its conversion. However, both countries face challenges in translating bioeconomy potential into scaled implementation—Brazil's Amazon bioeconomy generated only R$5.4 billion annually in Pará state despite vast potential (Costa et al., 2021), while Indonesia's similar initiatives remain largely aspirational. The constraint appears to be infrastructure for value chain integration rather than resource availability: processing facilities, quality certification systems, and market access mechanisms that enable small-scale forest communities to capture value without conversion to agriculture. This suggests a financing gap distinct from technology adoption—one requiring investment in market-making infrastructure rather than production subsidies.

7. Conclusions

This comparative analysis reveals systematic gaps between stated policy ambitions and realized implementation outcomes across four major emerging economies. While policy approaches vary substantially—from India's state-organized financing model to South Africa's JETP framework—all four countries exhibit financing shortfalls ranging from 33% to 77% of stated targets. However, interpreting these implementation gaps through the analytical framework of firm-level financial heterogeneity developed by Capelle et al. (2025) and applied empirically by De Haas et al. (2024) suggests that aggregate capital scarcity represents only a partial explanation. The underlying constraints operate through firm-specific financial positions that systematically structure technology adoption patterns and thereby limit policy effectiveness.

The pecking order mechanism documented by Capelle et al. (2025) generates observable patterns wherein financially constrained firms adopt incrementally cleaner but still emission-intensive technologies, while only unconstrained firms access frontier low-emission capital vintages. This heterogeneity manifests in multiple policy domains. Green credit programs face a fundamental targeting challenge: supporting frontier technology adoption requires precise identification mechanisms to avoid subsidizing incremental improvements that constrained firms would have pursued independently along their optimal pecking order trajectories. Such precision proves administratively demanding and requires dynamic adjustment as technologies mature and relative prices shift. Blended finance structures confront an inherent tension between leverage maximization—achieved by supporting near-commercial incremental improvements—and genuine additionality, which requires substantial public capital shares to enable frontier technology adoption by constrained firms. Observed configurations gravitate toward high-leverage arrangements that may generate limited emission reductions beyond business-as-usual trajectories. Just transition programs exhibit systematic gaps in serving workers and communities dependent on financially constrained firms that cannot finance technology transitions even with worker retraining support. This pattern indicates that labour market interventions alone prove insufficient without complementary firm-level financial mechanisms. Free permit allocation under carbon pricing regimes can substantially reduce economic costs when firms face financial constraints, yet optimal allocation mechanisms would require differentiation by firm financial position—a dimension not yet incorporated in existing policy designs.

The alternative financing model demonstrated by India—characterized by Larsen (2025) as "state-organized financing with limited fiscal expenditure"—challenges conventional assumptions that fiscal capacity or international capital inflows constitute absolute prerequisites for scaled green industrial policy implementation. India's approach leverages domestic market scale, concentrated state ownership across the financial sector, and strategic focus on a single mature technology (solar PV) to mobilize private capital with minimal public expenditure. However, the specific conditions enabling this model—particularly financial sector state control and domestic market scale sufficient to justify manufacturing investments—constrain its applicability to smaller economies or sectors with less mature technologies. Moreover, even within India's relatively successful framework, mid-capitalization firms facing moderate financial constraints remain systematically underserved, suggesting that state coordination alone does not fully resolve firm heterogeneity challenges.

Across all four country cases, regional cooperation mechanisms remain limited despite apparent complementary capabilities. Brazil's green hydrogen initiatives involve partnerships predominantly with European buyers and technology providers; Indonesia's JETP framework explicitly channels international public finance; India's renewable energy expansion includes export-oriented manufacturing; South Africa's JETP incorporates peer learning components. However, South-South cooperation remains underdeveloped relative to potential synergies: Brazil's biofuel production experience could inform parallel programs in India and Indonesia; India's solar manufacturing capabilities could support deployment across African and Latin American markets; Indonesia's geothermal development expertise could benefit volcanic regions globally. Current cooperation architectures privilege North-South relationships, potentially missing opportunities for peer learning, technology adaptation, and coordinated negotiating positions in international climate finance forums. The institutional explanation for this South-South cooperation deficit warrants further investigation, as it may reflect coordination failures, historical aid architecture path dependencies, or strategic calculations by Northern donors and technology providers seeking to maintain leverage.

The empirical patterns documented here—complemented by global finance data (IRENA & CPI, 2025), firm-level theoretical predictions (Capelle et al., 2025), and country-specific innovations (Larsen, 2025)—indicate that effective policy design must differentiate instruments according to investment characteristics rather than applying uniform approaches. De Haas et al. (2024) demonstrate that credit constraints reduce investment in redeployable green assets (machinery, vehicles) by 30-36 percentage points, suggesting that preferential credit lines could catalyze substantial increases in this category. Conversely, credit constraints show minimal effects on site-specific abatement infrastructure, indicating that alternative de-risking instruments—first loss guarantees, subordinated public debt—would prove more effective by addressing collateral deficiencies that standard lending cannot accommodate. Management capacity improvements, which affect all investment categories equally, require distinct intervention modalities emphasizing technical assistance and knowledge transfer rather than financial instruments alone. Montague et al. (2024) estimate that reducing weighted average cost of capital by 200 basis points across developing economies would lower cumulative clean energy financing costs by USD 15 trillion through 2050, indicating substantial potential returns to comprehensive de-risking and institutional development programs. However, realizing these gains requires coordinated deployment across risk-sharing instruments, capacity-building initiatives, and financial sector institutional reforms—a policy integration challenge that existing fragmented approaches have not achieved.

Several dimensions of firm-level financial heterogeneity and its policy implications remain underexplored. Future research extending firm-level analysis across broader country samples could test whether the patterns observed here generalize or exhibit country-specific variations. Examination of interaction effects between domestic financial sector development and green credit policy effectiveness would clarify whether financial deepening amplifies or substitutes for targeted green finance interventions. Assessment of optimal policy instrument mixes incorporating implementation costs—monitoring requirements, verification systems, moral hazard risks—would provide more realistic cost-benefit analysis than our qualitative assessment permits. Longitudinal studies tracking how firms progress through technology pecking orders under different policy regimes would illuminate dynamic adjustment mechanisms and identify critical intervention timing. Additionally, political economy analysis of why observed policies deviate systematically from theoretically optimal designs—why blended finance emphasizes leverage over additionality, why green credit programs rarely differentiate by firm financial position—would contribute to understanding implementation constraints beyond technical design considerations.

Looking forward, green industrial financing effectiveness will increasingly reflect not merely capital costs or availability but rather institutional autonomy—the capacity to navigate fragmented global financial architectures while preserving policy space and infrastructure control (Farrell & Newman, 2023). For large emerging economies including India, Brazil, and Indonesia, the challenge evolves from managing rollover risk toward preserving infrastructure optionality: maintaining control over financing structures in ports, power grids, and digital networks that generate long-lived path dependencies (Xu & Yao, 2015; Gallagher, 2016). Project-level financing structures increasingly determine whether green infrastructure development locks in technological sovereignty or structural dependence (Tagliapietra & Zachmann, 2023). Rapid improvements in cross-border settlement infrastructure reduce transaction frictions but may obscure deteriorating external positions until adjustment becomes unavoidable—a particular risk where institutional capacity to manage current account deficits remains limited (Eichengreen et al., 2022).

For middle powers, preserving strategic optionality depends on three conditions: economic scale, institutional credibility, and geopolitical manoeuvring room (Roberts et al., 2023). India's positioning across competing semiconductor supply chains, Brazil's nearshoring advantages in clean technology manufacturing, and Vietnam's diversified infrastructure relationships while integrating into US-Japan production networks illustrate how institutional depth can enable multi-system navigation—provided intensifying geopolitical competition does not force binary alignments (Steinberg & Shih, 2024). Against substantially higher public debt ratios than prevailed in the early 2010s, the fiscal cost of policy errors has risen markedly (Kose et al., 2021). Whether analytical frameworks centered on cyclical factors and interest rate spreads can adequately capture structural differentiation in green transition capacity remains an open question. The evidence presented here suggests that by the late 2020s, outcomes may diverge primarily according to institutional positioning rather than conventional macroeconomic fundamentals, indicating that current modelling approaches may systematically underestimate the importance of institutional factors in determining transition trajectories.

The persistent implementation gaps documented across four diverse emerging economies—despite varying political systems, economic structures, and climate policy frameworks—indicate that financial constraints at both firm and system levels constitute binding rather than merely limiting factors in green industrial transitions. Addressing these constraints requires moving beyond aggregate capital mobilization toward differentiated policy designs that explicitly account for firm financial heterogeneity, technology characteristics, and institutional capacity. Whether emerging economies successfully navigate the dual mandate of decarbonization and development depends less on discovering novel policy instruments than on systematically applying existing theoretical and empirical insights regarding how financial constraints shape technology adoption patterns. The integration of firm heterogeneity into policy design—recognizing that frontier technology adoption requires financial support calibrated to firm-specific constraints—represents a crucial frontier for both research and implementation effectiveness.

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