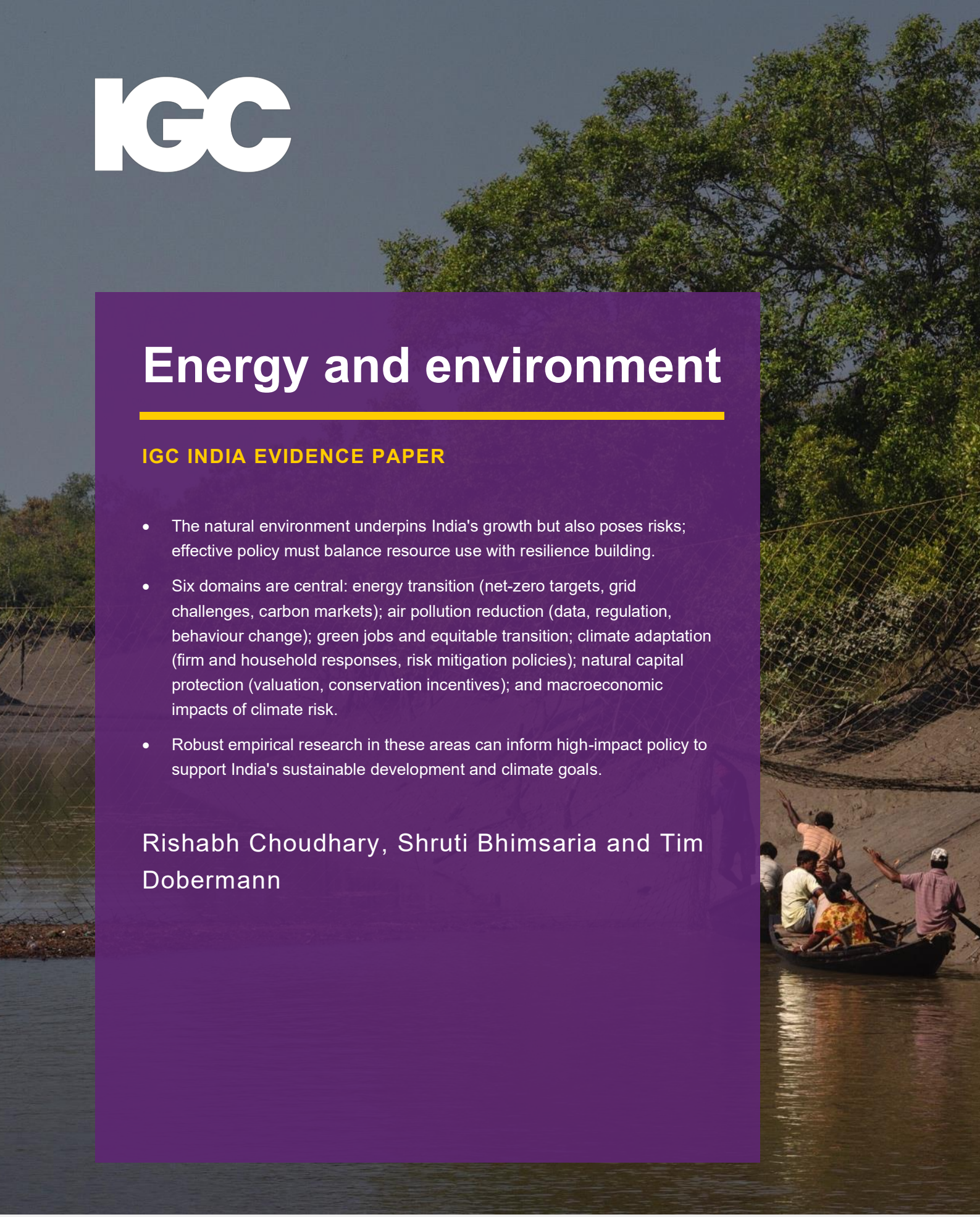

Energy and environment

IGC INDIA EVIDENCE PAPER

- The natural environment underpins India's growth but also poses risks; effective policy must balance resource use with resilience building.
- Six domains are central: energy transition (net-zero targets, grid challenges, carbon markets); air pollution reduction (data, regulation, behaviour change); green jobs and equitable transition; climate adaptation (firm and household responses, risk mitigation policies); natural capital protection (valuation, conservation incentives); and macroeconomic impacts of climate risk.
- Robust empirical research in these areas can inform high-impact policy to support India's sustainable development and climate goals.

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Parts of this report were edited and formatted using AI tools; all content has been reviewed and edited by the authors.

DIRECTED BY LSE UNIVERSITY OF OXFORD

FUNDED BY UKaid from the British people

Introduction

The natural environment is fundamental to economic growth, providing essential resources such as food, water, energy, and raw materials. However, it also poses significant risks—climate shocks, biodiversity loss, and extreme weather events—that can undermine development and human wellbeing. Managing this duality is critical for India, a country with vast ecological wealth but high climate vulnerability. Policymakers must harness natural resources to drive growth while minimising environmental harm and enhancing resilience where damage is unavoidable.

This report outlines six critical domains central to India's sustainable growth strategy, identifying areas where rigorous research can directly inform high-impact policy. First, India's energy transition—anchored in its net-zero commitment by 2070 and rapid renewable deployment—has made progress but continues to face structural challenges in grid integration, distribution losses, consumer behaviour, and pricing mechanisms. The expansion of market-based instruments, such as carbon markets, underscores the need for robust institutions, credible data, and careful design. Second, addressing air pollution—particularly from industrial activity, vehicles, and open burning—requires improved data infrastructure, innovative regulatory tools like emissions trading, and behavioural and urban mobility reforms. Third, as India shifts toward a low-carbon economy, understanding the employment effects of green growth—including job creation, skill transitions, and gendered impacts—is key to designing an equitable transition. Fourth, adaptation is increasingly urgent as climate shocks threaten productivity, infrastructure, and livelihoods. Research must assess how firms and households adjust to heat, floods, and volatility, and identify policies—such as insurance, resilient infrastructure, and social protection—that can mitigate risks. Fifth, safeguarding India's natural capital—forests, biodiversity, and ecosystem services—is essential for long-term economic resilience. Priorities include strengthening valuation, aligning incentives with conservation, and integrating nature into planning. Finally, climate change has significant macroeconomic implications, affecting inflation, financial stability, and public investment. Embedding climate risk into fiscal, monetary, and financial policy frameworks is a frontier challenge. Drawing from the International Growth Centre's global evidence paper on energy and environment (Balboni et al., 2024), this report highlights opportunities for empirical research to generate actionable insights that support India's climate and development goals.

Energy

India's energy transition lies at the heart of its development and climate strategy. As the world's third-largest emitter and a country still undergoing structural transformation, India must balance rising energy demand with decarbonisation, energy security, and equity. While the natural environment provides the resources necessary for growth—such as coal, solar radiation, wind, and hydropower—it also contributes to long-run risks through high emissions intensity, grid vulnerability, and growing exposure to climate-related shocks. Therefore, India's energy system must be restructured to meet development needs without locking into high-carbon infrastructure.

India has made significant progress towards its Paris Agreement commitments. Its updated Nationally Determined Contributions (NDCs) articulate the "Panchamrit" goals, including increasing non-fossil energy capacity to 500 GW by 2030; meeting 50% of energy demand from renewables; reducing projected carbon emissions by one billion tonnes; cutting emissions intensity of GDP by 45% from 2005 levels; and achieving net-zero emissions by 2070. According to India's fourth Biennial Update Report (BUR-4), emissions intensity fell by 36% between 2005 and 2020, and non-fossil fuel capacity had reached 47% of the energy mix by December 2024—placing India within reach of its 2030 targets. Additionally, forest and tree cover have created a cumulative carbon sink of 2.29 billion tonnes, approaching the NDC target of 2.5–3.0 billion tonnes by 2030.

However, challenges persist. The energy sector remains the single largest contributor to emissions—accounting for roughly 76% of the national total—even as land use and forestry offset around 22%. Meeting India's climate and growth objectives will require deeper reform of its energy system, supported by robust data, flexible institutions, and well-designed markets. In 2022, the Energy Conservation Act was amended to enable the launch of the Carbon Credit Trading Scheme (CCTS), introducing compliance and offset mechanisms to reduce emissions in energy-intensive sectors such as steel, cement, and aluminium. This amendment signals a growing reliance on market-based instruments to achieve climate targets.

India's Long-Term Low Emission Development Strategy (LT-LEDS) charts a broad pathway for climate action, identifying seven key transitions—from low-carbon electricity and industrial systems to sustainable urbanisation and climate-resilient infrastructure. However, translating this vision into action requires overcoming technical and financial barriers, institutional coordination failures, and the absence of a robust ecosystem for data-driven policymaking. Within this landscape, two policy domains stand out as foundational to India's energy transition: first, the design and scaling of inclusive, high-integrity carbon

markets and pricing instruments, and second, the integration of renewable energy and efficiency-enhancing technologies across the grid and distribution systems.

India's energy transition is pivotal for meeting its net-zero targets and sustaining economic growth, expanding access to affordable energy, and enhancing resilience. Market-based instruments can play a central role in delivering cost-effective mitigation. At the same time, reforms in grid infrastructure, DISCOM performance, consumer behaviour, and finance are necessary to ensure that clean energy is deployed at scale. The effectiveness of these efforts will depend not only on technological and regulatory solutions but also on bridging critical knowledge gaps—particularly around behavioural responses, institutional capacity, and political economy constraints. Future research and policy innovation must generate credible, context-specific evidence to support an energy transition that is efficient, equitable, and growth-aligned. The following sections examine these two domains in detail, outlining India's recent progress, ongoing challenges, and key priorities for policy and research.

I. Markets and mechanisms for low-carbon development

As one of the fastest-growing major economies, India faces the challenge of reducing emissions while sustaining high economic growth. The country's developmental needs—ranging from industrial expansion to improved access to energy—necessitate a climate strategy that is both ambitious and economically viable. In this context, well-designed market-based instruments can help align environmental goals with India's growth trajectory. Instruments such as carbon markets, pricing mechanisms, and fiscal incentives offer a flexible, cost-effective way to incentivise emissions reductions across sectors while minimising economic distortions. They can support technological upgrading, resource efficiency, and long-term competitiveness, particularly in trade-exposed sectors. However, achieving this balance requires careful policy design, robust institutions, and a strong foundation of credible data.

India has begun to make important strides in this direction, notably through the Carbon Credit Trading Scheme (CCTS) launch in 2023. Building on the earlier Perform-Achieve-Trade (PAT) mechanism, the CCTS marks a shift toward a formal compliance carbon market. The scheme sets sectoral emissions obligations for nine energy-intensive industries—including steel, cement, and aluminium—and creates offset opportunities in sectors including agriculture, forestry, and renewable energy. While the institutional architecture is promising, the ultimate success of the CCTS will depend on addressing several challenges: ensuring robust MRV (monitoring, reporting, and verification) systems, preventing market manipulation or over-crediting, managing price volatility, and aligning sectoral caps with India's broader decarbonisation goals.

Here, India's experience with subnational pollution markets offers valuable lessons. Pilots such as the Emissions Trading Scheme for Particulate Matter (ETS-PM) in Gujarat—implemented by IGC-affiliated researchers in partnership with the Gujarat Pollution Control Board—demonstrated that emissions trading can reduce air pollution (by 24%) more cost-effectively than traditional regulation, without imposing additional costs on firms. These pilots are not just isolated experiments; they are building regulatory capacity, data infrastructure, and technical expertise in state pollution control boards and among market participants. As more states—such as Maharashtra and Rajasthan—explore similar schemes, a foundation is laid for national-scale implementation. Moreover, these markets are already delivering climate and public health co-benefits by targeting pollutants that often accompany carbon emissions. As a result, they can support multiple policy goals: reducing GHGs, improving air quality, and advancing industrial competitiveness.

International experience reinforces this potential. For example, Goulder et al. (2023) assess China's national carbon market, which employs a tradable performance standard (TPS), highlighting lessons on efficiency, sectoral coverage, and dynamic baseline setting. These lessons are highly relevant for India as it refines the CCTS and develops supporting institutions. India's early experiments with market-based instruments have already created a valuable testbed that yields environmental gains and lays the institutional groundwork for a more ambitious and credible national carbon market. Future research and policy design should focus on scaling these efforts, understanding behavioural responses from firms, and ensuring environmental integrity and equity in market outcomes.

India's exposure to international carbon pricing pressures has also grown. The European Union's Carbon Border Adjustment Mechanism (CBAM), which imposes tariffs on carbon-intensive imports, will directly affect Indian steel, aluminium, and fertiliser exports. The tariffs pose risks for competitiveness and trade but also create an impetus for India to accelerate domestic decarbonisation in exposed sectors. There is a pressing need for research to assess the likely economic impacts of CBAM across different sectors and firm sizes, identify which exporters are most vulnerable, and evaluate the effectiveness of various policy responses.

In parallel, voluntary carbon markets (VCMs) offer an additional pathway to finance mitigation, particularly in sectors not covered by the compliance market. India has considerable potential to generate high-integrity carbon credits through nature-based solutions such as land use, forestry, agriculture, and decentralised waste management— in sectors that also deliver co-benefits for rural livelihoods and ecosystem resilience. However, concerns around additionality, permanence, and over-crediting continue to undermine credibility,

particularly in contexts with limited verification and enforcement capacity. These challenges are compounded by institutional gaps and a limited understanding of how market participants—such as landowners, aggregators, and project developers—interact, negotiate, and respond to incentives. There is a significant research opportunity to study the behavioural dynamics of these actors, the impact of different contract structures on project quality, and the role of trust, information, and infrastructure in enabling long-term participation.

As India moves towards a more market-oriented approach to climate mitigation, developing instruments that enable effective price discovery and active industry participation will be essential. Transparent, reliable price signals can guide investment, encourage innovation, and reduce the cost of compliance while fostering a competitive environment for low-carbon technologies. At the same time, policy instruments must actively engage firms as regulated entities and partners in shaping the transition, requiring close coordination with industry bodies, sector-specific roadmaps, and mechanisms that reward early movers.

II. Enabling India’s energy transition

Achieving India's ambitious climate and development goals hinges on successfully transforming its energy system—from one dominated by fossil fuels to a cleaner, more efficient, and resilient model. While significant progress has been made in scaling up renewable energy capacity, particularly solar and wind, challenges persist in integrating this capacity into the grid, addressing persistent distribution inefficiencies, and mobilising the technological and behavioural changes needed to drive system-wide transformation. A well-rounded transition must address the supply, network infrastructure, institutional capacity, and demand-side dynamics underpinning energy service delivery.

a) Strengthening grid flexibility and integration

A critical bottleneck lies in the limited flexibility of India's power grid. As the share of variable renewable energy increases, maintaining grid stability will require major investments in storage, forecasting, and grid-balancing mechanisms. Technologies such as battery storage, pumped hydro, and flexible thermal capacity must be strategically deployed to manage intermittency and peak loads. Research is urgently needed to assess the cost-effectiveness of these technologies under Indian conditions and to inform investment decisions on the appropriate mix of firm and flexible power sources.

b) Addressing distribution sector fragilities

At the same time, the persistent financial fragility of electricity distribution companies (DISCOMs) poses a major risk to the effectiveness of the energy transition. Their poor financial health—driven by high technical and commercial losses, delayed payments, electricity theft and inadequate cost recovery—

discourages investment in grid upgrades, weakens incentives to purchase renewable power, and limits their ability to adopt technologies critical for a flexible and low-carbon energy system. Despite multiple rounds of reform and central support—most recently through the Revamped Distribution Sector Scheme (RDSS)—losses remain high, particularly in lower-income states. Technological fixes, such as the rollout of smart meters, can help reduce losses and improve operational efficiency. However, their success depends on consumer acceptance, billing accuracy, and institutional readiness. Research can play a key role in understanding implementation bottlenecks, evaluating impacts on revenue recovery, and identifying conditions under which such technologies succeed.

c) Understanding and shaping consumer behaviour

Understanding and shaping consumer behaviour will also be central to the transition. Tariff structures are often politically constrained and poorly targeted, leading to inefficient consumption and unsustainable subsidy burdens. Agricultural consumers, in particular, benefit from deeply subsidised power, which discourages conservation and imposes fiscal pressure on state budgets. Designing effective demand-side policies requires better data on electricity usage, price responsiveness, and payment behaviours across consumer segments. There is a pressing need for empirical studies that evaluate the impact of time-of-use pricing, smart metering feedback, and subsidy reforms, particularly in rural and peri-urban contexts where behavioural responses may diverge from urban norms. At the same time, smart technologies present an opportunity to modernise distribution and improve service delivery. Research can help identify enabling conditions, assess cost-benefit trade-offs, and explore how to build trust and uptake among consumers and local utilities.

d) Technological advancements and finance

Financing the energy transition remains a structural constraint. While India has attracted significant capital into grid-scale renewables, large investment gaps persist in distribution infrastructure, storage, and decentralised energy systems such as rooftop solar. Mobilising private capital at scale will require supportive financial instruments—such as blended finance, green bonds, and credit guarantees—as well as regulatory clarity and greater ease of conducting business. Evaluating the effectiveness of these mechanisms, particularly in lower-income states or underserved sectors, is an important area for future research.

A politically sustainable energy transition must also address subsidy reform and just transition challenges. Policies must account for the livelihoods, fiscal implications, and distributional impacts of decarbonisation—especially for politically sensitive groups such as farmers and informal workers. Research that unpacks the political economy of energy reform, identifies viable compensation

mechanisms, and tests narratives that build public support can help craft durable, inclusive transition strategies.

Environment

I. Air pollution

Air pollution is one of India's most urgent and complex environmental challenges, with far-reaching consequences for public health, labour productivity, and long-term economic development. Major contributors include industrial emissions, vehicular exhaust, open burning of crop residues, and household biomass use. In 2019, ambient and household air pollution caused approximately 1.67 million premature deaths, leading to an estimated economic loss of USD 28.8 billion—equivalent to around 1.36% of India's GDP (Lancet, 2019).

Urban areas are particularly affected, with pollution levels frequently exceeding safe thresholds for extended periods. These effects are especially evident in the National Capital Region, where severe winter pollution episodes have repeatedly forced school closures lasting several days or even weeks. Vehicular emissions—especially from diesel trucks, two-wheelers, and poorly regulated public fleets—combine with industrial pollutants and construction dust to produce severe smog events. Traffic congestion, poor last-mile connectivity, and behavioural preferences for private vehicles further exacerbate the crisis. Informal settlements near traffic corridors or industrial clusters bear disproportionate exposure, compounding health inequities and reducing economic opportunity.

These problems are further magnified by the lack of a robust, reliable, and spatially dense data infrastructure. India's existing monitoring network—managed by the Central and State Pollution Control Boards—covers only a fraction of its cities and towns, with large gaps in peri-urban and rural areas. Many small industrial zones and informal workspaces fall entirely outside the purview of regular monitoring. The absence of high-resolution, real-time pollution data hinders the ability to target interventions, track policy effectiveness, or assess the full economic costs of exposure. This data vacuum also weakens regulatory capacity and undermines public accountability.

Strengthening air quality governance in India thus requires not only sector-specific interventions but also major improvements in environmental data systems, institutional capacity, and policy coordination. With the right tools and incentives, progress on air pollution can deliver wide-ranging co-benefits, from improved health outcomes and lower healthcare costs to enhanced worker productivity, climate mitigation, and more livable cities.

a) Strengthening air pollution data infrastructure

India's current monitoring infrastructure remains limited in both coverage and resolution. While metropolitan centres such as Delhi, Mumbai, and Bengaluru have relatively better monitoring networks, decision-making in these large urban areas still relies heavily on a handful of Continuous Emissions Monitoring Systems (CEMS). While technically advanced, these monitoring systems are often too sparse to capture intra-city pollution variability. As a result, large segments of these cities are left unmonitored, creating serious blind spots in policy design and enforcement. Without hyperlocal, real-time data, city governments cannot identify pollution hotspots, accurately assess the impact of interventions, or implement spatially targeted solutions such as low-emission zones, traffic restrictions, or public health advisories. Inadequate data also weakens early warning systems and emergency response during severe pollution episodes, as seen repeatedly in the National Capital Region.

Investing in building high-resolution, publicly accessible datasets in underserved geographies such as Tier-2 cities, industrial belts, and peri-urban settlements is also essential. These data systems can inform smarter urban planning and enable economic modelling of pollution exposure by location, occupation, and income group. Measuring labour productivity losses, education disruptions, and health effects more accurately can strengthen the evidence base for policy prioritisation. Special attention is also needed to monitor indoor air pollution in informal workspaces and low-income households, where biomass and industrial by-products generate high exposure levels.

b) Building market-based institutions and regulatory capacity

India is also beginning to experiment with more flexible, cost-effective regulatory approaches to control pollution. A notable example is the Emissions Trading Scheme for Particulate Matter (ETS-PM) piloted in Surat. Developed in partnership with the Gujarat Pollution Control Board and researchers from the University of Chicago and J-PAL South Asia, the scheme led to a 20–30% reduction in PM emissions. It achieved over 99% compliance without raising firm costs (Greenstone et al., 2025). In addition to environmental gains, the pilot also helped build institutional capacity in emissions monitoring and market regulation. These developments are important not only for scaling similar schemes in other states but also for laying the groundwork for broader carbon market infrastructure, which will require significant investment with time. The co-benefits of particulate matter control—such as reductions in short-lived climate pollutants—also reinforce the strategic value of aligning local air quality goals with national climate objectives.

c) Residual crop burning

Open burning in India is a seasonal but urgent challenge, particularly across northern India during the post-harvest winter months. Crop residue burning in Punjab, Haryana, and western Uttar Pradesh (some of the most polluted states in India) generates vast clouds of $PM_{2.5}$ and black carbon that degrade air quality across the Indo-Gangetic Plain, including in Delhi. Despite regulatory bans and subsidies for in-situ management tools such as Happy Seeders, adoption remains patchy due to cost, labour shortages, and weak enforcement. Interventions must be strengthened through real-time satellite detection, local enforcement alerts, and deeper integration of environmental goals into agricultural policy. Research on the cost-effectiveness and behavioural uptake of solutions like residue collection incentives, ecosystem payments, and crop diversification is needed.

d) Vehicular emissions and urban transportation reforms

This area offers another high-impact frontier. Road transport is now one of the largest contributors to urban air pollution, driven by the rapid rise of private vehicles, poor enforcement of emission norms, and inadequate public transit systems. Diesel-fuelled trucks, two-wheelers, and ageing public fleets contribute heavily to NO_2 and $PM_{2.5}$ levels, especially during peak hours. A multi-pronged strategy is needed: accelerating electric vehicle adoption—particularly for high-usage segments such as delivery fleets and autorickshaws; investing in last-mile connectivity and non-motorised transit to complement metro and BRT expansion; and exploring congestion pricing or low-emission zones to internalise pollution costs. Behavioural nudges like carpooling incentives, real-time pollution displays, or eco-routing apps may also reduce reliance on private vehicles. Rigorous evidence is needed to evaluate these policies in Indian settings—including their distributional impacts—to ensure that clean mobility transitions are effective and equitable.

II. Green growth and jobs

A shift to green growth can potentially deliver environmental gains and employment benefits. As India pursues its energy transition and low-carbon development pathway, understanding the employment consequences of this shift—across sectors, regions, and demographic groups—is crucial. Global evidence suggests that well-designed green policies can generate new jobs, particularly in renewable energy, infrastructure, and environmental services, though effects vary by context and policy design. In India, where employment creation remains a key policy priority, assessing the labour market impacts of green investment and regulation is essential to designing a just transition that supports both growth and equity.

a) Employment effects of green transition

Evidence from advanced economies shows that green growth can positively impact employment, though effects are uneven across sectors and skill levels. In OECD countries, Barra and Ruggiero (2019) found that a 10% increase in green energy production is associated with a 0.3% increase in employment. In Germany, Lehr et al. (2012) projected a net gain of approximately 150,000 jobs by 2030 from renewable energy investments. In the United States, Popp et al. (2020) found that green fiscal stimulus created 15 jobs per USD 1 million invested, particularly in construction and waste management sectors. Vona et al. (2016) found that environmental regulations increased green employment shares modestly, though gains were largely in high-skilled occupations. However, not all effects are positive—Aldieri and Vinci (2018) report that green innovation in R&D-intensive sectors may displace workers, highlighting the need for careful attention to labour market frictions and redistribution.

The evidence base is thinner in developing economies, but some promising results have been seen. Dinkelman (2011) found that rural electrification in South Africa increased women's employment by 13.5 percentage points within five years. Environmental taxes have also positively affected employment across both OECD and non-OECD countries (Noubissi Domguia et al., 2022). Hanna et al. (2024) argue that in lower-income settings, green investments may yield higher employment and productivity gains due to greater marginal returns.

However, India lacks systematic evidence on how its green transition affects employment. Future research could explore which sectors—such as solar, wind, construction, transport, and waste—create jobs and assess their formality, quality, and durability. Given India's labour market heterogeneity, understanding distributional impacts across regions, caste groups, and skill levels is especially critical.

b) Distributional dimensions and gender

The employment impacts of green growth are not neutral. Evidence from South Africa (Dinkelman, 2011) underscores the transformative role of green infrastructure in increasing women's employment. Similar dynamics may be relevant in India, where gender disparities in labour force participation remain persistent. Analysing how renewable energy expansion, urban infrastructure upgrades, and climate-smart agriculture influence women's work opportunities—particularly in rural areas—can inform the design of inclusive green investments.

Likewise, a just transition must account for potential job losses in carbon-intensive sectors. Lessons from Aldieri and Vinci (2018) suggest that green innovation may displace workers in traditional manufacturing sectors without retraining and social protection. Therefore, India's transition strategy should be

complemented by targeted skilling programmes, labour mobility support, and income protection to mitigate transition risks for vulnerable workers.

c) Policy instruments and long-term effects

Environmental regulations, green public procurement, and fiscal instruments such as green subsidies or environmental taxes will likely shape labour market outcomes. While global studies such as those by Vona et al. (2016) and Noubissi Domguia et al. (2022) suggest that such policies can stimulate job creation, there is little empirical evidence on how similar interventions have affected employment in India's diverse economic landscape. More research is needed on the effectiveness of current and past schemes—such as the FAME electric vehicle programme or renewable energy auctions—in generating employment and catalysing skill development.

Furthermore, there is a lack of longitudinal evidence on the sustainability of green jobs in India. Popp et al. (2020) highlight the importance of evaluating the post-implementation effects of the green stimulus. In India, where job quality and informality remain concerns, understanding the long-term impacts of green public investment on job stability, wages, and upward mobility is critical.

Future research can address these knowledge gaps to help craft a green employment strategy that supports India's climate objectives while enhancing economic inclusion and resilience.

Climate adaptation

The impacts of climate change on household and firm productivity in India reveal significant challenges, particularly in the agriculture and manufacturing sectors. Indian agriculture, predominantly composed of smallholders, highly depends on favourable weather conditions (including precipitation and temperature). Climate change adversely affects agricultural productivity, leading to increased costs and reduced income for households reliant on farming. Erratic weather patterns have reduced crop yields, with estimates suggesting a 7%–13% decline in agricultural productivity over the next three decades due to global warming (Jacoby et al., 2015). The impacts of climate change have already led to changes in cropping patterns and declining food production (Roy et al., 2024), as well as lower agricultural productivity (Ghosh and Ghosal, 2021), thereby likely affecting rural incomes. Small farmholders face heightened vulnerability, as evidenced in Madagascar (Harvey et al., 2014), necessitating the adoption of climate-smart agricultural practices to enhance resilience and productivity (Joshi and Tyagi, 2019).

There is evidence that global warming impacts the manufacturing sector's output by affecting labour productivity in India. Hotter years reduce economic

output in developing countries, primarily due to decreased worker productivity and increased absenteeism, with climate control mitigating these effects. For instance, Indian factories experience a 2% annual output drop per degree Celsius (Somanathan et al., 2021). Dua and Garg (2024) find that rising temperatures significantly reduce total factor productivity and labour productivity growth in India's economy, particularly in the manufacturing and services sectors, highlighting the need for climate mitigation policies. Beyond labour productivity, climate change can also cause capital and infrastructure damage. Extreme weather can disrupt supply chains, damage transport infrastructure essential for trade, and restrict people's ability to travel. While some of these damages are not explicitly modelled for India, there is scope for future research to provide a comprehensive cost-benefit analysis of different policy options.

India is highly vulnerable to floods, and the severity of extreme events is expected to increase. The country ranks among the top ten globally in terms of human mortality due to floods, and over 10% of its total geographical area is flood-prone (NDMA, GoI). Factors such as considerable population exposure, climate change, and rapid growth and development in flood-prone areas contribute to increased losses from floods. The frequency and associated risks of floods in the Indian sub-continent are projected to increase significantly due to climate change, with multi-day events rising faster than single-day events, impacting agriculture and infrastructure (Ali et al., 2019).

Empirical evidence indicates that flooding negatively impacts firm performance in the U.S. and Europe. Jia et al. (forthcoming) find that increased flood risk from 1998–2018 reduced U.S. firm entry, employment, and output, lowering aggregate output by 0.53% in 2018, with 23% from direct damages and 77% from long-run adjustments. These findings emphasise the importance of considering firms' and workers' adjustments to flood risk in evaluating natural disaster consequences. Some studies indicate positive growth effects after floods in Europe, as natural disasters provide firms with opportunities to update capital stock and adopt new technologies, acting as "creative destruction" (Noth and Rehbein, 2019; Leiter et al., 2009). Evidence from European firms suggests significant and persistent effects on firm performance, even leading to firm exit. However, frequent floods do not worsen performance, suggesting firms adapt in flood-prone areas (Fatica et al., 2022).

I. Assessing the impacts of climate shocks on firms and workers

Despite growing exposure to climate risks, there is limited systematic evidence on how Indian firms and labour markets are affected by extreme weather events such as flooding and heatwaves. Quantifying the economic consequences of these shocks—on firm entry, productivity, employment, and exit—remains an important research priority. There is also a lack of understanding of how climate

disruptions ripple through supply chains and regional labour markets, particularly in informal and small-scale enterprises that dominate the Indian economy.

While international studies offer valuable insights, most are based on high-income contexts. It is unclear to what extent their findings apply to India, where firms operate under very different institutional, infrastructural, and financial constraints. Comparative research across emerging markets could help illuminate how local conditions shape firm resilience and adaptation.

In particular, the impact of floods on firm performance in India remains underexplored. Research is needed to understand how flooding influences business dynamics, including patterns of firm entry, survival, investment, and employment. Understanding how firms adjust—both in the short and long term—and what factors support or hinder their adaptability is essential for designing effective policy responses. Moreover, comparing adaptation strategies in India with those observed in other settings, such as Europe or the United States, can help identify constraints and opportunities unique to the Indian context. Such work would provide a stronger empirical foundation for policies to improve firm-level climate resilience.

II. Identifying enablers of adaptation and resilience

Understanding the conditions that enable firms and communities to adapt effectively is essential. These include access to finance, reliable infrastructure, local governance capacity, and information systems. For example, credit availability may determine whether firms invest in flood defences or energy-efficient cooling. Similarly, early warning systems, insurance mechanisms, and public investments in climate-resilient infrastructure could significantly reduce losses.

Evidence from Bangladesh demonstrates how financial instruments like disaster insurance can support adaptation. Mobarak et al. (2021) show that flood-affected households offered insurance with a conditional loan were more likely to invest in riskier but higher-return livelihoods, suggesting a pathway for enhancing resilience. Complementary findings from the IGC's evidence paper on sustainable growth highlight the importance of embedding insurance into broader climate resilience strategies in low-income settings (International Growth Centre, 2023).

Another promising area is the integration of climate resilience into social protection programmes. The graduation approach to poverty alleviation—which combines asset transfers, skills training, and mentoring—has shown strong evidence of building household resilience and reducing poverty in multiple countries. Leveraging such programmes to incorporate climate adaptation—

such as climate-resilient livelihoods or disaster preparedness—could strengthen both welfare and climate resilience outcomes.

Despite their importance, few studies rigorously evaluate the effectiveness of these factors in India. There is a pressing need to examine how policy tools—such as targeted subsidies, public works programmes, or urban planning reforms—can build long-term adaptive capacity. Research that links firm and household surveys with geospatial data on hazards and infrastructure could provide valuable insights.

India's vulnerability to climate shocks is increasing. Building a robust adaptation strategy for households, firms, and regions requires bridging these evidence gaps. A stronger empirical foundation will be critical for designing policies that sustain productivity, protect livelihoods, and ensure macroeconomic stability in a changing climate.

Natural capital

Natural capital—ecosystems, biodiversity, and natural resources—is foundational in sustaining economic growth and human wellbeing (Arrow et al., 2012; Dasgupta, 2021). Despite occupying just 2.4% of the world's land area, India harbours 7-8% of all recorded species, including 45,500 floral and 91,000 faunal species, with exceptional endemism in groups like amphibians (110 species) and reptiles (156 species) (Parikh et al., 2012). Its Eastern Himalayas and Western Ghats—two of the world's 34 biodiversity hotspots—exemplify this richness yet remain understudied despite hosting 40% endemic species in the Himalayas and critical amphibian diversity in the Ghats. The degradation of these assets poses significant risks to environmental stability, public health, and economic resilience. For instance, India's vulture population collapse, driven by veterinary drug use, led to a surge in waterborne diseases, with mortality impacts comparable to projected heat-related deaths by the century's end (Frank and Sudarshan, 2023). Similarly, mangrove forests, which protect coastal communities from cyclones, often go undervalued until their loss exacerbates disasters—a lesson starkly illustrated during the 1999 Odisha super-cyclone, where villages shielded by mangroves suffered significantly less damage (Das and Vincent, 2009; Hochard et al., 2019). Such cases underscore the need to integrate natural capital into policy frameworks to mitigate systemic risks.

Globally, ecosystems are under unprecedented strain. The world is experiencing its sixth mass extinction (Kolbert, 2014), while coral reef coverage has declined by over 50% since the 1950s, diminishing vital services like fisheries and coastal protection (Eddy et al., 2021). In India, the Western Ghats exemplify the trade-offs inherent in natural capital management: upstream

forests regulate water flows and prevent soil erosion, but reforestation could reduce runoff critical for irrigating dry-season paddy crops, highlighting conflicts between conservation and local livelihoods (Lele et al., 2011). Meanwhile, tropical peatlands and forests continue to degrade due to agricultural expansion and resource extraction (Barbier and Burgess, 2021; Feng et al., 2022). Although some regions, like Brazil, have demonstrated that deforestation can be curbed through policy intervention (Burgess et al., 2022), sustaining such progress remains challenging, reflecting the fragility of conservation efforts.

Advances in remote sensing have revolutionised environmental monitoring, enabling precise tracking of land use changes (Hansen et al., 2013). These tools have been instrumental in evaluating conservation policies—for example, assessing deforestation drivers in Indonesia (Balboni et al., 2023). However, significant gaps persist in translating data into actionable policies, particularly in low- and middle-income countries like India.

I. Valuation of ecosystem services

Quantifying the economic value of ecosystems is increasingly recognised as a tool for integrating environmental concerns into development policy. India has made notable progress through the Natural Capital Accounting and Valuation of Ecosystem Services (NCAVES) initiative, with ecosystem accounts developed for forests, wetlands, and mangroves. Studies estimate that India's coastal ecosystems generate tens of billions of dollars annually in recreational and protective value (Mukhopadhyay et al., 2020). Forests, similarly, support rural livelihoods and ecosystem functions critical to agriculture, water regulation, and disaster resilience.

Despite this progress, several gaps constrain the policy relevance of valuation efforts. First, there is limited coverage of ecologically important systems such as Himalayan grasslands, peatlands, and urban green areas—ecosystems central to adaptation but poorly quantified. Second, valuation studies often use inconsistent methods and are not regularly updated, limiting their comparability and practical use. Third, ecosystem valuations in actual budgetary and planning processes remain limited. For example, links between valuation data and allocations under the Green India Mission or MGNREGA remain underexplored. Finally, while efforts toward Green GDP accounting are underway, they have yet to influence fiscal policy meaningfully.

Future research should focus on expanding valuation to underrepresented ecosystems, standardising methodologies, and evaluating how ecosystem valuations can more effectively inform planning, investment, and regulation. The aim should be to ensure that natural capital is recognised in environmental terms and as a critical asset within India's broader development strategy.

II. Policy design and local incentives

Effective conservation must align global environmental goals with the interests of local stakeholders. For instance, including women in forest governance in India and Nepal has improved conservation outcomes (Leisher et al., 2016). Similarly, policies must consider the unequal burden of environmental degradation on marginalised communities (Walker, 2012). Many ecosystem services, such as flood regulation, generate off-site benefits, creating a mismatch between who bears the cost and who reaps the rewards (Foster and Briceno-Garmendia, 2010). Resolving such distributive tensions is central to politically feasible conservation. Incentive structures—such as payments for ecosystem services—can help realign local and global interests but require strong institutional capacity and community engagement.

India's diverse ecosystems—from mangroves in the Sundarbans to watersheds in the Western Ghats—present fertile ground for further research. Understanding how these natural systems support livelihoods, health, and climate resilience is essential. To meet this challenge, interdisciplinary collaboration is required, drawing on ecology, economics, and public policy. Future work should prioritise integrating natural capital into economic planning, designing targeted incentives, and expanding data collection efforts to bridge the gap between ecological knowledge and development policy.

Climate and macroeconomic stability

As climate change intensifies, the macroeconomic implications for India are becoming increasingly salient. These include direct impacts on inflation, productivity, financial stability, and long-term growth. Given India's dual challenge of high climate vulnerability and ambitious development goals, integrating climate considerations into macroeconomic and central banking frameworks is no longer optional—it is imperative.

Several evidence gaps in this area in India need to be addressed. First, there is limited India-specific quantification of the macroeconomic costs of climate shocks, including impacts on agriculture, infrastructure, and migration. Second, research is needed to assess how different monetary policy tools perform in the face of climate-induced volatility. Third, India needs rigorous evaluations of climate finance instruments—such as green banks or transition finance facilities. Finally, integrated climate-macro models that can inform medium- to long-term policymaking are critical for navigating the uncertainty of climate impacts.

I. Managing climate shocks for economic stability

India is exposed to physical climate risks (heatwaves, floods, and cyclones) and transition risks (arising from domestic or global mitigation efforts). These shocks can undermine economic stability through multiple transmission channels. First, climate-induced supply-side disruptions to food and energy can induce persistent inflationary pressures, challenging inflation-targeting regimes. Second, transition policies—such as carbon pricing—may shift relative prices, affecting monetary policy transmission. Third, climate shocks reduce labour and total factor productivity, depress output, and strain employment, as seen in India's manufacturing sector (Somanathan et al., 2021). While some work has begun to quantify these channels, macroeconomic models incorporating India-specific climate shocks remain nascent. There is a pressing need for modelling that integrates physical and transition risks, non-linearities, and macro-financial feedback loops.

These impacts also strain fiscal capacity as governments face rising demand for post-disaster relief, agricultural subsidies, infrastructure repair, and targeted transfers. India currently lacks robust public financial management systems that explicitly account for climate shocks in budget planning, contingency reserves, and fiscal risk assessment. Future research should examine how climate risks could be embedded into India's fiscal frameworks—including borrowing rules, expenditure management, and fiscal buffers—to enable more climate-resilient macro policy.

On the financial stability front, central banks are developing climate stress tests to assess systemic financial risks. Building robust stress testing frameworks for banks and financial institutions is a frontier policy priority for India. Building these frameworks involves detailed exposure mapping across vulnerable sectors like agriculture, real estate, and energy-intensive industries. Developing India-specific climate scenarios that capture geographic and sectoral risks is essential. It must be supported by investments in data infrastructure and tools that allow climate variables to be embedded into financial supervision and risk assessments. While the RBI has initiated discussions on climate risk, institutionalising such stress testing and embedding it into regulatory frameworks remains a frontier area for research and innovation.

II. Climate finance and the role of public investments

Achieving India's climate goals—including net-zero emissions by 2070 and ambitious 2030 renewable energy and emissions intensity targets—will require unprecedented investment in clean energy, transport, adaptation infrastructure, and green technologies, bringing several macro-financial questions to the fore: What is the scale and nature of India's mitigation and adaptation finance needs? How can domestic and foreign capital be mobilised? What role can the

central bank play in enabling these transitions? Mobilising green finance will require an ecosystem that includes policy clarity, financial sector readiness, and a pipeline of investable green projects. Public finance will play a critical role, both in direct investment and in crowding in private capital. One needs to understand how to integrate adaptation and mitigation into public investment frameworks and how to design green fiscal tools—such as green bonds, carbon taxes, or targeted subsidies—in a way that is economically efficient and socially equitable.

India has made early progress with green bonds and climate budget tagging at the state level. However, it lacks a national framework for climate-responsive budgeting or systematic assessments of fiscal multipliers for green investments. Future research could examine the distributional impacts of green fiscal policies, the cost-effectiveness of various instruments, and the institutional reforms needed to mainstream climate finance into fiscal planning at both central and subnational levels.

III. Industrial policy and green transition

India's success in its green transition will depend on aligning industrial and macroeconomic policy. The country must attract green R&D investment, scale clean energy technologies, and enable climate-smart industrialisation. Sectors like solar, battery storage, and green hydrogen present opportunities but also require FDI, intellectual property management, and domestic capability building. India must also learn from international experiences—such as China's dominance in solar manufacturing or Brazil's ethanol policy—while tailoring policies to domestic constraints. These efforts must be coordinated with macro policies related to capital flows, exchange rates, and industrial financing.

IV. Fiscal policy for adaptation and resilience

Beyond mitigation, fiscal policy is central to building climate resilience, particularly in vulnerable sectors and regions. Public expenditure on early warning systems, rural infrastructure, agricultural resilience, and social protection can reduce climate shocks' economic and human toll.

India has a long tradition of using public works (for example, MGNREGA), disaster response funds, and targeted subsidies. However, these instruments are rarely evaluated in terms of their adaptive potential. Ex-ante fiscal planning tools, such as climate contingency funds, adaptive safety nets, or parametric insurance schemes, are limited. Recent evidence from Bangladesh (Balboni et al., 2023; Burgess et al., 2022) shows that well-designed insurance and asset transfer programmes can significantly enhance household resilience to climate shocks—highlighting models India could consider.

As India moves to scale rural development programmes and social protection schemes, there is a unique opportunity to design in a climate-smart way—targeting regions most exposed to shocks, incentivising resilient livelihoods, and embedding flexibility for rapid scale-up during extreme events. Evaluating these opportunities through a climate lens is an important research and policy frontier.

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