A High-Growth, Low-Emission Pathway for India

Results from REMIND

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CSEP RESEARCH

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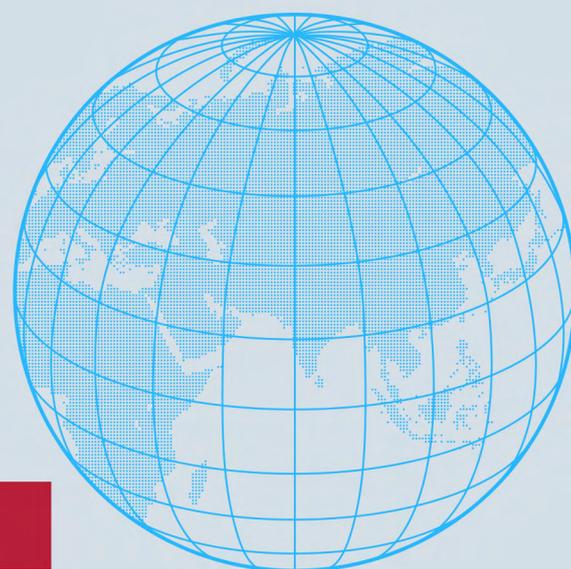## Results from REMIND[*]

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Abbreviations

ADB	Asian Development Bank
ASPI	Asia Society Policy Institute
BAU	Business as Usual
BF-BOF	Blast Furnace–Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CCTS	Carbon Credit Trading Scheme
CEA	Central Electricity Authority
CEEW	Council on Energy, Environment and Water
CES	Constant Elasticity of Substitution
COP	Conference of the Parties
CPI	Climate Policy Initiative
CRES	Constrained Renewable Energy Scenario
Curr_pol	Current Policies Scenario
DEA	Department of Economic Affairs
DisComs	Distribution Companies
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EJ	Exajoule
ERW	Enhanced Rock Weathering
FE	Final Energy
F-gas	Fluorinated Gas
GAMS	General Algebraic Modelling System
GCAM	Global Change Analysis Model
GDP	Gross Domestic Product
gH$_2$	Green Hydrogen
GHG	Greenhouse Gas
GJ	Gigajoule
GoI	Government of India
Gt	Gigatonne
GW	Gigawatt
H$_2$	Hydrogen
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
kWh	Kilowatt-hour
LPG	Liquefied Petroleum Gas
LULUCF	Land Use, Land Use Change, and Forestry
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MER	Market Exchange Rate
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MNRE	Ministry of New and Renewable Energy

MoEFCC	Ministry of Environment, Forest and Climate Change
MoSPI	Ministry of Statistics and Programme Implementation
Mt	Million Tonne
NDC	Nationally Determined Contribution
NFS	No Fossil-Fuel Scenario
NZ2070	Net-zero by 2070 Scenario
PIK	Potsdam Institute for Climate Impact Research
PLI	Production Linked Incentive
PPP	Purchasing Power Parity
PV	Photovoltaic
PyPSA	Python for Power System Analysis
R&D	Research and Development
RBI	Reserve Bank of India
RE	Renewable Energy
REMIND	REgional Model of INvestments and Development
RPO	Renewable Purchase Obligation
SSP	Shared Socioeconomic Pathway
TFP	Total Factor Productivity
TIMES	The Integrated MARKAL-EFOM System
TU	Trillion Units (of electricity)
TW	Terawatt
TWh	Terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
URES	Unconstrained Renewable Energy Scenario
VIF	Vivekananda International Foundation

Executive Summary

India stands at a critical juncture in its development journey. With a population of 1.45 billion and aspirations to achieve high per-capita income by 2047, the country must simultaneously deliver on its commitment to reach net-zero CO_2 emissions by 2070. This study demonstrates that these objectives are not only compatible but mutually reinforcing, provided definitive action begins immediately.

The Challenge

India's CO_2 emissions have more than doubled in the past two decades to 3 billion tonnes, making it the world's third-largest emitter. Yet per-capita emissions remain well below the global average at 2 tonnes annually. The country's energy system remains heavily dependent on coal, which accounts for over 70% of electricity generation, making the power sector the single largest source of emissions.

To achieve near-high-income levels, India must sustain gross domestic product (GDP) growth exceeding 6% annually through 2050, which correlates with increased energy consumption and, traditionally, higher emissions. The fundamental question is whether India can decouple economic growth from emissions while maintaining energy security and ensuring a just transition for affected communities.

Our Approach

This study employs a customised version of the REgional Model of Investments and Development (REMIND) integrated assessment model (IAM), developed by the Potsdam Institute for Climate Impact Research (PIK), Germany, to create a high-growth, low-carbon scenario for India. Unlike conventional scenarios that assume moderate growth (projecting per-capita income around US$7,230 by 2050), REMIND–India is calibrated to high GDP growth averaging 6.2% per annum (p.a.) over 2025–2050. This enables per-capita incomes to increase fourfold from current levels to approximately US$11,400 by mid-century, approaching high-income levels.

The model incorporates political economy constraints governing coal phase-out through explicit bounds on retirement rates, recognising the social and economic importance of existing energy infrastructure.

We compare two scenarios: a **current policies scenario** (*Curr_pol*) reflecting India's emissions trajectory under the current level of effort and a **net-zero 2070 scenario** (*NZ2070*) that achieves zero CO_2 emissions by 2070 and is compatible with limiting global warming to 1.9°C. The analysis reveals several critical insights.

Key Findings

- *Emissions Trajectory:* Under the net-zero scenario, India's emissions peak at 4.2 gigatonne (Gt)-CO_2 around 2035, before declining steadily to 2.2 Gt by 2050 and reaching net-zero by 2070. This contrasts sharply with the *Curr_pol* scenario, where emissions would continue to rise to 5.6 Gt by 2045 and decline only to 4 Gt by 2070 (Figure ES–1).

Figure ES–1: Net CO₂ Emissions (Gt-CO₂/year)
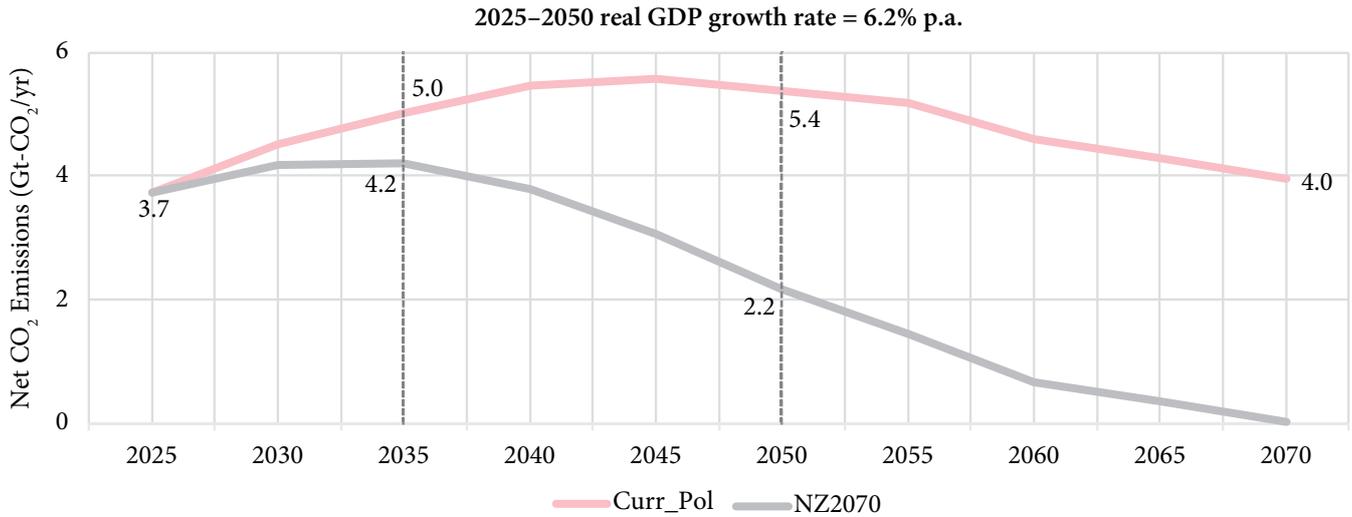
Source: Author estimates based on REMIND.

Note: Gt = gigatonne; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario.

The near-term increase in emissions in the net-zero pathway reflects continued fossil fuel use to meet growing energy demand during economic expansion, albeit at lower levels than under current policies. Crucially, this period lays essential groundwork—renewable capacity expansion, grid modernisation, and end-use transformation—that enables rapid decarbonisation post-2035.

- *Power Sector Transformation:* The electricity sector undergoes extensive transformation. Total generation capacity must expand from 0.6 terawatts (TW) currently to 1.6 TW by 2035 and 6.1 TW by 2050, driven overwhelmingly by solar

and wind deployment (Figure ES–2). Non-hydro renewables would generate 52% of total electricity by 2035, rising to 84% by 2050 and 96% by 2070 (Figure ES–3).

Coal generation capacity is estimated to peak around 2030 at 293 GW before declining gradually to 230 GW by 2040, 158 GW by 2050, and phasing out entirely before 2070 (Figure ES–2). This measured approach avoids premature asset stranding while preventing new coal lock-in and minimising political–economic disruption from coal phase-out.

Figure ES–2: Electricity Generation and Storage Capacity (TW)
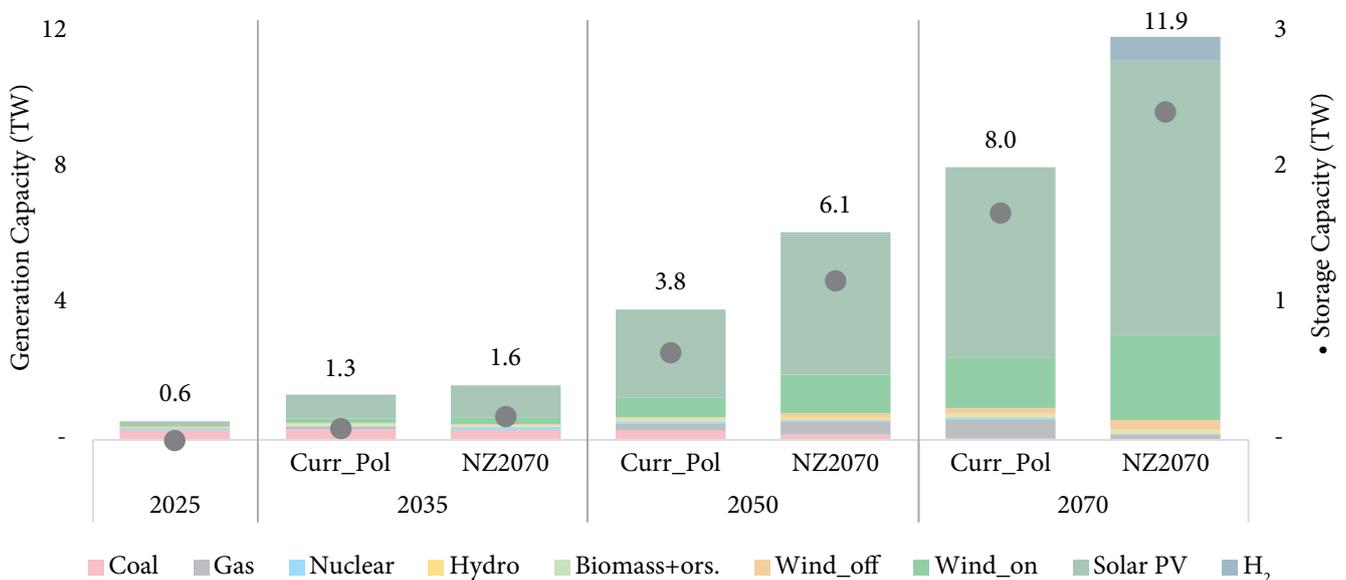
Source: Author estimates based on REMIND.

Note: TW = terawatt; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; PV = photovoltaic; H₂ = hydrogen.

Figure ES–3: Electricity Generation (TU/year)
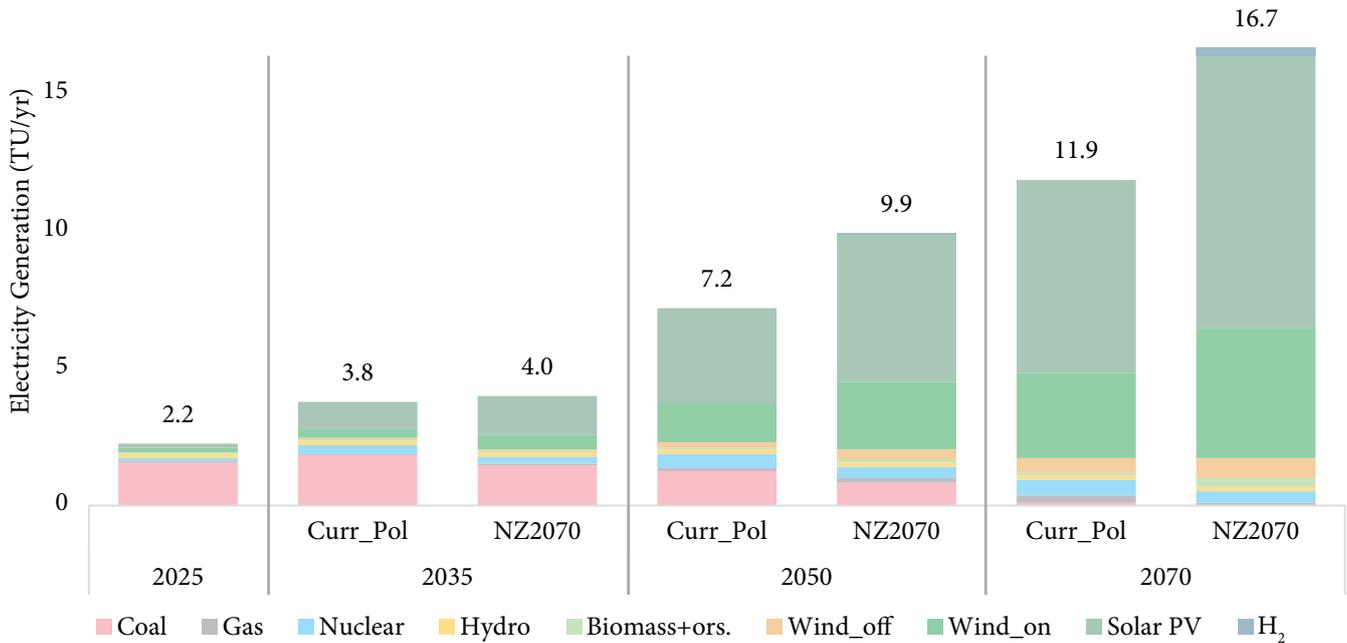
Source: Author estimates based on REMIND.

Note: TU = trillion units; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; PV = photovoltaic; H_2 = hydrogen.

- **Energy Storage and Grid Infrastructure:** Massive renewable deployment necessitates parallel expansion of storage and transmission infrastructure. Storage capacity must reach 172 GW by 2035—double the level projected under current policies—to balance supply from variable renewable sources (Figure ES–2). By 2050, storage capacity must reach 1.1 TW, complemented by green hydrogen (gH_2)-based generation to provide long-duration seasonal storage.

  Grid investments must more than triple to approximately US$236 billion annually by 2035, representing half of all energy-sector investments during this period—60% higher than under current policies. This expansion is critical as renewable generation will occur predominantly in Renewable Energy (RE)-rich regions in the northwest and the south, distant from many major demand centres. Without commensurate transmission capacity, clean energy would be curtailed and fossil fuel reliance would continue.

- **Electrification and Efficiency:** Electricity's share in final energy (FE) must increase from about 20% currently to 50% by 2050, reflecting significant shifts in transport, industry, and buildings.

Electrification, combined with fuel switching to renewables and efficiency improvements, enables the energy intensity of GDP to decline from 2.3 GJ/US$ currently to 0.83 GJ/US$ by 2050.

- **Industrial Decarbonisation:** Steel production is projected to nearly triple to 460 Mt by 2050, with production shifting from conventional blast furnace routes towards direct reduction processes using gas and, ultimately, gH_2 and electric arc furnaces (EAFs) using scrap.

  Cement production doubles to 670 Mt annually by mid-century, with carbon intensity falling from 0.6 to 0.25 tonnes of CO_2 per tonne of cement through increased use of alternative materials, energy efficiency, fuel switching, and ultimately carbon capture technology.

- **Investment Requirements:** The transition requires additional annual investment of approximately US$62 billion during 2026–2035, representing about 0.85% of GDP above current policy levels. This rises to approximately US$380 billion annually (1.55% of GDP) during 2036–2050. However, these investments would reduce expenditure on imported fossil fuels, resulting in savings of 1.2% of GDP through 2050.

Figure ES–4: Energy-Sector Investments *(Supply Side; US\$$_{2024}$ billion per year)*
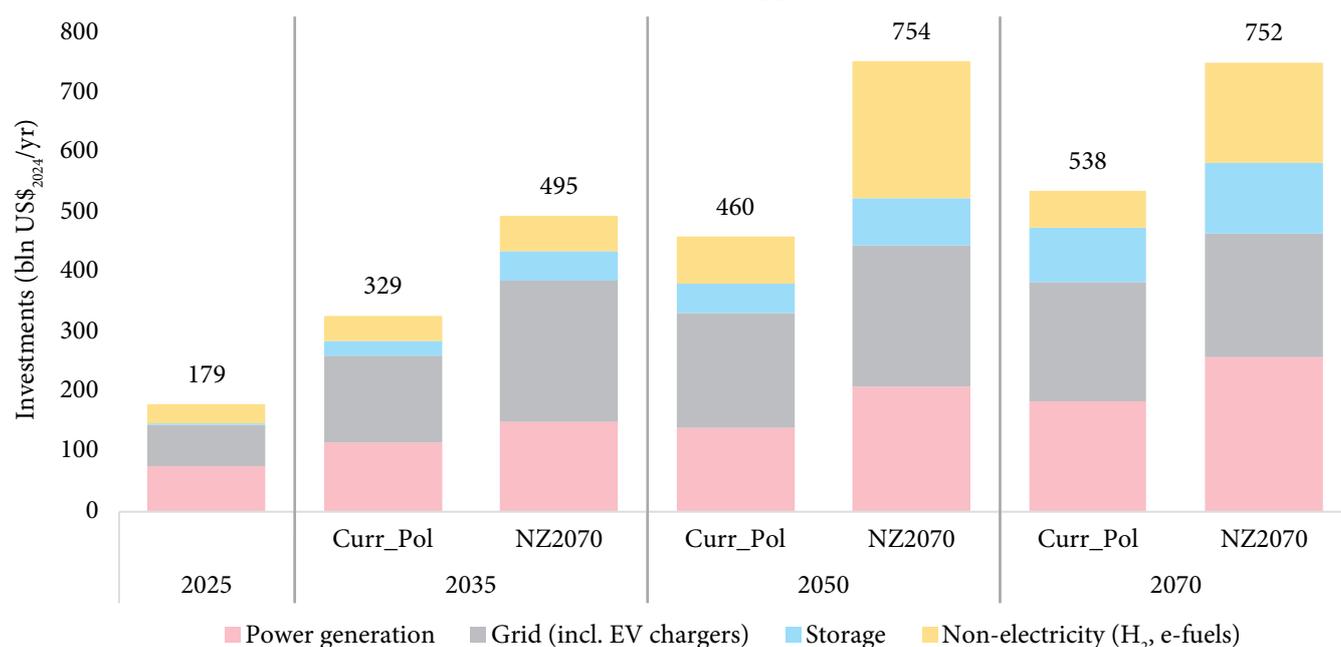
Source: Author estimates based on REMIND.

Note: Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; EV = electric vehicle; H$_2$ = hydrogen.

Critically, about 80% of the total investment needs must be raised from domestic sources through higher savings, redirection of investments from brown to green sectors, innovative financing mechanisms (blended finance, green bonds, etc.), and additional private capital mobilisation. This would push general investment rates from 30–31% currently to 34% of GDP by 2035. The remaining 20% of the total, roughly US\$51 billion annually in the near term, requires international climate finance scaled up to approximately six times the recent levels.

Policy Recommendations: The Five Pillars for 2035

Based on these findings, we propose five key pillars for India's 2035 climate targets:

- *Emission Intensity Reduction:* Reduce emission intensity of GDP by 65% compared to 2005 levels, ensuring emissions peak around 2035 before declining. This represents a significant enhancement of the current 45% target for 2030.

- *Renewable Energy (RE) Expansion:* Achieve 80% of cumulative electric power installed capacity from non-fossil-fuel sources, with an objective of 1,200 GW of RE capacity (excluding large

hydro) by 2035. This requires average annual capacity additions of 150 GW during 2030–2035, representing a 2.5-fold increase over current 2030 targets.

- *Peaking and Phasing-Down Coal Generation:* Peak unabated coal use for power generation before 2035, implying no new unabated coal plants commissioned post-2030, with existing plants beginning gradual retirement starting with older, inefficient units. This timeline provides adequate time to coal-producing states (which will see a decline in coal demand from 2040 onwards) for economic restructuring while preventing new coal lock-in.

- *Accelerated Electrification:* Double the rate of electrification across end-use sectors, prioritising railway traction, passenger vehicles, and light commercial vehicles in the near term, gradually expanding to other transport modes and industrial applications as technology costs decline.

- *Expanded Carbon Market:* Include the power sector in the forthcoming Carbon Credit Trading Scheme (CCTS) alongside industries already covered, with progressively tightened carbon intensity targets aligned with long-term emission trajectories.

Essential Enabling Policies

Beyond these targets, several enabling policies are critical:

- *Energy Price Rationalisation:* Current electricity pricing, characterised by extensive cross-subsidies, provides perverse incentives that discourage efficiency and undermine renewable competitiveness. Reforms eliminating wasteful subsidies while protecting vulnerable consumers through direct benefit transfers would improve system efficiency.

- *Market Structure Reform:* The electricity sector must shift from long-term agreements towards exchange-based trading mechanisms that accommodate renewable intermittency through real-time and day-ahead markets, enabling more efficient balancing of variable generation.

- *Carbon Pricing:* A carbon price reaching US$100 per tonne by 2035 would provide technology-neutral incentives for emissions reductions, generating revenues for clean energy investments and just transition programmes. As carbon pricing matures, existing mandates such as renewable purchase obligations (RPOs) would become obsolete, with market forces naturally driving the shift towards cleaner energy.

- *Just Transition Measures:* Coal-dependent states (Jharkhand, Odisha, Chhattisgarh, and parts of Madhya Pradesh) require comprehensive policies including retraining programmes, economic diversification strategies, and social protection measures to manage employment and revenue impacts. The geographic redistribution of economic benefits—with renewable-rich and relatively higher-income states (Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Andhra Pradesh) gaining substantially—necessitates careful policy attention to distributional impacts.

The Cost of Delay

The timing of India's decarbonisation efforts critically determines overall costs. Delayed action would necessitate deployment of expensive negative emission technologies (such as enhanced rock weathering [ERW] and carbon capture and storage [CCS]) post-2070 to compensate for excess emissions, with implicit carbon prices exceeding US$1,200 per tonne by 2080—nearly three times higher than the US$429 per tonne under the recommended pathway. These technologies remain largely unproven at scale and face significant resource constraints.

In contrast, the proposed pathway achieves net-zero through conventional mitigation measures, with investments coinciding with lower abatement costs and avoiding dependence on expensive and unproven technologies. The implicit carbon price rises from US$5.50 per tonne currently to US$100 by 2035 and US$241 by 2050, reflecting the increasing but manageable marginal cost of abatement.

Conclusion

This analysis establishes that India can pursue an ambitious growth trajectory while establishing a credible path to net-zero emissions by 2070. The critical insight is that actions taken over the next decade—the period through 2035—will lay the groundwork for accelerated decarbonisation when clean technologies become more mature and cost-competitive, yielding emission reductions in subsequent years.

The proposed targets represent an integrated strategy where renewable expansion, storage and grid investment, coal phase-out, electrification, and carbon pricing reinforce each other. The estimated investment requirements, while substantial, are manageable and far more efficient than the expensive corrections that delayed action would necessitate. India's experience in navigating this transition could provide valuable lessons for other developing economies seeking to reconcile growth imperatives with climate responsibilities.

Abstract

India seeks to achieve a high per-capita income by 2047 while delivering on its commitment to reach net-zero CO_2 emissions by 2070—objectives traditionally viewed as competing priorities. This study employs the REMIND-IAM to develop high-growth, low-carbon scenarios for India, demonstrating the feasibility of reconciling development aspirations with climate objectives. We calibrate REMIND–India to high GDP growth rates (6.2% p.a. over 2025–2050) and compare a current policies scenario with a net-zero 2070 pathway compatible with limiting global warming to 1.9°C.

Results show that India's emissions must peak at 4.2 Gt-CO_2 around 2035 before declining steadily to net zero by 2070. This trajectory requires accelerated RE expansion to 1,200 GW by 2035 (2.5-fold increase from 2030 targets), accompanied by substantial grid and storage investments. Coal generation capacity peaks around 2030 before a gradual phase-out, while electrification increases across transport, industry, and buildings. Critical groundwork must be laid during this period to enable economy-wide emissions reduction from 2035 onwards and avoid locking in high-emission infrastructure.

Based on these findings, we propose five policy pillars for India's 2035 targets: 65% reduction in emission intensity, 80% non-fossil electricity capacity, peaking unabated coal use, a doubled electrification pace, and an expanded carbon market. The transition necessitates additional investments of approximately 1.4% of GDP annually through 2050 in energy supply sectors, predominantly from domestic sources. Analysis of alternative scenarios reveals that a delayed transition would impose substantially higher costs, underscoring the economic imperative of near-term climate action.

1. Introduction

At the Conference of the Parties (COP) in 2021, India pledged to reduce the level of carbon emissions to net zero by 2070 and updated its first nationally determined contributions (NDCs) for 2030 (Government of India [GoI], 2022). This was the first time the country committed to reducing the absolute level of emissions. Its new position reflected an acknowledgement of the seriousness of the problem of climate change and of the opportunities presented by low-carbon technologies.

In its updated NDCs, India pledged to reduce the emissions intensity of GDP by 45% by 2030 from 2005 levels, up from the earlier target of 33–35%, and to increase the share of non-fossil-fuel-based electricity generation capacity to about 50% of cumulative installed capacity by 2030, up from the previous target of 40% (GoI, 2022). India also reaffirmed its earlier commitment to creating an additional carbon sink of 2.5–3 Gt-CO_2 equivalent by 2030 through afforestation.[1] It presented the updated targets as a step forward towards the country's long-term goal of reaching net-zero emissions.

Under the Paris Agreement, India is due to submit its second NDCs for the period 2026–2035. The new NDCs must take into account COP28's response to the first Global Stocktake in 2023 that urged all countries to commit to stronger climate action. The stocktake showed that the current climate change mitigation measures of all countries taken together were insufficient to limit global warming to well below 2°C, as targeted in the Paris Agreement (United Nations Framework Convention on Climate Change [UNFCCC], 2023). Given India's size, its future emission trajectory has a significant role in global warming outcomes.

What should be India's new NDCs that, while credibly demonstrating the country's commitment to reducing emissions to net zero by 2070, are compatible with its legitimate economic development ambition of achieving high per-capita income levels by 2047—the centenary of its independence—as envisaged under the *Viksit Bharat* (developed India) goal of its government?

In this paper, we present a model pathway of India's energy transition, consistent with the country's

current policies and circumstances, aligned with its long-term development and climate goals, and compatible with the Paris Agreement's global warming target. This pathway shows how concerted policy action and technological developments could enable India to meet an increasing share of its energy demand from renewables without any loss of welfare. This would effectively decouple emissions from economic growth, ultimately leading to a decline in emissions, as is already happening in some countries (Freire-González, Padilla Rosa & Raymond, 2024). The investment requirement of such a transition is also analysed.

We use the REMIND-IAM developed by the PIK, Germany, to generate net-zero scenario pathways for India, making this the first study on India based on REMIND.

IAMs, such as REMIND, play a crucial role in climate policy analysis by integrating complex interactions among energy systems, the economy, land use, and the climate. REMIND, in particular, simulates global decarbonisation pathways and assesses scenarios to meet specific climate targets by iteratively adjusting carbon price trajectories until the desired emission reduction is achieved. Such models allow for the evaluation of impacts and trade-offs of policy instruments, including carbon pricing, across regions and sectors. These models have been foundational in Intergovernmental Panel on Climate Change (IPCC) assessment reports on climate change mitigation, and more recently, they have been used by central banks to assess macroeconomic risks from climate policies.

The following section (Section 2) discusses India's development imperatives and climate policies, outlining its broad domestic strategy for meeting a growing energy demand and lowering carbon emissions. Section 3 provides an overview of existing studies on India's decarbonisation pathways based on other models. Section 4 describes the REMIND–India model setup used for this study. Section 5 presents the results from the modelled scenarios, followed by a discussion in Section 6. Section 7 outlines a medium-term decarbonisation strategy for India based on the analysis in this study. Section 8 provides the conclusion.

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[1] The baseline to measure additionality of the afforestation target was not explicitly mentioned in the official submission to the UNFCCC, but the Indian Ministry of Environment has stated that to be 2005 (Ministry of Environment, Forest and Climate Change, 2024a).

2. India's Development Ambitions and Climate Policy

India's economic aspirations intersect with global climate imperatives. With a population of 1.45 billion and a GDP of US$3.9 trillion, India's dual commitment to achieving net-zero emissions by 2070 while attaining high-income country status by 2047 presents an unprecedented challenge that demands careful policy planning. While the country has made significant progress in providing energy access, achieving near-universal household electrification by 2019, vast gaps remain in meeting development needs. Per-capita energy consumption in India is only about one-third of the global average (International Energy Agency [IEA], 2021), with some states like Bihar consuming less than 20% of the global average. Meanwhile, a large part of the population relies on traditional biomass for cooking due to a lack of affordable access to clean cooking fuel, causing severe health issues and premature deaths due to indoor air pollution.

The demand for energy is expected to continue rising with the increasing share of the urban population and the consequent economic transformation. To reach high per-capita income levels, India must sustain an annual growth rate of more than 7.5% p.a. over the next 25 years, raising per-capita income from US$2,700 to US$14,000 (in current dollar rates). This is higher than the average GDP growth rate of 6.8% p.a. over the past 25 years (excluding 2020 as the pandemic year) (Ministry of Statistics and Programme Implementation [MoSPI], n.d.). A rapid economic expansion traditionally correlates with increased energy consumption and, consequently, higher emissions. So far, India's NDC on emission reduction has focused on lowering near-term emission intensity. While this indicates some decoupling of growth and emission, over the long term, it is not enough to achieve net-zero emissions. A simple back-of-the-envelope calculation shows that if India maintains the current rate of emission intensity reduction while growing at 7.5% p.a. (Ministry of Environment, Forest and Climate Change [MoEFCC], 2024b), its absolute emissions would potentially be more than double from the current levels by 2047, contradicting the net-zero pathway.

The decarbonisation challenge is further amplified by its current emissions trajectory and the carbon intensity of its energy system. India's CO_2 emissions have more than doubled over the last two decades to 3 Gt, and it currently accounts for approximately 7% of global CO_2 emissions (Figure 1), making it the world's third-largest emitter after China and the US. However, its per-capita emissions at 2 tonnes p.a. remain well below the global average of 4.7 tonnes.

Figure 1: India CO₂ Emissions by Sector (Gt/year)
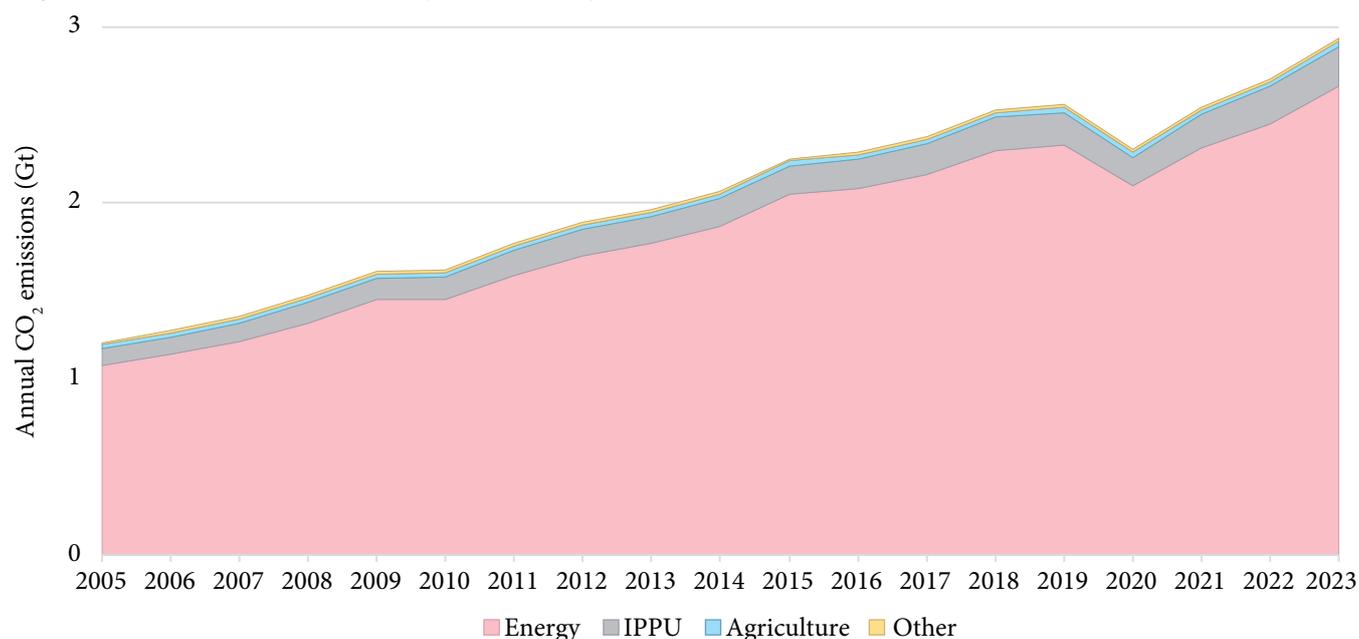
Source: Potsdam Institute for Climate Impact Research; Climate Watch (n.d.).

Note: Gt = gigatonne; IPPU = Industrial Processes and Product Use.

Nearly 90% of emissions are on account of energy production, which is highly dominated by coal use in the power sector (Table 1).

Table 1: India Energy Supply and Consumption, 2023–24

	Coal (EJ)	Oil (EJ)	Gas (EJ)	Electricity* (EJ)	Total (EJ)	% of FE	Share of Electricity in FE (%)
Primary Energy Supply	22.9	10.8	2.7	1.5	37.9	–	–
FE Consumption	7.6	10.0	2.3	5.6	25.5	–	22
Agriculture	–	0.02	0.01	0.9	0.9	3.7	97
Buildings	–	1.4	0.4	1.8	3.6	14	50
Industry	7.6	1.8	1.3	2.3	13.1	51	18
Transport	–	2.3	0.6	0.1	3.0	12	4.0
Other	–	4.4	–	0.4	4.8	19	8.2

Source: India Climate and Energy Dashboard; NITI Aayog.

*Note: *Electricity includes hydro, nuclear, and non-biomass renewables. EJ = exajoule; FE = final energy.*

Coal demand in India nearly tripled between 2000 and 2019 (IEA, 2021), as the country built new power plants to ensure a reliable power supply and meet a growing power demand. Coal currently contributes to over 70% of total electricity generation (Central Electricity Authority [CEA], n.d.), making the power sector the single largest source of the country's CO_2 emissions (Climate Watch, n.d.). While coal-based generation capacity has remained around 250–255 GW (including non-utility/captive capacity) since 2019, RE generation capacity, driven by wind and solar installations, has nearly doubled since then to 171 GW (excluding large hydro) by the end of 2024. The share of renewables in India's electricity mix, however, remains low at 13.5% (CEA, n.d.). Hence, the average carbon intensity of electricity in India at 729 g-CO_2/kWh is extremely high compared to the global average of 445 g-CO_2/kWh in 2024 (IEA, 2025).

To increase the share of renewables in the electricity mix, the Central government has imposed an RPO on utilities and large industrial consumers with captive power generation to procure a certain share of power from RE generators (including large hydro). The RPO target for 2025 is set at 27.1% and is intended to increase to 43.3% by 2030.[2] Several complementary policies have been put in place at the central and state levels to support the uptake of RE, such as granting RE generators "must-run" status. The Central government also targets achieving 280 GW solar and 140 GW wind capacities by 2030 to meet its 500 GW non-fossil-fuel power generation capacity target,

as part of the updated NDC (Ministry of New and Renewable Energy [MNRE], 2023).

India has also launched the National Hydrogen Mission with a target of 5 million tonnes of gH_2 production annually by 2030, positioning itself as a major producer of this clean energy carrier. Similarly, incentive schemes to promote solar agricultural pumps among farmers and grid-connected solar rooftop photovoltaics (PVs) among households have been implemented. In addition, subsidies and tax benefits are being provided for manufacturing and adoption of electric vehicles to mitigate transport sector emissions, where sectoral oil demand has doubled since 2000. Industrial policy, such as the Production Linked Incentive (PLI) scheme for high-efficiency solar modules, which aims to build domestic manufacturing capacity, is also being framed in a manner to support this transition.

Furthermore, India's upcoming CCTS, operationalised through the Energy Conservation (Amendment) Act, 2022, enforces emission-intensity reduction targets across select industries and establishes a market mechanism for trading of carbon credits among entities to encourage uptake of greener technologies and RE. There is, however, a considerable scope for strengthening these commitments, notably through setting sector-specific medium-term targets with the aim of setting out an emissions trajectory consistent with the country's economic and climate ambitions.

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[2] Many states and utilities have failed to meet their RPO targets, indicating a lack of compliance (Prayas, n.d.).

Ahluwalia and Patel (2024) argue that the successful transition to net-zero emissions will require a "whole-of-the-economy" approach, involving all relevant ministries at the Central government level, as well as different state governments and, in some cases, local governments. A knowledge of the financial implications of various mitigation actions would help to identify the most cost-effective strategies, which is particularly crucial in an economy where public resources are constrained.[3] Additionally, the identification of investment requirements would facilitate the planning of the fiscal transition of government finances, given that a net-zero energy system implies the eventual phase-out of fossil fuels, taxes from the sale of which contribute disproportionately to government revenues (Bhandari & Dwivedi, 2022).

This necessitates an integrated assessment of the energy and economic systems at the country level, which is the objective of this study. IAMs are valuable tools which can afford policymakers the ability to quantify the economic costs and emissions savings associated with different policy instruments.

In a recent study, Das et al. (2025) used the Global Change Analysis Model (GCAM) IAM[4] to project economy-wide transition pathways for India under different macroeconomic trajectories, low-carbon technology preferences, and energy efficiency and behavioural change levels. Their multi-scenario framework highlights the relative impact of various interventions. For instance, scenarios with high energy efficiency improvements and lifestyle changes show the potential to significantly lower long-term energy demand, demonstrating the importance of demand-side interventions alongside a shift to renewables on the supply-side. Another scenario shows that emissions would increase the most under a high manufacturing-led economic growth policy, unless strong industrial decarbonisation measures are implemented. In this context, the authors identify power pricing reforms as key to promoting industrial electrification. Similarly, a carbon pricing policy would be crucial for the adoption of technologies such as CCS. However, the analysis shows that the required carbon price to achieve the target emissions level would be significantly lower with complementary policies. Moreover, it shows that the economic burden of the transition could be substantially lowered by early implementation of complementary policies.

Several other studies have employed different IAMs and energy system models to generate model pathways of India's energy transition. Durga et al. (2022) and Bhattacharya et al. (2024) provide a systematic review of such studies, including an inter-model comparison.

3. Literature Review

Das et al. (2023) employ the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) optimisation model with hourly temporal resolution over 2015–2085, incorporating operational flexibility constraints to project different technology pathways for achieving net-zero power sector by 2050 and 2060. Their analysis projects a renewable-dominated future with solar and wind contributing 85% of generation capacity by 2050 and 90% by 2060. Solar capacity reaches 2000 GW by 2050 and 3000 GW by 2060, and wind expands to 800 GW (500 GW onshore, 300 GW offshore) and 1350 GW by the respective years. Nuclear capacity remains constrained at 60 GW by 2050 and 80 GW by 2060. Storage emerges as a critical infrastructure, with capacity needs reaching 956 GW by 2050 and 2054 GW by 2060. The study identifies 6-hour battery storage as optimal for India's solar-dominated profile, whereas pumped hydro becomes less competitive post-2030 due to declining battery costs. Unabated coal capacity peaks around 2030 in the 2050 net-zero scenario and by 2025 in the 2060 scenario, with some asset stranding expected in the years thereafter. The economic requirement of this transition is estimated at US$1.6 trillion as additional investment for net-zero power system by 2050 and a little lower at US$1.4 trillion for the 2060 scenario, translating to US$153–160 billion annually between 2031–2060.

Bhattacharya et al. (2024) utilise the Integrated MARKAL-EFOM System (TIMES) model to explore nuclear penetration scenarios from 3.8% (current level) to 45% of generation by 2070. Electricity demand growth is assumed at 4.1% p.a. between 2020 and 2070. Under the high nuclear plus renewables scenario, the study estimates an annual capacity addition requirement of 19.6 GW nuclear and 98 GW of RE during the 2020–2070 period. Nuclear power is primarily observed to displace solar and battery storage in the different scenarios with varying shares.

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[3] The gross fiscal deficit of the Centre and the states combined is estimated at around 7.5% of the GDP in 2024–2025 (Reserve Bank of India [RBI], n.d.).

[4] See for reference PNNL (n.d.).

Solar capacity projections range from 1800–5800 GW by 2070, with wind being around 2800 GW. Economic analysis reveals transition costs remain relatively technology-agnostic, ranging between US$26.5–29 trillion through 2070. However, the cost of electricity generation and transmission combined is 14% higher in the renewables-dominated scenario, compared to the high nuclear scenario.

A study by Rodrigues et al. (2024) using Python for Power System Analysis (PyPSA) projects India's on-grid electricity demand increasing fourfold from 1210 TWh in 2019 to 4985 TWh or 5246 TWh in low-carbon and business-as-usual scenarios, respectively, by 2050. Three supply scenarios explore different constraints: constrained renewable energy scenario (CRES) limits capacity to 748 GW solar and 695 GW wind by 2050; unconstrained renewable energy scenario (URES) optimises generation capacity requirements under least-cost assumptions; and no fossil-fuel scenario (NFS) prohibits new coal/gas plants post-2025 and attains zero-emission electricity generation by 2050 from nuclear and RE sources. In URES and NFS, solar capacity reaches 1472 GW and 1839 GW, respectively, by 2050, and wind reaches 421 GW and 368 GW, respectively. Coal generation peaks in 2030 in both scenarios, and in the URES, its contribution declines to 8% by 2050, though it remains crucial for daily and seasonal peak management. Reduction in baseload coal generation capacity in the NFS raises battery storage requirement to 7.1 TWh in 2050, relative to 5.2 TWh in the URES (6-hour duration in both cases). Additional investments of US$1.2–1.6 trillion would be required through 2050 in generation and storage capacity, with high sensitivity to battery pack costs.

Focusing on the industrial sector, Dayal, Agarwal, and Hingne (2025) find that without additional policies, India's industrial emissions could triple, reaching 50% of total emissions, by 2050. Within the sector, steel, cement, and chemicals production account for two-thirds of sectoral emissions and are projected to reach 2.7 Gt-CO_2e by 2050. The authors suggest three policy levers that could contribute to significant emissions reduction, viz., industrial electrification and gH_2 mandates, energy and material efficiency mandates, and carbon pricing reaching US$50/tonne-$CO_2$ by 2050. They find that process-related emissions will be harder to abate than energy-re-

lated emissions and would depend, to a large extent, on factors such as gH_2 supply costs. They estimate industrial hydrogen (H_2) demand to reach 22 Mt by 2050. In the short term, external pressures from international border carbon adjustment tariffs, combined with domestic measures, such as the CCTS call for accelerated deployment of low-carbon technologies. This could, however, raise production costs for the industry due to high fuel costs and potentially reduce export earnings.

4. REMIND–India Modelling Framework

The vast majority of scenarios developed using IAMs for international climate policy assume a continuation of the historically observed patterns of economic growth (Shared Socioeconomic Pathway [SSP2] scenarios). Under such assumptions, India's income levels are generally projected to grow from US$2,860 per capita in 2025 to approximately US$7,230 per capita by mid-century (4.3% p.a. growth; at market exchange rates (MERs), in US$, 2024), which falls substantially below the targeted levels.

In this paper, we use REMIND to develop a customised high-growth, low-carbon scenario for India under a welfare neutral framework (PIK, n.d.).[5] REMIND is a global multi-regional IAM that combines economic growth dynamics with a detailed representation of the energy system to explore long-term transformation pathways under climate constraints. Appendix 1 provides more information on the model.

REMIND–India is calibrated to high long-term GDP growth rates (7.7% p.a. over 2026–2035, 5.3% p.a. over 2036–2050, and 3.8% p.a. over 2051–2075) to produce India-specific energy transition scenarios that align with its domestic economic ambitions. India's population is assumed to continue growing at a decreasing rate and peak around 2060 at 1.63 billion. The scenarios thus generated project India's GDP per capita to grow nearly four times over current levels to US$11,400 by 2050. This ambitious growth trajectory would enable India to approach high-income status by mid-century. Appendix 2 provides the Cobb–Douglas disaggregates of output over the model horizon.

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[5] The model optimisation ensures no loss of consumption/GDP in the climate policy/*NZ2070* scenario compared to reference/Business as Usual (BAU) scenario.

In addition to high-growth assumptions, the analysis incorporates political economy constraints governing coal phase-out and current energy infrastructure. The *NZ2070* scenario reflects these constraints through explicit bounds on coal power capacity retirement rates, calibrated to be restrictive in the near to medium term and more permissive over longer time horizons.[6]

For further sector-specific assumptions, please refer to Supplementary Material 2 in Patel et al. (forthcoming).

The study presents two scenarios:

(i) *Curr_pol* under high growth, which represents India's emissions trajectory based on existing climate and energy policies without additional ambition beyond what has already been committed.

(ii) Net-zero scenario (*NZ2070*), where we project a Paris-aligned decarbonisation pathway achieving net-zero CO_2 emissions by 2070, which is consistent with limiting global warming to 1.9°C before the end of the century (66% confidence), while maintaining a high economic growth, demonstrating that climate action need not compromise economic aspirations.

4.1 Limitations

This study primarily focuses on supply-side dynamics within the energy and industry sectors, examining the transformation of the economy-wide energy supply mix and technological transition of the power generation and industrial processes required to achieve India's decarbonisation objectives. While REMIND presents granular end-use demand (such as transport demand by vehicle type) and behavioural factors (like mode of transport and adoption of energy-efficient appliances), this analysis does not explore this due to challenges in data validation and the limitations of long-term models in capturing detailed consumer behaviour and technology adoption patterns. Instead, it focuses on aggregate energy consumption patterns within the demand-side sectors viz., transport, buildings, and industry.

In addition, REMIND's long-term model horizon does not explicitly model spatio-temporal power system dynamics, such as grid constraints and despatchable generation needs, potentially underestimating integration challenges for variable RE. Cooling demand modelling is based on income and geography rather than expected climate outcomes and may underestimate adaptation requirements under high-warming scenarios. Finally, the model assumes efficient land use, such that competing demands for land between food production, forest conservation, urbanisation, and energy infrastructure (solar and biofuels) are met.

5. Results

This section presents the emission trajectories and their distribution across the different sectors of the economy, namely, electricity, industry, transport, and buildings, before highlighting the details of India's energy system transformation under the two scenarios. The power sector transformation receives particular attention given its central role in enabling economy-wide decarbonisation, followed by an analysis of the investment requirements of the transition. Industrial decarbonisation of steel and cement production is also presented. The section concludes with an examination of the implicit carbon price as a result of the mitigation efforts.

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[6] Maximum annual increase in coal-based generation capacity that is early retired is 0.15% per year before 2035, increasing to 1% per year by 2050 and 4.5% per year after 2060.

5.1 Overall Emissions Path

Figure 2: Net CO_2 Emissions (Gt-CO_2/year)
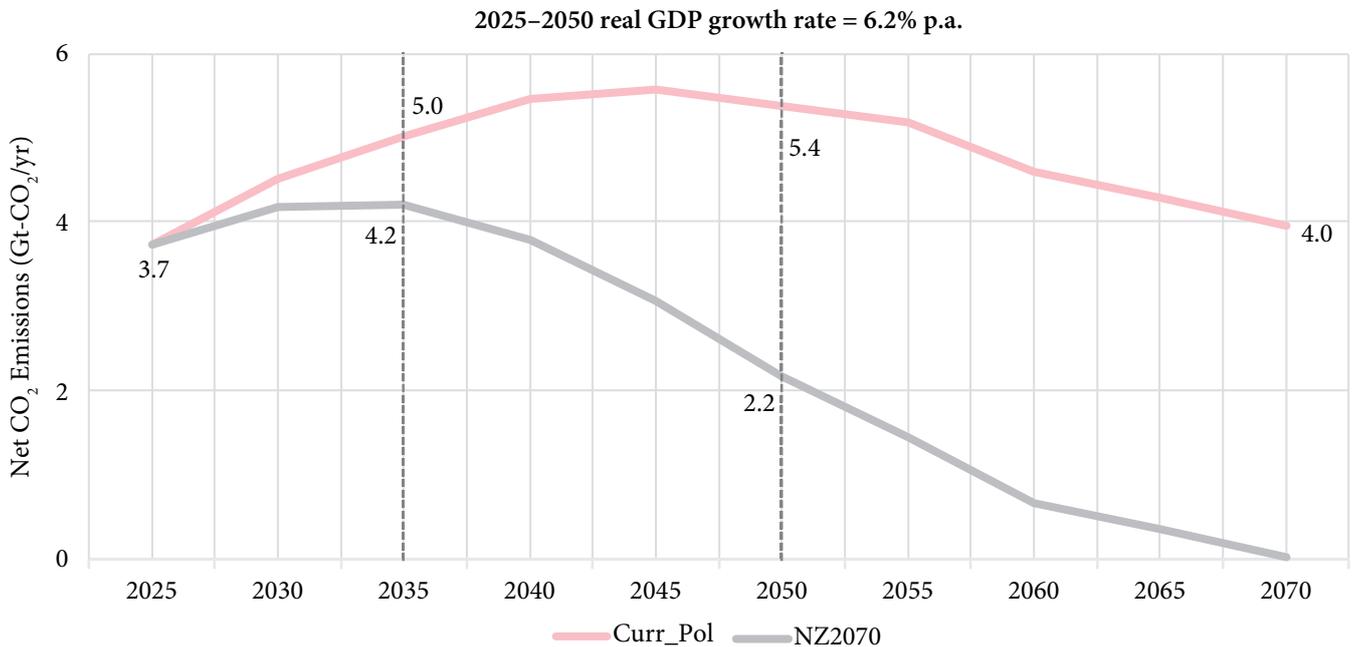
2025–2050 real GDP growth rate = 6.2% p.a.

Source: Author estimates based on REMIND.

Note: Gt = gigatonne; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario.

Under current policies (*Curr_pol* scenario; red curve in Figure 2), India's net CO_2 emissions would rise from 3.0 Gt in 2023 to 5.0 Gt in 2035, and further to 5.4 Gt by 2050 before gradually declining to 4.0 Gt by 2070. This is clearly incompatible with an emission constrained world, and inconsistent with India's long-term objective of achieving net-zero emissions.

The *NZ2070* scenario, depicted by the blue curve in Figure 2, presents a markedly different trajectory: emissions peak at 4.2 Gt in 2035 before declining sharply to 2.2 Gt in 2050 and reaching net-zero by 2070. This represents a 16.5% reduction compared to the current policy scenario in 2035, with the majority of reductions concentrated in the power, transport, buildings, and non-electric sectors. The gap widens to 60% by 2050.

A critical observation is that projected emissions in 2035 under the *NZ2070* scenario are 40% higher than the 2023 actual emissions. This near-term increase reflects India's continued economic development and

industrialisation, implying sustained use of fossil fuels in the near term to meet the growing energy demand, albeit in lower amounts compared to the baseline. During this period, despite an aggregate increase in fossil fuel use, renewables start to displace coal in power generation and transport electrification gains pace. The trend accelerates markedly post-2035, as use of coal for power generation starts phasing down and industrial production also starts to decarbonise.

Sectoral Emission Dynamics

Beyond 2035, the *NZ2070* emission pathway begins diverging significantly from business-as-usual, and by mid-century, the sectoral transformation becomes pronounced (Figure 3). The electricity sector, which remains the largest emitting sector until 2035 with 1.3 Gt-CO_2—roughly the same as current levels, but 19% lower than projections in *Curr_pol* scenario— becomes substantially decarbonised from massive expansion of RE capacity and achieves near-zero emissions by 2070.

Figure 3: Emissions by Sector (Gt-CO₂/year)
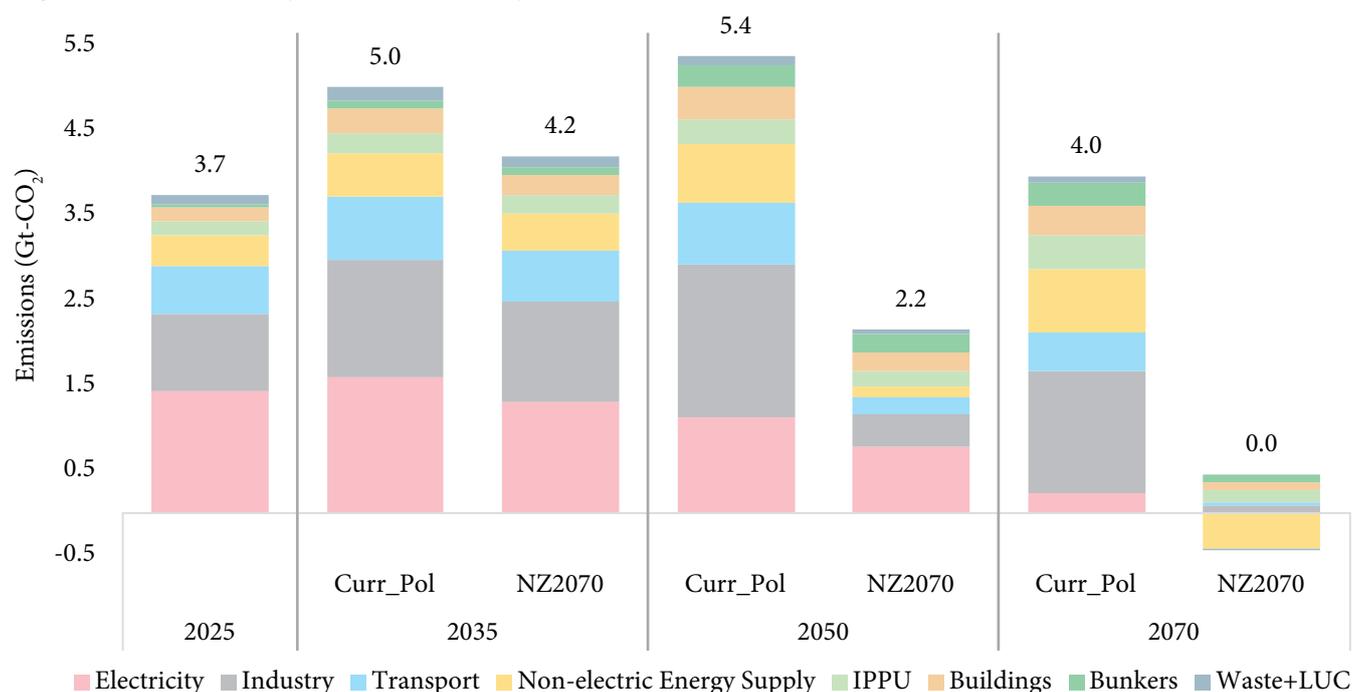
Source: Author estimates based on REMIND.

Note: Gt = gigatonne; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; IPPU = Industrial Processes and Product Use; LUC = land use change.

Industrial emissions are projected to increase by 31% over current levels in the *NZ2070* scenario, owing to high materials demand in a rapidly growing economy. These are energy and process-related CO_2 emissions from industries such as cement and steel, highlighting the challenges of industrial decarbonisation. However, efficiency improvement measures would already be underway before 2035, which will manifest into increased use of scrap steel and higher energy efficiency in primary steel and cement production, and as a result, emissions start to fall from 2035 onwards. Rate of decarbonisation is projected to accelerate thereafter, and industrial emissions decline to 0.4 Gt-CO₂ by 2050, compared to 1.8 Gt-CO₂ in the *Curr_pol* case, through direct electrification, energy efficiency, higher scrap availability and adoption of gH₂ and CCS technologies as they get cheaper.

Transport sector emissions are projected to remain around current levels in the *NZ2070* scenario in 2035, but beyond that, as electrification accelerates from continuous vehicle stock replacement, its emissions decline substantially to 0.2 Gt-CO₂, compared to 0.7 Gt-CO₂ in the *Curr_pol* scenario in 2050.

Some modes of transport, such as aviation, shipping and long-distance road freight, will continue to rely on conventional technologies but will be increasingly fuelled with sustainable alternatives like biofuels and e-fuels by 2070. The production of these fuels, especially biofuels, will involve CCS generating negative emissions[7] by 2070 (in the non-electric sector). These negative emissions would offset residual CO_2 emissions from the hard-to-abate sectors in the economy.

The buildings sector emissions remain relatively stable at 0.2 Gt-CO₂ through 2050 before declining in the net-zero scenario, reflecting the interplay between growing cooling demand with rising incomes, urbanisation, and efficiency improvements. These are lower than the projections in the *Curr_pol* scenario (0.4 Gt-CO₂), owing to higher electrification and efficiency improvements through the use of heat pumps.

5.2 Drivers of Emission Reductions

The transition to a low-emission economy is driven by three interconnected factors: increased electrification, switching to non-fossil energy sources, and improved energy efficiency.

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[7] Negative emissions imply removal of CO_2 from the atmosphere using technologies like direct air capture, ERW, bio-energy production with CCS, etc.

Electrification

Electrification of end-use demand emerges as a cornerstone of the energy transition. While the share of electricity in FE is expected to increase under current policies, reaching 30% by 2050 from about 20% at present, the share would need to be much higher to achieve a substantial reduction in emissions. The net-zero scenario projects share of electricity to be 50% by 2050, reflecting profound shifts in energy use in the transport, industry, and building energy services. Electrification on its own would not lead to significant emission reduction, unless it is accompanied by a switch to non-fossil sources of electricity generation.

Fuel Switching

Alongside electrification, the carbon intensity of energy supply decreases significantly. Emissions per unit of FE in the *Curr_pol* scenario remain over 70 Gt-CO_2/EJ around mid-century. In the *NZ2070* pathway, the intensity is projected to be about half that level, 36.5 Gt-CO_2/EJ in 2050, and approaching zero by 2070. This reduction results from the shift from fossil fuels to renewables, gH_2 and its derivatives, and sustainable biofuels.

Electrification combined with a switch to RE also contributes to a dramatic reduction in primary energy demand, owing to fewer energy conversion losses and higher energy efficiency of directly electrifiable end-use applications. For example, electric vehicles benefit from the superior efficiency of electric motors compared to internal combustion engines, reducing overall energy demand even as vehicle numbers grow.

Energy Intensity Reduction

Structural change of the economy towards less energy-intensive goods and services provides the third pillar of decarbonisation. This includes the use of more energy-efficient equipment and industrial processes (which in part will happen with electrification), and behavioural shifts such as the use of public transport instead of private. FE consumption per unit of GDP declines in both scenarios as incomes grow and efficient technologies become more accessible. However, the *NZ2070* scenario accelerates this trend. Energy intensity falls from approximately 2.3 GJ/US$ of GDP (2024 Purchasing Power Parity [PPP]) in 2025 to 0.83 GJ/US$ in 2050 and 0.47 GJ/US$ by 2070 in the *NZ2070* scenario.

5.3 Energy System Transformation

Total FE consumption (including bunkers) grows substantially in both scenarios, reflecting India's economic expansion. Under *Curr_pol*, FE increases from 38.5 EJ in 2025 to 60.4 EJ in 2035, 84.5 EJ in 2050, and 95.9 EJ in 2070. The *NZ2070* scenario shows more modest growth: 56.0 EJ in 2035 (7.3% lower than *Curr_pol*), 65.7 EJ in 2050 (22% lower), and 78.7 EJ in 2070 (18% lower).

These reductions reflect both efficiency improvements and fuel switching. The composition of FE undergoes a significant transformation in the *NZ2070* scenario, as shown in Figure 4.

Use of solid fuels, predominantly coal, for power generation and industrial heat and processes, and also biomass, is projected to increase marginally—from 15.8 EJ in 2025 to 16.2 EJ in 2035 under the *NZ2070* scenario (compared to 18.5 in the *Curr_pol* scenario). Given that coal has the highest carbon intensity among all fuels, its use is projected to phase out rapidly by 2035 onwards, resulting in the share of solid fuels in FE dropping to only 10% by 2050 (6.6 EJ).

Consumption of liquid fuels follows a different pattern. Under the *NZ2070* pathway, FE derived from liquid fuels, i.e., petroleum products, increases significantly, from 13.3 EJ in 2025 to 22.2 EJ in 2035 (vs 25.2 EJ in *Curr_pol*), owing to higher transport demand linked to high income growth. It thereafter declines to 18.4 EJ in 2050 as a result of reduced demand from the transport sector on account of electrification (particularly of passenger vehicles and light commercial vehicles) and modal shift from road to rail for freight movement. Supply of liquid fuels is projected to stay around the same level by 2070, but with an increasing share of liquid biofuels and gH_2-derived e-fuels to meet the energy demand of hard-to-abate transport applications, viz., aviation, shipping, and some long-haul road freight.

Figure 4: Final Energy by Fuel/Carrier (exajoule; including bunkers)
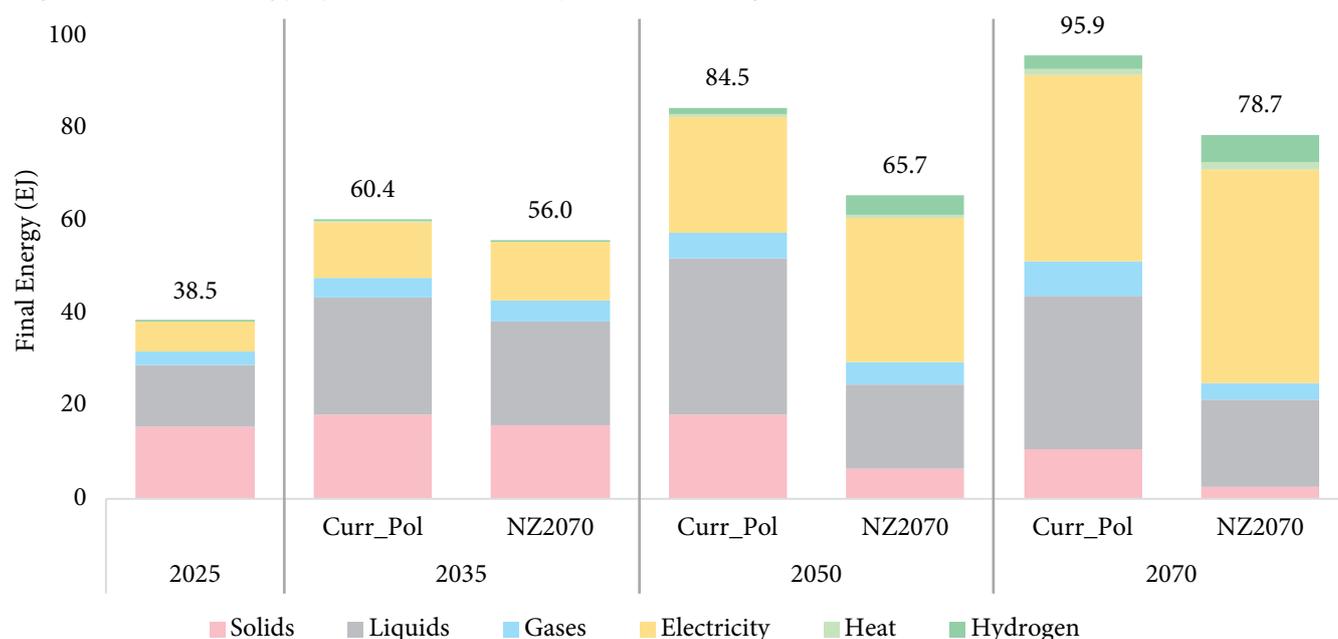
Source: Author estimates based on REMIND.

Note: Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario.

Gaseous fuels, primarily natural gas, are projected to serve as a transition fuel wherein their consumption rises initially from 2.7 EJ in 2025 to 4.9 EJ in 2050 (compared to 5.8 in the *Curr_pol* scenario) and then declines to 3.5 EJ by 2070 with an increasing share of biogas and e-fuels.

Green H_2 emerges as a significant energy carrier only after 2035 in the net-zero scenario. Its direct use is projected to reach 4.3 EJ (vs 1.2 EJ in *Curr_pol*) by 2050 or 6% of the total FE, rising to 5.7 EJ by 2070 (7% of total).

Electricity consumption undergoes rapid growth. From 6.5 EJ in 2025, it reaches 12.4 EJ in 2035 under the *NZ2070* pathway—a modest rise in the near term relative to 11.9 EJ in the *Curr_pol* scenario. It then accelerates to 31 EJ in 2050 and 46.2 EJ in 2070. This sevenfold increase over 45 years underscores the centrality of electrification to the energy transition,

especially so for a developing country under high economic growth. See Appendix 3 for energy flow (Sankey) diagrams for all sectors by year.

5.4 Power Sector Transformation

Electricity generation undergoes a major transition in the *NZ2070* scenario, serving as the basis for economy-wide decarbonisation.

Total electricity generation must expand rapidly to meet both growing electricity demand from economic development and increased electrification of end-uses. Generation is projected to increase from 2.2 trillion units (TU) in 2025 to 4.0 TU in 2035, 9.9 TU in 2050, and 16.7 TU in 2070 under the *NZ2070* scenario, compared to 3.8 TU, 7.2 TU and 11.9 TU in the *Curr_pol* scenario in the respective years. This represents more than a sevenfold increase over 45 years.

Figure 5: Electricity Generation (TU/year)
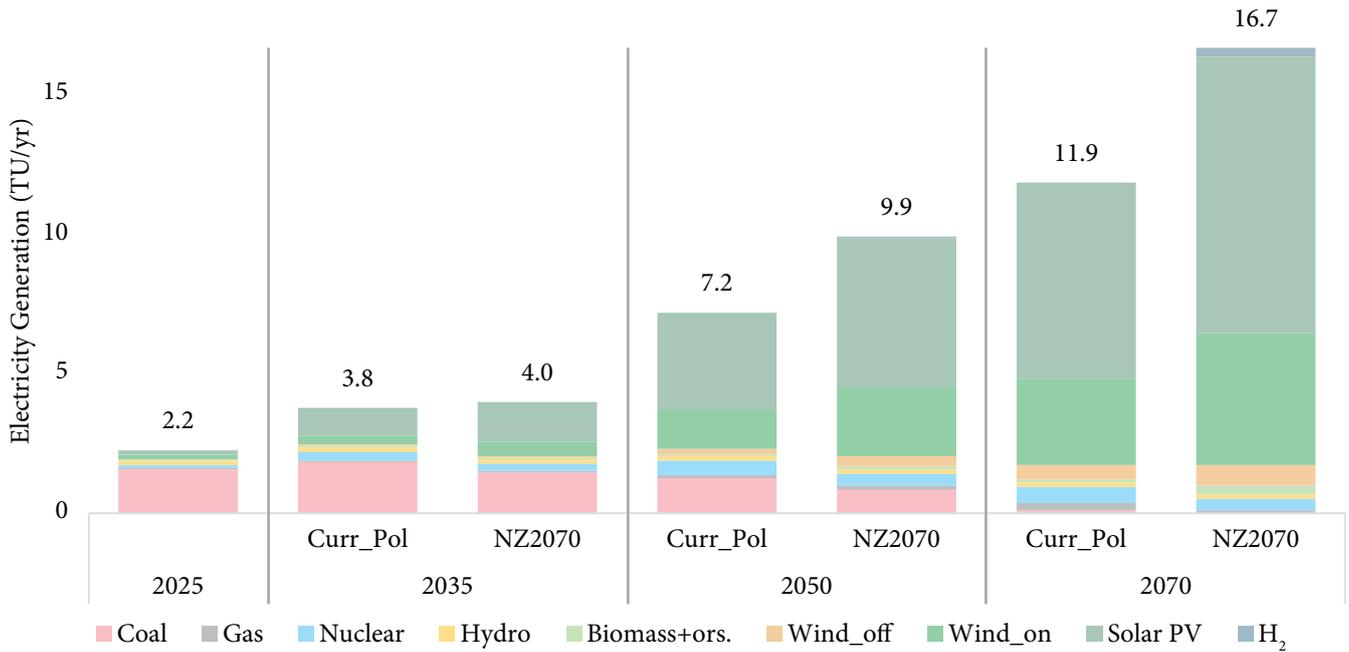
Source: Author estimates based on REMIND.

Note: TU = trillion units; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; PV = photovoltaic; H_2 = hydrogen.

Figure 6: Electricity Generation and Storage Capacity (TW)
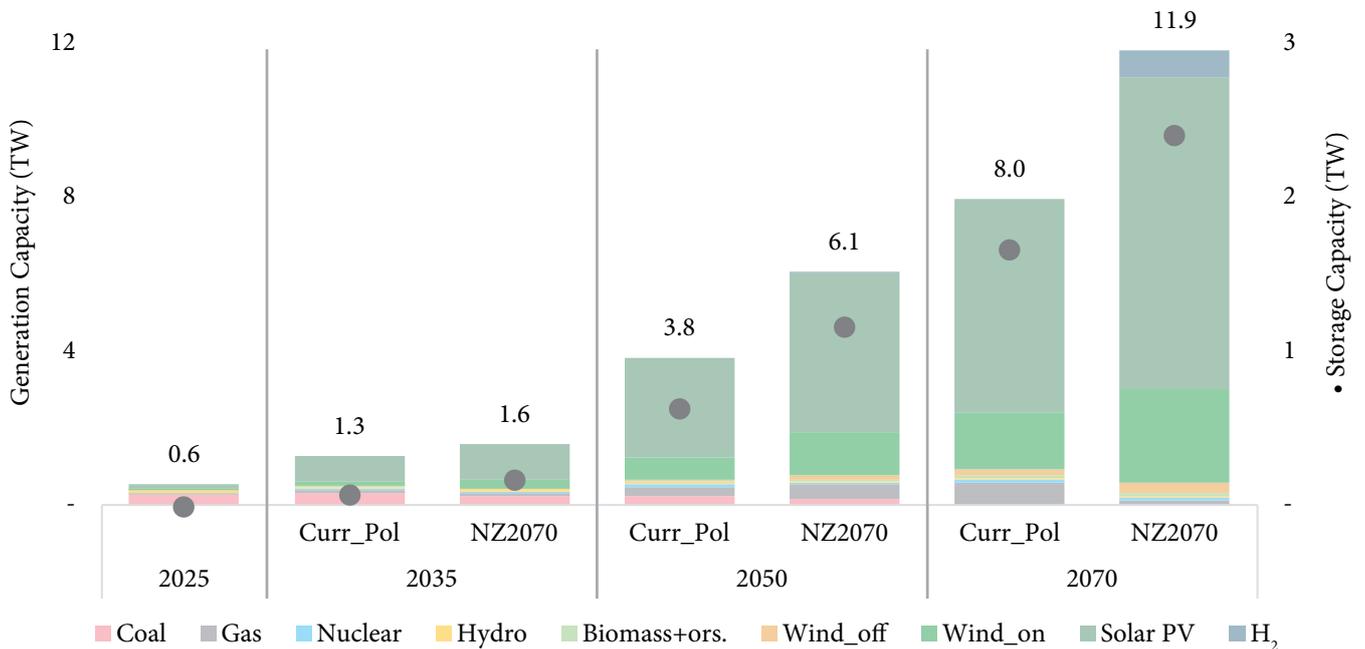
Source: Author estimates based on REMIND.

Note: TW = terawatt; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; PV = photovoltaic; H_2 = hydrogen.

Total generation capacity must expand even more rapidly than generation itself, due to the lower capacity factors of solar and wind plants. Under the *NZ2070* scenario, total capacity grows from 0.6 TW in 2025 to 1.6 TW in 2035, 6.1 TW in 2050, and 11.9 TW by 2070. Solar PV and wind dominate capacity additions, collectively reaching approximately 10 TW by 2070.

Coal Generation Trajectory

Coal generation follows a carefully managed decline, given its high carbon-intensity on the one hand and India's political-economy constraints on the other. Under the *NZ2070* scenario, coal capacity peaks around 2030 at 293 GW, then declines gradually to 230 GW by 2040, and is fully phased out by 2070. However, in the *Curr_pol* scenario, coal capacity is projected to peak by 2040 at 320 GW, and the rate of phase-out is much slower, retaining a significant share of the current plants until the mid-2050s.

Electricity generation from coal is projected to increase in the short-term but return to current levels by 2035. Its share in the electricity mix however falls from 70% at present to half of that by 2035 (compared to 48% in the *Curr_pol* scenario). The decline in coal generation is moderate until 2040, but it accelerates thereafter such that by mid-century the share of coal in the electricity mix is just under 10%.

Capacity utilisation of coal power plants is estimated at around 65% until 2040, which then gradually declines to 50% by 2060 under the *NZ2070* projections.

Gas, Nuclear, and Hydro Power

Gas-based generation capacity is projected to expand modestly through mid-century in the *NZ2070* pathway. This expansion is higher in the medium term than projected in the *Curr_pol* scenario, as gas power plants would be required to meet peak power demand and provide flexibility (given they are relatively easy to ramp up or down) as variable renewables scale up. Even so, the share of gas in the electricity mix will remain at under 2% by 2050. After that, as short-duration battery storage becomes more widely deployed, gas plants will increasingly operate at lower capacity factors, serving primarily as peaking and backup capacity, and will be gradually phased down with the availability of long-duration storage options (such as gH$_2$).

As coal is phased out, nuclear capacity is increased to provide baseload power. Nuclear capacity is projected to reach 62 GW by 2050 under the *NZ2070* scenario—an almost sevenfold growth over the current levels. Its share in the electricity mix, however, would remain under 5%, similar to current levels. The nuclear deployment projected in the scenario is actually lower than the capacity target announced by the government, i.e. to achieve 100 GW of nuclear installations (including small modular reactors) by 2047.

This reflects the model's assessment that renewables with storage will prove to be more cost-effective than nuclear under the expected technology cost trajectories.

Large hydro capacity is capped at current levels (50 GW) throughout the projection period, reflecting constrained capacity expansion potential due to environmental concerns, climate uncertainty, and geographic availability.

Renewable Energy Expansion

RE sources such as solar PV and wind (onshore and offshore) drive the transformation of India's power sector. Non-hydro renewables are projected to generate 52% of total electricity in the country by 2035 in the *NZ2070* scenario (vs 38% in *Curr_pol*), 84% by 2050, and 96% by 2070.

The pace of renewable deployment is initially constrained to current levels such that RE capacity in the *NZ2070* pathway remains at the current policy level until 2030, reaching 420 GW of combined solar PV and wind capacity by that year. Post-2030, deployment is projected to greatly accelerate. During the 2030–2035 period, annual capacity additions are projected at 150 GW per year, increasing wind and solar capacity by over 2.5 times by 2035. This would bring total renewable capacity to 1.2 TW by 2035. We recommend targeting a similar expansion of RE capacity by 2035 as part of our medium-term decarbonisation strategy.

The scale-up of RE is projected to continue at a faster rate in the subsequent years to substitute for coal power, as energy demand and electrification gains pace. In the *NZ2070* pathway, cumulative RE capacity would exceed 5 TW by 2050, and reach nearly 11 TW by 2070 to attain an almost fully decarbonised energy system (including the non-electric sector, e.g. gH$_2$ production).

Energy Storage

The massive expansion of variable RE necessitates substantial investment in energy storage to balance supply and demand. Over the medium-term, some balancing would be provided by gas power plants, but eventually, grid-scale batteries will offer the most cost-effective and sustainable solution.

Storage capacity (including some pumped-storage hydropower) is projected to increase to 172 GW in 2035—approximately twice as much as projected

under the *Curr_pol* scenario. By 2050, storage capacity is projected to reach 640 GW. This expansion reflects declining battery costs and the need for reliable storage capacity to manage intraday RE supply variability.

For seasonal variability in RE generation, i.e., during extended periods of reduced solar output or low wind, long-duration storage solutions would be needed (when gas plants can no longer be used due to emission constraints). For such cases, deployment of gH$_2$-based generation capacity is projected (30 GW in 2050 in the net-zero scenario). Green H$_2$ would be produced during periods of excess renewable generation, stored, and then used in fuel cells or H$_2$-fired gas turbines during generation shortfalls, effectively serving as long-duration energy storage.

5.5 Investment Estimates

The transformation for the power sector entails substantial but manageable investment requirements (Figure 7). Annual investment in electricity generation capacity is projected to double to US$151 billion by 2035 under the *NZ2070* scenario. This is about 30% higher than the investment estimated under the

Curr_pol scenario. Investment projected in 2050 is close to US$210 billion in the net-zero pathway, with nearly 80% of it dedicated to deploying solar PV and onshore wind capacity.

The composition of these investments changes considerably over time, shifting more towards renewables. Annual investment in coal capacity drops by a third to US$5.1 billion by 2030 in the *NZ2070* pathway, and no new investment is projected beyond 2035. In the *Curr_pol* scenario, investment in coal continues at around the present level until 2035 (US$14.3 billion) and drops by 45% by 2040. Investment in gas capacity rises fourfold to US$9 billion by 2035 in the net-zero scenario and continues until 2050, whereas in the *Curr_pol* case, investment in gas is moderate in the medium term, reaching US$11 billion by 2050 and increasing further thereafter.

Investment in new nuclear capacity is projected to be lower in the *NZ2070* scenario than expected under current policies, consistent with projections for capacity addition seen above. H$_2$-based generation capacity investments emerge post-2050, when demand for long-duration storage rises.

Figure 7: Investments in Electricity Generation (US$$_{2024}$ billion per year)

Source: Author estimates based on REMIND.

Note: Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; PV = photovoltaic; H$_2$ = hydrogen

Broader Energy System Investments

The massive expansion in generation capacity must be accompanied by an equally large expansion of the grid infrastructure. Considering this, grid investments are expected to be three times as much as the current levels by 2035 in the *NZ2070* scenario (US$236 billion) and continue at similar levels through 2050. This is 60% and 23% higher than investments projected under *Curr_pol* in the respective years.

Concurrent investment in deploying storage capacity is projected to reach US$48.5 billion by 2035 (twice as much as expected under *Curr_pol*) and US$79 billion by 2050.

Investments in non-electric energy infrastructure (gas pipelines, gH_2 production, transport, and storage, as well as e-fuels production facilities) emerge as a new category, reaching substantial levels by mid-century in the *NZ2070* scenario (US$230 billion; compared to US$79 billion in *Curr_pol*).

Overall, total energy sector investments in the short term are broadly aligned with those estimated in other studies.[8] See Table A2 in Appendix 4 for more details.

5.6 Industrial Decarbonisation

Industry will remain the dominant consumer of energy and some areas will be hard to decarbonise. In the *NZ2070* scenario, fossil fuels are projected to be the major source of FE in the medium term, but electricity gradually gains share to become the largest energy source, reaching 14.2 EJ by 2050 (compared to 11.7 EJ in *Curr_pol*), as coal-fired furnaces are replaced by electric furnaces and heat pumps in many applications. However, coal and biomass retain significant shares in the industrial energy mix through 2050, particularly in cement production and especially in regions where coal remains economically competitive. In contrast, in steel and chemicals, coal use is expected to fall to 40% and 20%, respectively, of current levels by 2050. By 2070, coal is nearly phased-out from industry and replaced by a combination of electricity, gH_2, and biomass. The sector would also be the biggest direct consumer of gH_2 in 2070, particularly for steel production and chemicals and fertiliser manufacturing.

Figure 8: Energy-Sector Investments (Supply Side; US$$_{2024}$ billion per year)
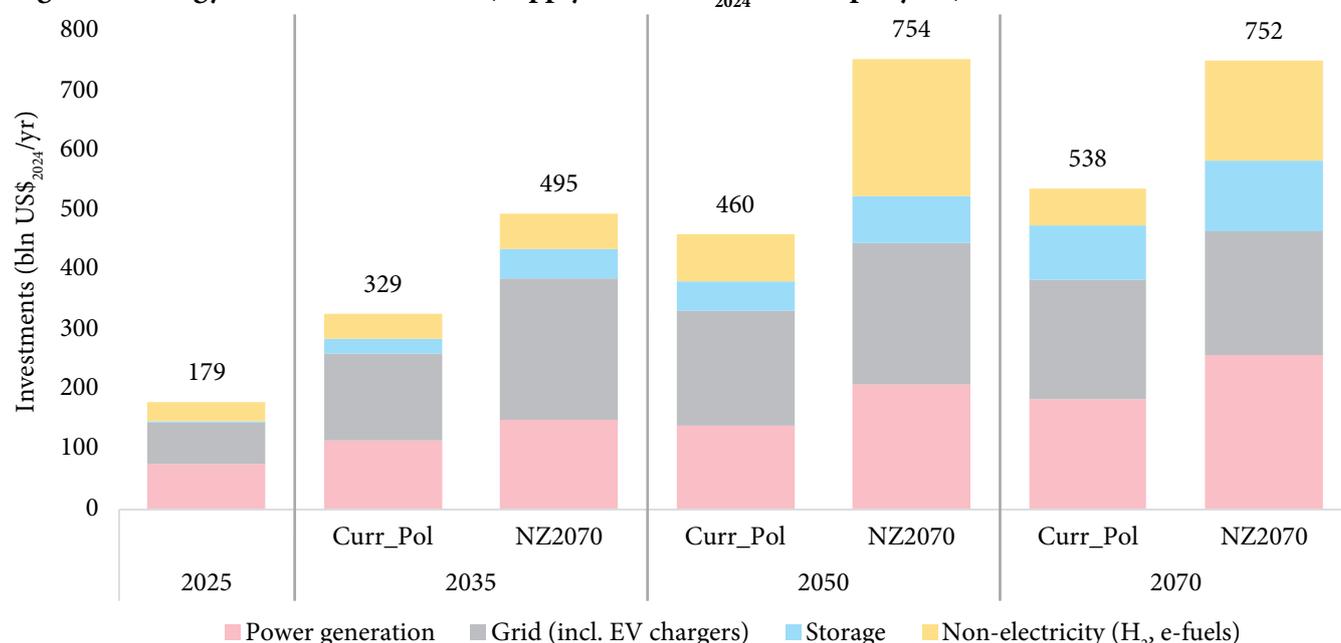
Source: Author estimates based on REMIND.

Note: Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; EV = electric vehicle; H_2 = hydrogen.

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[8]   See for reference Asian Development Bank [ADB] (2023); Asia Society Policy Institute [ASPI] (2022); IEA (2021); Singh & Sidhu/Council on Energy, Environment and Water [CEEW] (2021); McCollum et al. (2018); and Vivekananda International Foundation [VIF] (2022).

Figure 9: Steel Production—India (Mt/year)
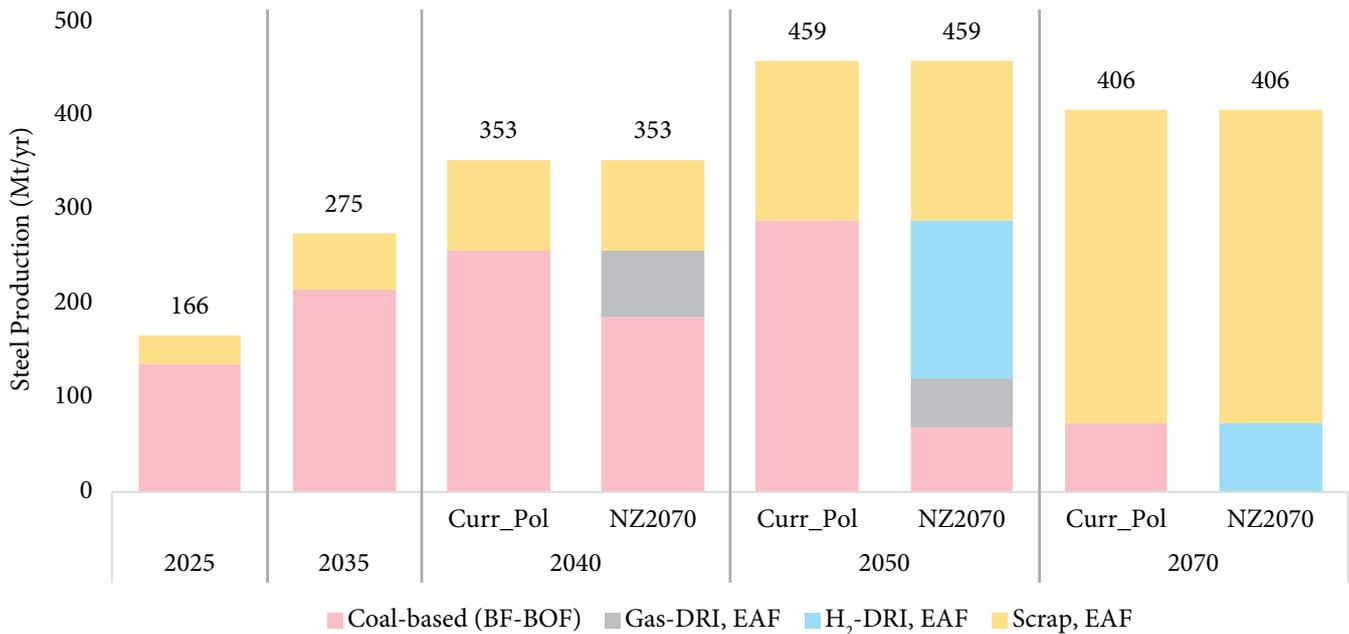
Source: Author estimates based on REMIND.

Note: Mt = million tonne; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario; BF-BOF = blast furnace–basic oxygen furnace; DRI = direct reduced iron; EAF = electric arc furnace.

Steel

India's steel production is projected to nearly triple from current levels to 460 Mt by 2050. This expansion reflects infrastructure development and manufacturing growth, supporting economic development.

The technological composition of steel production undergoes dramatic transformation. Currently dominated by coal-based blast furnace-basic oxygen furnace (BF-BOF) routes (80% of total production), the sector shifts toward cleaner production methods from 2035 onwards. Direct reduction iron (DRI) processes using natural gas emerge as a transitional technology, followed by gH$_2$-based DRI, which becomes the dominant method of primary steel production by 2050 (36% of total). Beyond 2050, EAFs using scrap steel expand as scrap availability increases globally, making scrap-based EAF the major route of steel production in India.

Cement

Cement production is projected to nearly double over current levels by the mid-century to 670 Mt/year, driven by demand for urban infrastructure and housing associated with higher income levels. The carbon intensity of cement production falls from approximately 0.6 t-CO$_2$ per tonne of cement in 2025 to around 0.25 t-CO$_2$/t-cement by 2050 under the *NZ2070* scenario, and to 0.12 t-CO$_2$/t-cement by 2070—much lower than levels projected under *Curr_pol*.

This decarbonisation is expected to be achieved through multiple levels: increased use of alternative cementitious materials (such as fly ash and slag) to reduce clinker content, energy efficiency improvements in clinker production, switching from coal to cleaner fuels such as biomass and electricity for kiln heating, and deployment of carbon capture technology to eliminate process emissions from calcination (the chemical reaction that releases CO$_2$ when limestone is converted to clinker).

Given exogenous demand, steel, and cement production projections remain identical across both scenarios, reflecting the model's welfare-neutral framework. This implies that the total consumption of goods and services in a region is not affected across policy scenarios, ensuring that climate mitigation measures do not impose consumption losses on the population.

Figure 10: Carbon Intensity of Cement Production—India (t-CO$_2$/t-Cement)
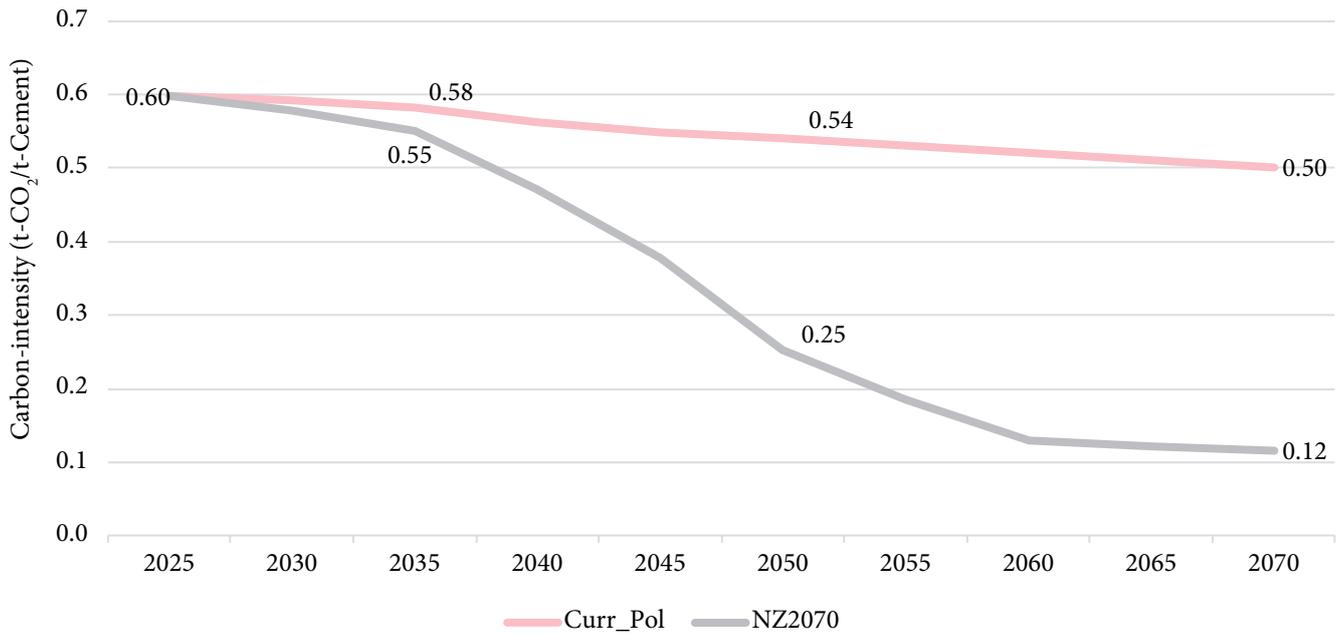
Source: Author estimates based on REMIND.

Note: t = tonne; Curr_pol = current policies scenario; NZ2070 = net-zero by 2070 scenario.

5.7 Implicit Carbon Price

The emission reductions envisaged in the *NZ2070* scenario imply a steadily rising marginal cost of abatement. This is the implicit carbon price paid by way of investments and expenditures on technological deployment, such as renewables and e-fuels, across sectors and shows the economy-wide mitigation effort. The carbon price is estimated to rise from US$5.5 per tonne of CO$_2$ at present to US$100 by 2035, US$241/t-CO$_2$ by 2050, and US$429/t-CO$_2$ by 2070 in the *NZ2070* scenario. These rising price levels reflect the increasing marginal cost of abatement as the economy decarbonises, and the remaining emissions become harder to eliminate.

Figure 11: Implicit Carbon Price in the Net-zero by 2070 Scenario (US$$_{2024}$/t-CO$_2$)
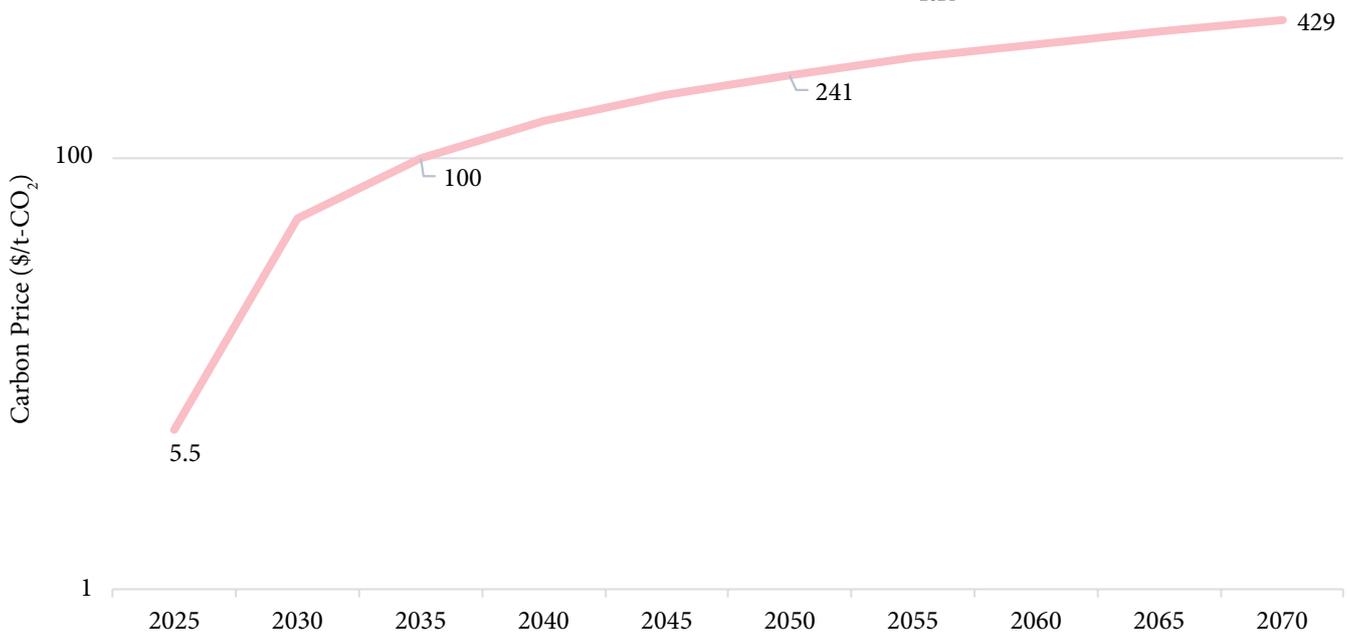
Source: Author estimates based on REMIND.

Note: t = tonne.

6. Discussion

6.1 Compatibility of Growth and Climate Action

The modelling results demonstrate the feasibility of achieving net-zero emissions by 2070 while maintaining robust economic growth. The 6.2% annual GDP growth rate through 2050 enables India to approach high-income status and simultaneously pursue aggressive decarbonisation. These findings challenge the conventional narrative that suggests fundamental trade-offs between development and climate objectives.

The transition pathway reveals critical temporal dynamics. Near-term emissions increase through 2035 reflect sustained use of fossil fuels for development needs and infrastructure expansion. However, substantial groundwork must be carried out over this period—renewable capacity expansion, grid modernisation, and industrial transformation—to accelerate decarbonisation post-2035. The 16% emissions reduction by 2035 compared to current policies, although modest in absolute terms, will be a result of enhanced action in crucial sectors, especially power generation, and will represent a significant deviation from the baseline trajectory given the projected economic growth.

6.2 Ensuring a Just Transition

The *NZ2070* scenario's "slow coal phase-out" approach recognises practical concerns. It acknowledges the economic importance of existing coal infrastructure and the need to avoid asset stranding while ensuring energy security during the transition. Large-scale premature retirement would lead to economic losses and raise energy prices, which would be politically unacceptable. The gradual decline allows coal assets to operate through much of their economic lifetime while preventing new coal lock-in. It also allows more time for managing the phase-down of coal mining, which is projected from 2040 onwards, and will be a major structural change.

Coal-dependent states such as Jharkhand, Odisha, Chhattisgarh, and parts of Madhya Pradesh—which currently derive substantial revenue from coal mining royalties and employ hundreds of thousands in mining and associated industries—face economic disruption as coal production peaks and starts to decline. Coal miners, thermal power plant workers, and communities built around coal economies will experience job losses and economic dislocation without proactive intervention.

Conversely, states with abundant RE potential—Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Andhra Pradesh for solar and wind, and coastal states for offshore wind—stand to gain significantly through RE deployment, manufacturing hubs for clean energy equipment (solar panels, wind turbines, and batteries), and new employment in installation, operation, and maintenance.

This will create significant regional and sectoral winners and losers, necessitating careful policy attention to distributional impacts, which are not modelled in detail in this paper.

The geographic redistribution of economic benefits would require comprehensive just transition policies, including retraining programmes for displaced workers, economic diversification strategies for coal-dependent regions, additional Central government transfers to transition-affected states, and social protection measures to support vulnerable communities. Without explicit attention to these distributional consequences, political resistance from losing regions and sectors could derail the transition, making just transition not merely an equity concern but a prerequisite for climate policy success.

6.3 Technological Implications

The analysis highlights technology-specific deployment challenges and opportunities. New solar and wind deployment must average 150 GW annually during 2030–2035, tripling from current installation rates. This acceleration requires massive supply chain development, manufacturing scale-up, land acquisition, and grid expansion. Whether India can physically execute this buildout pace would depend on policy frameworks, regulatory streamlining, and industrial ecosystem development. Supply chain disruptions, land acquisition delays, or grid congestion could constrain deployment below modelled levels.

Storage capacity would be a critical enabler for rapid RE integration. Grid-scale batteries will prove essential for a short duration balancing over the medium-term. The emergence of gH_2-based seasonal storage post-2050 suggests limitations of batteries for long-duration periods, necessitating the development of gH_2 and e-fuels as storable energy carriers over the long term. Policy must support storage deployment with comparable priority to generation.

Transmission capacity could become the binding constraint for a renewable-based electrified economy if not addressed proactively. The massive deployment of RE would occur predominantly in resource-rich regions with high solar irradiation (such as Rajasthan and Gujarat) and strong wind corridors (coastal areas and select inland zones), which are often geographically distant from major demand centres in urban and industrial hubs. Without commensurate expansion of inter-regional transmission capacity, this renewable generation cannot reach load centres, leading to curtailment of clean energy and continued reliance on local fossil fuel generation. Moreover, the integration of variable renewable sources requires a more flexible, digitally enabled grid capable of managing bidirectional power flows, accommodating distributed generation, and coordinating with storage systems. The projected grid investments—accounting for nearly half of all energy-sector investments in 2035—reflect this imperative. Delays or underinvestment in transmission infrastructure would create physical constraints and jeopardise renewables deployment.

The increased share of renewables, as projected, would also necessitate fundamental shifts in electricity market structure. The current system, dominated by long-term power purchase agreements between generators and distribution companies (DisComs), is not optimal for managing the intermittency of solar and wind power. As RE capacity scales up, the electricity sector must shift towards exchange-based trading mechanisms that allow for more flexible procurement. Power exchanges can accommodate the variable nature of renewable generation by enabling real-time and day-ahead markets where supply and demand can be balanced more efficiently. This would provide price signals that encourage demand-side responses. Such market mechanisms, combined with appropriate regulatory frameworks, would facilitate better integration of renewables into the grid and reduce the overall system costs of the transition.

Sector-specific challenges also exist in the industry. Steel production's transition to gH_2-based direct reduction route requires massive new investments and process technology maturation. Cement sector decarbonisation faces fundamental process-based emission constraints, suggesting a need for scalable carbon capture solutions. The persistence of industrial emissions through 2050 indicates these sectors as critical tailbacks requiring targeted innovation support.

Finally, the analysis assumes favourable costs for solar and wind and continued cost declines for batteries and electrolysers based on historical learning rates. If costs become unfavourable or learning slows due to geopolitical factors, material shortage, technology transfer restrictions, or other reasons, the economy shifts unfavourably.

Given the scale for domestic demand of these products, if India can capture value chains domestically through manufacturing policies, it could shield itself from global uncertainties to some extent. Import substitution opportunity as a result of the energy transition thus becomes an economic development strategy. But it should not come at the cost of innovation, such that domestically manufactured goods are technologically inferior to foreign products. In fact, breakthrough innovations could accelerate the transition. Policy should support continued private sector research and development (R&D) in green steelmaking, sustainable aviation fuels, and carbon capture technologies, and some public investments could also be allocated for demonstration projects.

6.4 Additional Investment Requirements

Relative to the *Curr_pol* scenario, the *NZ2070* pathway requires additional annual investment of approximately US$175 billion per year (in 2024 dollars) during the 2026–2050 period, representing about 1.4% of total GDP. These investments would reduce expenditure on expensive imported fossil fuels, resulting in savings of 1.2% of GDP over the same period.

Critically, the near-term investment requirement is more modest given the deliberate rate of renewables expansion. During the 2026–2035 period, additional investment requirements amount to approximately US$62 billion per year, or about 0.85% of GDP. This lower near-term burden provides time for investment capacity to scale up and for learning-by-doing to reduce technology costs. Additional investments during the period 2036–2050 increase to US$380 billion per year (1.55% of GDP).

Approximately 80% of total investment requirements must be met from domestic sources (Bhattacharya et al., 2024). This requires higher domestic savings rates, the redirection of investments away from fossil fuel infrastructure towards clean energy, innovative financing mechanisms such as blended finance structures and green bonds, institutional investor participation, and the mobilisation of additional

private investment. Risk mitigation measures addressing technology, regulatory, and currency risks will become essential to mobilise private capital at scale. Overall, the model projects the general investment rate in the economy increasing to 34% of GDP by 2035 in the *NZ2070* scenario, up from current levels around 30–31%.

The remaining 20% of total investment requirements—roughly US$51 billion annually during 2026–2035—must be raised from external sources. This comprises non-concessional multilateral and bilateral finance, as well as private international flows, including foreign direct investment. The required level represents approximately six times the level of international climate flows to India in 2021–2022 (Climate Policy Initiative [CPI], 2024), highlighting the need for scaled-up international climate finance. An analysis by Raj and Mohan (2025) suggests that there is room to widen India's current account deficit to accommodate these additional capital inflows without destabilising the external balance.

This gap highlights that even with aggressive domestic resource mobilisation, international cooperation on financial assistance would remain the critical enabler of India's ambitious climate action. Reform of multilateral institutions and bilateral agreements on financial support and technology transfer requires strengthened international frameworks beyond current mechanisms.

6.5 Rationalising Energy Prices

Energy price rationalisation emerges as a critical policy lever for accelerating India's transition to RE and improving overall energy efficiency. Current electricity pricing structures in India are characterised by extensive cross-subsidies, where agricultural and residential consumers receive heavily subsidised electricity, whereas commercial and industrial users pay above-cost tariffs. These inefficient subsidies provide perverse incentives that encourage inefficient energy usage, discourage investment in energy efficiency measures, and undermine the competitiveness of RE despite its declining costs and environmental benefits. Critically, existing energy prices fail to account for the externalities caused by pollution—including air quality impacts that lead to innumerable premature deaths annually, health expenditures, and broader environmental damages—effectively socialising these costs.

Reforming these distortions is essential to creating a level playing field where renewables can compete on merit and reflect their genuine advantages in avoided health and environmental damages. Beyond subsidy rationalisation, implementing sophisticated pricing mechanisms such as time-of-day tariffs—which charge higher rates during peak demand periods and lower rates when renewable generation is abundant—can incentivise demand shifting and better align consumption with renewable availability, thereby reducing the demand for storage. These reforms would reduce behavioural shifts, like switching to energy-efficient appliances, better building designs, etc., which otherwise may not occur through statutory advice.

Similarly, locational marginal pricing that reflects transmission constraints and regional generation costs can guide efficient siting of both generation and consumption, thereby reducing grid congestion and curtailment.

Concerns about affordability and equity render energy price reforms politically challenging, but they can be designed in a manner to protect genuinely vulnerable consumers through direct benefit transfers while eliminating wasteful subsidies (as was done for Liquefied Petroleum Gas [LPG] price reforms). This should help in saving scarce public resources for the energy transition and simultaneously improve system efficiency and RE competitiveness.

Carbon pricing provides a powerful complement to energy price rationalisation by directly addressing the climate externality that current prices ignore. A well-designed carbon price—whether through a direct carbon tax or an emissions trading scheme—would make fossil fuels more expensive in proportion to their carbon intensity and automatically improve the relative competitiveness of renewables and low-carbon alternatives without requiring technology-specific subsidies or mandates.

The implicit carbon prices in the *NZ2070* scenario, reaching US$100/t-$CO_2$, suggest the scale of price signal needed to drive the economy-wide transition, unlike the sectoral approach currently followed. An explicit carbon price would generate substantial government revenues that could be recycled to reduce distortionary taxes elsewhere, fund clean energy investments, support just transition programmes for affected workers and communities, or provide compensation to vulnerable households, thereby addressing equity concerns while maintaining the efficiency benefits of carbon pricing.

Expanding India's proposed carbon market mechanism (i.e., the CCTS) to cover the power sector and progressively tightening carbon intensity targets would create market-based incentives for emissions reductions across the economy. It would provide technology-neutral incentives, allowing market actors to discover the most cost-effective abatement opportunities rather than imposing technological mandates. The price signals will also encourage innovation in low-carbon technologies and practices.

Policies such as price rationalisation require sustained policy commitment over the long-term and would depend on building durable political coalitions supporting the transition. Policy reversals, bureaucratic delays, or regulatory uncertainty could deter investments and significantly slow progress.

6.6 Implications of Delayed Transition

The timing of India's decarbonisation efforts is important in determining the cumulative emissions generated before achieving net zero and the cost of achieving it. Analysis of alternative scenarios (Appendix 5) demonstrates that if India pursues an even slower coal phase-out trajectory, with emissions peaking at higher levels (4.8 Gt-CO_2 in 2035) and remaining higher than those projected under the *NZ2070* scenario through 2070, maintaining 1.9°C compatibility would require the deployment of large-scale negative-emission technologies to offset the excess emissions hence caused. Under such a scenario, net-negative emissions are projected from 2075 onwards through ERW. The implicit carbon price in such a scenario would escalate to over US$1,200 per tonne of CO_2 by 2080, nearly three times higher than the US$429 per tonne estimated under the *NZ2070* pathway, reflecting the substantially greater marginal costs of atmospheric carbon removal compared to emissions avoidance.

Currently, these negative emission technologies remain largely unproven at scale, face significant resource constraints (such as land and water requirements), and impose an extremely high cost burden. In contrast, the *NZ2070* scenario—which peaks emissions at 4.2 Gt in 2035 before declining steadily to net-zero by 2070—avoids this expensive negative emissions route by frontloading mitigation efforts when abatement costs are lower and conventional mitigation options remain available. This comparison underscores that timely, gradual climate action will be more efficient than a delayed transition, which would impose far greater costs on future generations, constrain fiscal resources and require more disruptive technological deployments, and reinforces the imperative for making ambitious near-term emissions reductions.

7. Policy Recommendations

Based on the modelling results, the study proposes the following decarbonisation targets for India for 2035 with five key pillars:

- **Reduce emission intensity of GDP by 65% compared to 2005**, such that economy-wide emissions peak around 2035, with subsequent absolute declining thereafter. This provides a clear direction for decarbonisation without impeding near-term economic growth.

- **Achieve 80% cumulative electric power installed capacity from non-fossil-fuel sources**, with an objective of 1,200 GW of RE capacity (e.g., hydro) by 2035. This represents a 2.5-fold increase over the current target for 2030. Achieving this should increase the share of non-hydro renewables in India's electricity mix to 50% over the next 10 years.

- Peaking emissions around 2035 would require **unabated coal-based power generation to peak before 2035**. This implies that no new unabated coal plants are commissioned post 2030, and existing plants begin gradual retirement starting with older, more inefficient units. Such a timeline also gives ample time for coal-producing states to restructure the industry (which will see a decline in coal demand from 2040 onwards).

- **Double the pace of electrification.** With current technologies, this is carried out most cost-effectively in railway traction, passenger vehicles (cars and two-/three-wheelers), and light commercial vehicles. Gradually, this could expand to other road transport modes and industrial heating, as technology costs improve.

- **Expand and deepen carbon market.** The upcoming CCTS should be expanded to include the power sector, which is the largest emitting sector, and eventually all polluting industries. Furthermore, carbon intensity targets should be progressively tightened to align sectoral emissions with the country's long-term emission trajectory.

8. Conclusion

The REMIND–India model analysis demonstrates that India can chart a pathway to near-high per-capita income by 2050 and net-zero CO_2 emissions by 2070 while maintaining compatibility with global temperature objectives. This pathway requires profound transformation across the energy system—particularly massive RE expansion, accelerated electrification, strategic deployment of gH_2 for hard-to-abate sectors, and gradual coal phase-out—supported by substantial but manageable investment flows. Besides contributing to global climate change mitigation, the pathway also represents an optimal strategy for India to secure energy independence, reduce air pollution, and create economic opportunities in emerging technologies.

The near-term strategy through 2035 proves critical. Peaking emissions around 2035, achieving 1,200 GW of renewable capacity, ending new unabated coal generation capacity, and accelerating transport electrification would establish the trajectory towards the 2070 net-zero goal. These near-term actions require additional investment of roughly 0.85% of GDP annually.

The pathway represents an ambitious but feasible transformation of the energy system. Coal retains considerable shares through 2050, albeit declining, providing time for a managed transition. This approach reflects energy security concerns, existing infrastructure investments, and employment considerations in coal-dependent regions. The parallel massive renewable deployment would demonstrate a commitment to mitigation while managing socio-economic disruptions.

The pathway would however require sustained execution: building renewable projects at scale, expanding transmission grids, deploying storage, electrifying vehicles and industrial processes, and redirecting investment flows. The policy framework matters enormously to this effect and rationalising energy prices would be key to generating demand for low-carbon energy services and goods.

This modelling exercise operates under the critical assumption that the rest of the world continues concerted efforts towards mitigating climate change and honours international net-zero commitments, most notably the US and the EU achieving net-zero emissions by 2050 and China by 2060. These assumptions are foundational to the 1.9°C global warming constraint that underpins India's *NZ2070* pathway. The current geopolitical reality, particularly with the shift in climate policy position of the US—the second largest emitter globally—introduces considerable uncertainty into this assumption and raises questions about the stability of international climate cooperation. However, the accelerating economic competitiveness of clean energy technologies and the mounting evidence of climate impacts provide grounds for cautious optimism that scientific temperament and rational policymaking will ultimately prevail over short-term political considerations.

As the most populous and fast-growing economy, India's emissions trajectory would influence global climate outcomes. However, its transition pathway should be understood as occurring within a framework of global cooperation, where collective ambition enables individual countries to pursue more efficient pathways, with technology sharing and climate finance flows being key enablers of climate action.

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Appendices

Appendix 1: REgional Model of Investments and Development (REMIND)

REMIND is a modular, multi-regional model that provides an integrated assessment of the energy–economy–climate system spanning from 2005 to 2150. REMIND can also be integrated with the Model of Agricultural Production and its Impact on the Environment (MAgPIE) land use model to incorporate the land use, land use change, and forestry (LULUCF) sector.

REMIND functions as a general equilibrium model that combines a macroeconomic growth model (Ramsey-type)[9] with a bottom-up energy system model, implemented through the General Algebraic Modelling System (GAMS). The model identifies intertemporal Pareto-optimal solutions in economic and energy investments across 12 defined regions, describing different fuels and energy conversion technologies while representing trends in economic growth, cross-border trade in final goods, primary energy, and emissions credits.

The macroeconomic core operates as an optimal growth model with perfect foresight of economic agents and internalisation of external effects. It non-linearly optimises intertemporal global welfare to derive region-specific transformation pathways, subject to market-clearing and sustainability constraints and produces a decentralised market outcome through iterative solutions (Baumstark et al., 2021). The model's production functions comprise capital, labour, and FE, with FE demand determined by nested production functions and customisable constant elasticity of substitution (CES). REMIND uses GDP for investments in capital stock creation as well as for consumption, imports, and energy system expenses.

The energy system component generates FE demand through economic activity in transport, industry (steel, cement, chemicals, and others), and building sectors. The power module determines operational production decisions related to electricity supply, while the primary energy system separately describes fossil fuels, nuclear fuels, and renewables, including bioenergy. The model incorporates over 50 technologies that transform energy and distribute secondary energy carriers, with fossil fuel extraction costs calculated by a dedicated fossil module.

Environmental representation in REMIND covers all anthropogenic greenhouse gases (GHGs; both long- and short-lived) and air pollutants (aerosols), described by type and origin. These emissions are linked to specific anthropogenic activities: CO_2 to fossil fuel use, CH_4 to fossil fuel extraction and domestic energy consumption, and N_2O to source-specific energy supply. Fluorinated gases (f-gases) and land use change emissions are exogenously specified based on SSP scenarios and global warming targets.

REMIND accounts for important factors contributing to energy system inertia and path dependencies, including capacity vintage structure, technical learning curves for new technologies, and costs associated with rapid technology deployment. This focus on technological detail makes it particularly useful for depicting large-scale adoption and integration of new technologies and exploring cost-effective approaches to achieving exogenously prescribed climate targets. The model enables analysis of policy measures and technology choices for GHG emission abatement, with several energy sector policies modelled explicitly such as fuel taxes and energy subsidies.

The model's modular programming structure facilitates versatile configuration and expansion, with explicit data exchange between modules through well-defined input and output variables. REMIND's spatial resolution is determined by input data resolution, allowing for region- or country-specific modelling studies. This adaptable framework can be customised for multiple applications while balancing detail with computational runtime and numerical complexity, making it suitable for identifying first-best mitigation strategies that serve as reference scenarios compared against second-best scenarios influenced by regional or sectoral fragmentation or technology limitations.

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[9] The Ramsey Model (or the Ramsey–Cass–Koopmans model) is a foundational neoclassical economic framework that explains long-run economic growth by endogenising savings and consumption decisions.

Figure A1: Structure of REMIND
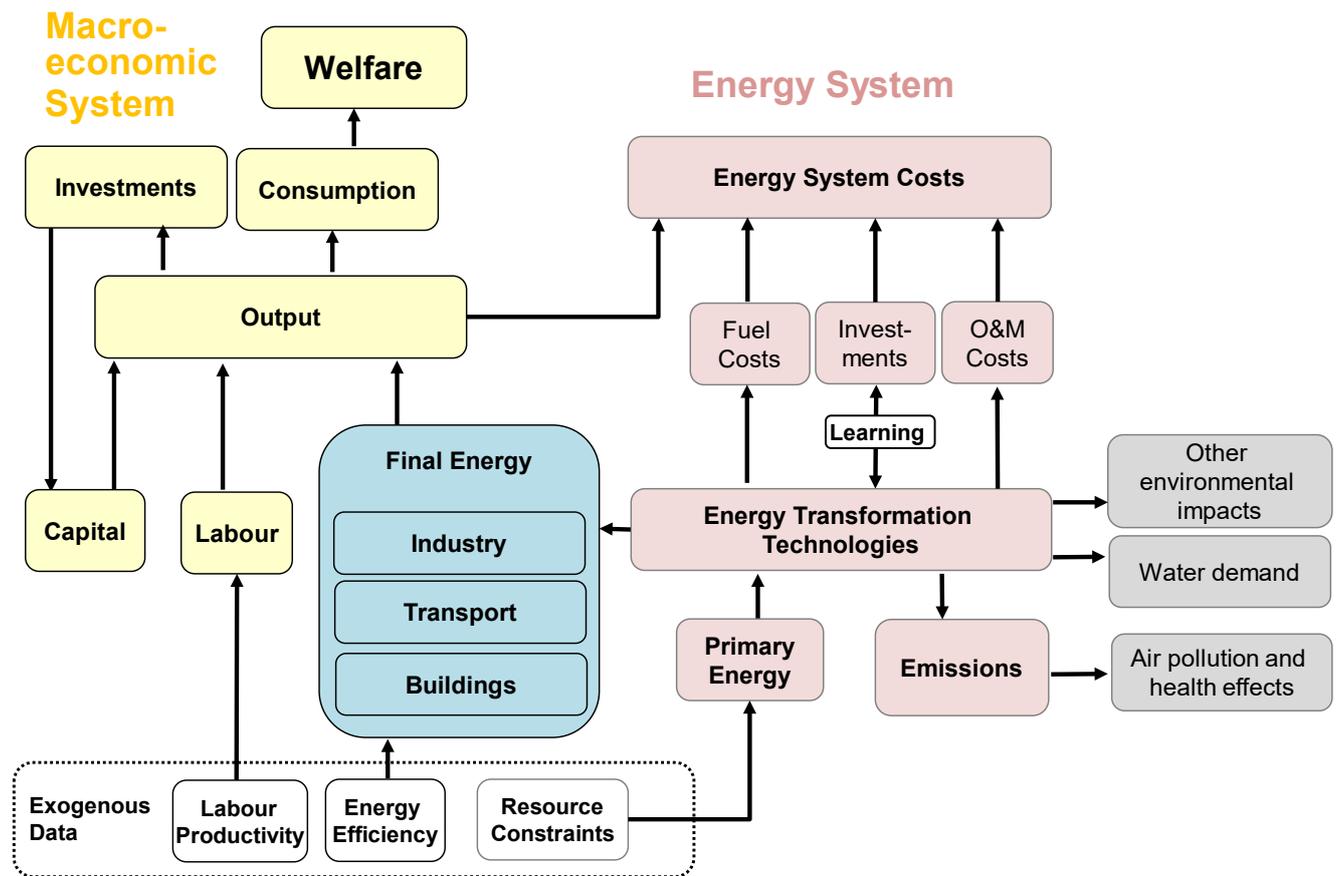
Source: *Baumstark et al., 2021.*

Appendix 2: Cobb–Douglas Disaggregates of Output

Table A1: Cobb–Douglas Disaggregates of Output over the Model Horizon (2025–2070)

$$GDP = TFP \times Capital\ Stock^{\alpha} \times Labour^{\beta} \times Energy^{\gamma}$$

	Capital Stock (US$ trillion, 2024)	Population (US$ Billion)	FE (EJ/Year)	TFP	GDP (MER; US$_{2024} trillion per year)
2025	12.40	1.45	38.61	1.42	5.23
2030	17.30	1.47	44.49	1.75	7.18
2035	24.94	1.51	51.19	2.17	10.18
2040	34.52	1.55	55.74	2.64	13.89
2045	46.33	1.58	58.55	3.12	18.11
2050	57.90	1.61	59.09	3.61	22.48
2055	71.66	1.62	60.49	4.12	27.43
2060	87.69	1.63	65.11	4.69	33.31
2070	127.88	1.61	68.84	5.96	46.96

Elasticities: α = 0.27; β = 0.62; γ = 0.11.

Source: *Author estimates based on REMIND.*

Note: *FE = final energy; EJ = exajoule; TFP = total factor productivity; MER = market exchange rate.*

Appendix 3: Energy Flow Diagrams

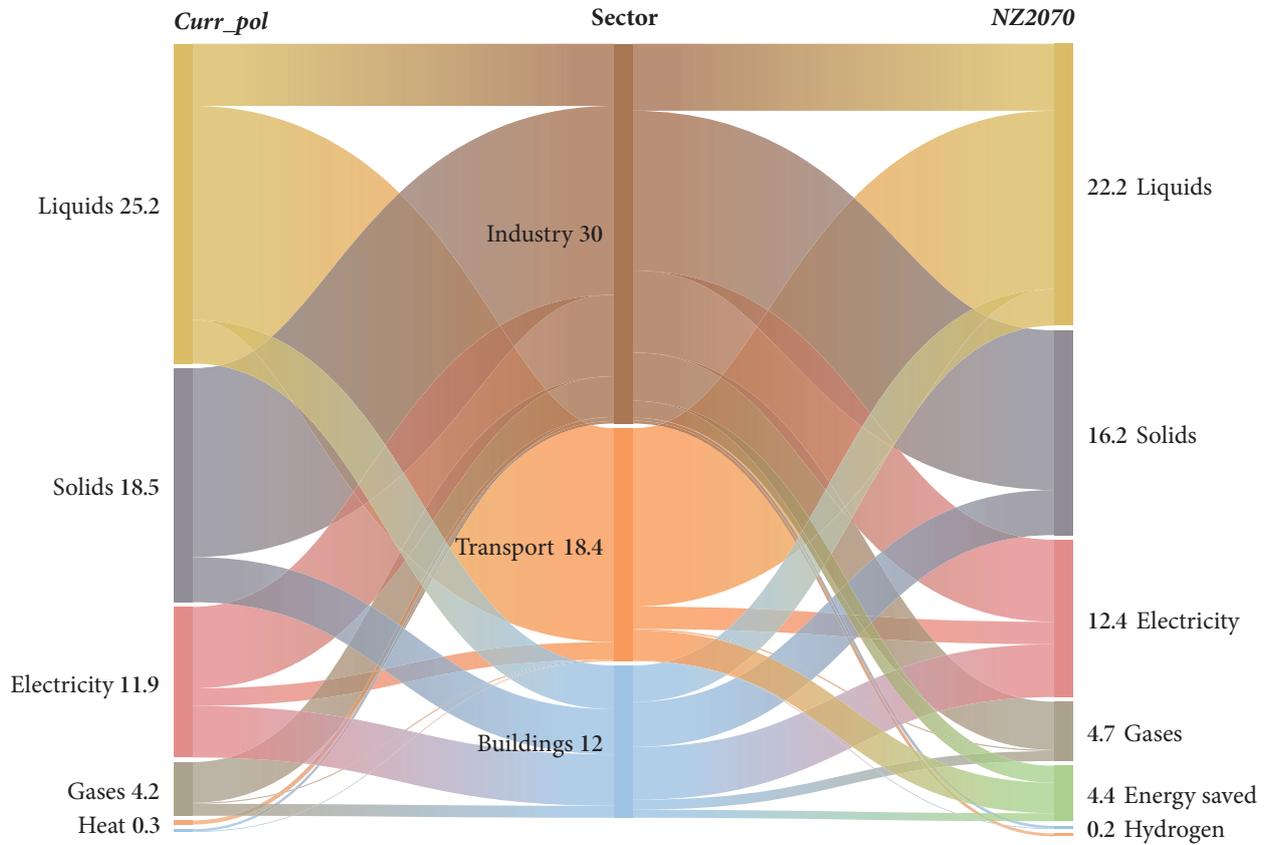## Figure A2: Final Energy by Sector, 2035 (EJ)

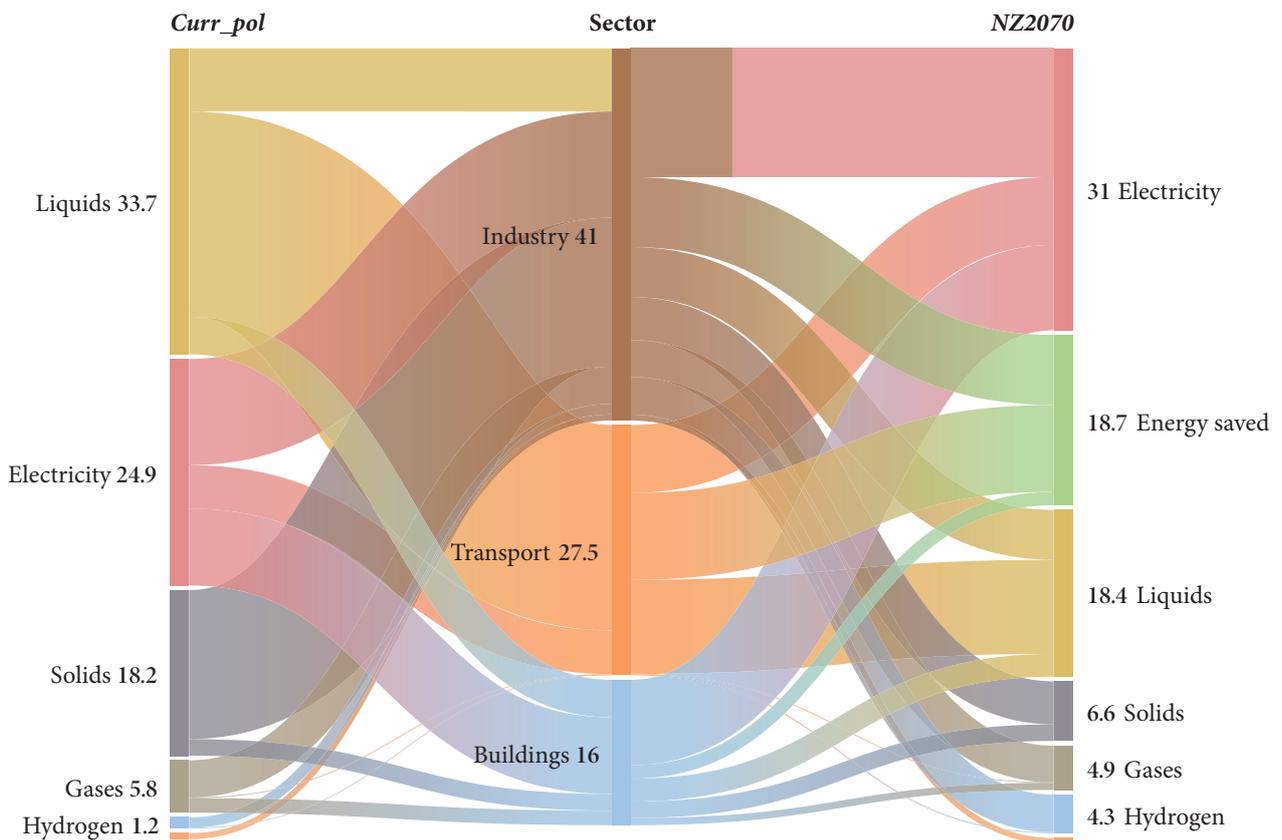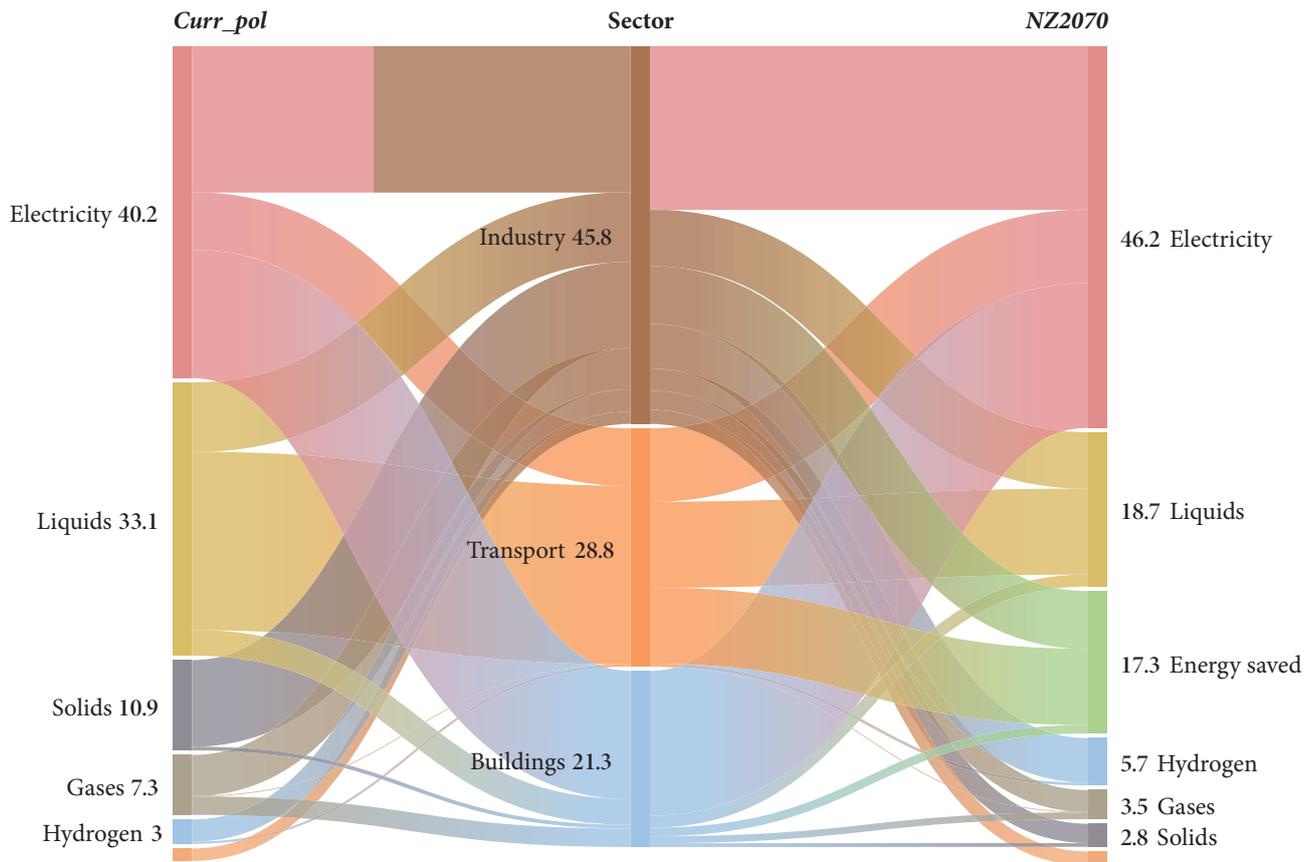## Figure A3: Final Energy by Sector, 2050 (EJ)

Figure A4: Final Energy by Sector, 2070 (EJ)

Source: (for Figures A2–A6): Author estimates based on REMIND.

Note: EJ = Exajoule.

Appendix 4: Alternate Estimates of Total Investment Requirements

Table A2: Alternate Estimates of Total Investment Requirements for India *(US$$_{2020}$ billion per year)*

	Sector	Time Period	Scenario	Total Investment (US$$_{2020}$ billion per year)
VIF, 2022	Power	2020–2070	NZ by 2070	334[#]
IEA, 2021	Power	2022–2030	NZ by 2070	160
McCollum et al., 2018	Energy	2016–2050	<2°C by 2100 (66%)	254
ADB, 2023	~Energy	2020–2050	NZ by ~2070	~185
MoEFCC, 2015	Energy+	2015–2030	NDCs by 2030	170
Singh & Sidhu/ CEEW, 2021	Energy+*	2020–2069	NZ by 2070	202
DEA, 2020	All**	2017–2030	NDCs by 2030	544
Gupta et al./ McKinsey, 2022	All	2020–2050	NZ by 2050	403
ASPI, 2022	All	2022–2060	NZ by 2070	259[##]

*Power, Transport, and H₂ sectors. • **Includes energy, forestry, and adaptation.

#Renewable energy-dominated scenario. • ##Refers to additional investments only.

Source: Various sources, compiled by the authors.

Note: Estimates inflated or deflated to harmonise the base year. NZ = net zero; NDCs = Nationally Determined Contributions; VIF = Vivekananda International Foundation; IEA = International Energy Agency; ADB = Asian Development Bank; MoEFCC = Ministry of Environment, Forest and Climate Change; CEEW = Council on Energy, Environment and Water; DEA = Department of Economic Affairs; ASPI = Asia Society Policy Institute.

Appendix 5: Implicit Carbon Price Under Slow Coal Phase-Out Scenario

Figure A5: Slower Coal Phase-Out with Higher Peak and Negative Emissions (Gt-CO₂/year)
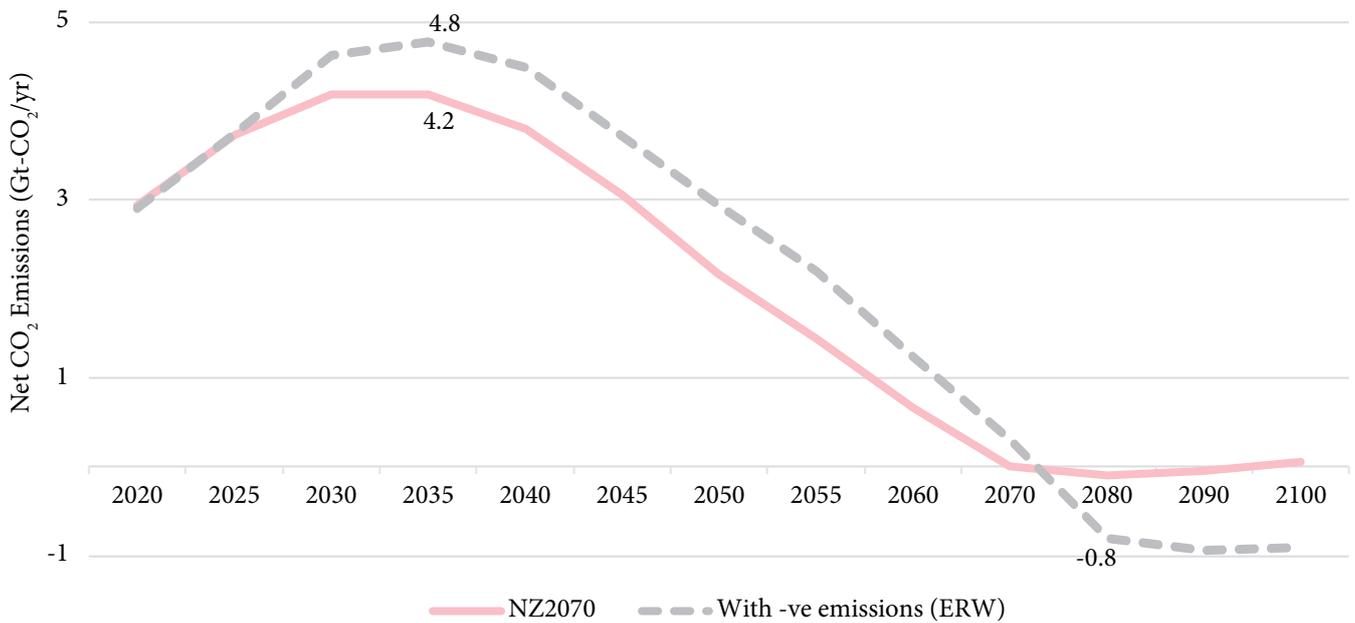
Source: Author estimates based on REMIND.

Note: Gt = gigatonne; ERW = enhanced rock weathering; NZ2070 = net-zero by 2070 scenario.

Figure A6: Carbon Price Under Higher Peak and Negative Emissions Scenario (US$₂₀₂₄/t-CO₂)
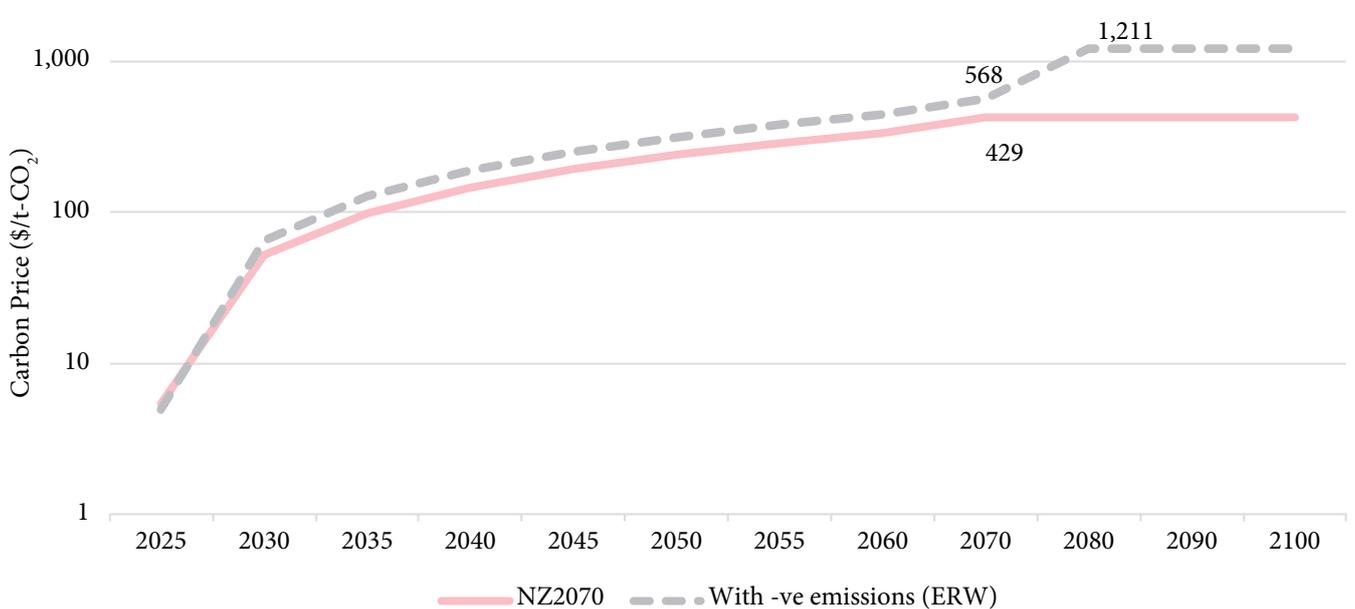
Source: Author estimates based on REMIND.

Note: t = tonne; ERW = enhanced rock weathering; NZ2070 = net-zero by 2070 scenario.

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