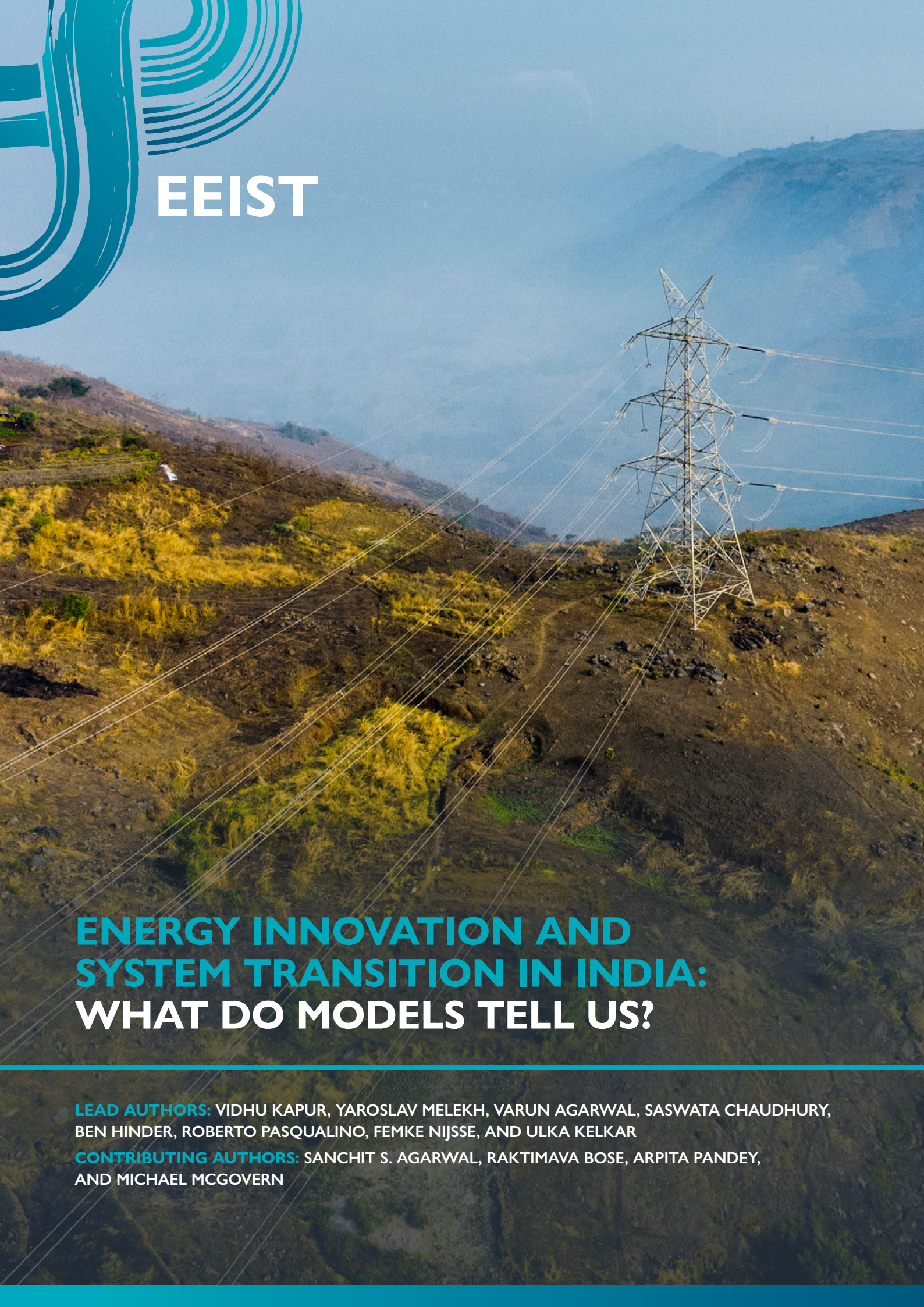




EEIST

ENERGY INNOVATION AND SYSTEM TRANSITION IN INDIA: WHAT DO MODELS TELL US?

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About

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change.

By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are: **UK** – University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies; **Brazil** – Federal University of Rio de Janeiro (UFRJ), University of Brasilia (UNB), University of Campinas (UNICAMP); **EU** – Scuola Superiore di Studi Universitari e di Perfezionamento Sant’Anna (SSSA); **China** – Beijing Normal University, Tsinghua University, Energy Research Institute; **India** – The Energy and Resources Institute, World Resources Institute.

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Foreword

In the grand tapestry of sustainable development, India has embarked on a remarkable journey of transitioning to a greener economy. The nation aspires to achieve net zero carbon emissions by 2070 and envisions becoming a US\$5 trillion economy by 2027-28. The path to this ambitious goal, filled with challenges and opportunities, is complex and multidimensional. It compels us to grapple with the pressing need to mitigate carbon emissions while ensuring that the benefits of growth are equitably distributed.

The Indian government's Department of Economic Affairs estimated a requirement of nearly US\$3tn by 2030 to fulfil nationally determined contributions for mitigation and adaptation. Further, the International Energy Agency projected an estimation of about US\$4tn solely for transitioning the energy system. This highlights the magnitude of the financial challenge at hand – and in fact, the resources available from governments alone are insufficient to meet it. Current estimates place climate finance contributions at around \$83bn annually – far short of the projected trillions needed.

Robust planning is imperative in this regard. India stands at the crossroads of economic growth and environmental sustainability, and the choices Indian policymakers make today will reverberate for generations and create ripples for transformation. These choices are not limited to infrastructure, technology and innovation; they encompass policy, governance and finance.

The challenges facing India on its path to sustainability are multidimensional. We must expand our renewable energy infrastructure, invest in energy efficiency, and implement policies that encourage sustainable practices across industries and stakeholders. Additionally, addressing social security concerns, particularly in healthcare and education, is of paramount importance to ensure that the benefits of growth are accessible to all segments of society. As the nation seeks to uplift its large and diverse population, it must simultaneously address the pressing need to mitigate carbon emissions. This complex interplay of factors necessitates a nuanced approach that goes beyond mere traditional cost and benefit and low-cost optimisation models. Instead, we can employ innovative approaches that consider system interactions and inherent complexities.

Economic models help us deconstruct this complexity and serve as a planning tool for the future transition. However, the efficacy of these models hinges on a standard framework and its underlying assumptions. Policymakers must carefully select the models that best align with a shared vision while planning transitions. TERI and WRI, as part of the Economics of Energy Innovation and System Transition (EEIST) consortium, have contributed significantly to several works on 'Risk-Opportunity Analysis' – a framework which can go a long way in shaping future pathways to combat climate change.

I commend the efforts of the authors for meticulously assembling and knitting meaningfully this web of challenges, opportunities and solutions into an accessible and comprehensive narrative. Their understanding of the complexities of India's energy transition and rich insights is laudable. This report offers a nuanced approach to addressing the multifaceted nature of energy transition in India, and will act as a valuable repository for policymakers, researchers and all stakeholders committed to shaping a sustainable future.

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Executive summary

India stands at a critical juncture in its journey to meet its 2070 net zero ambition. Despite the country’s renewable energy capacity having quadrupled over the last decade, fossil fuels still comprise over 80% of India’s primary energy supply. Meeting India’s increasing energy demand while phasing down fossil fuels will mean more than just scaling up renewable energy. It will require deploying energy storage in the power system, exploring the potential of green hydrogen production, and considering the supplementary role of low-carbon technologies like nuclear and natural gas, all while accounting for associated technology lock-ins. A systematic assessment of risks and opportunities associated with policy choices is key for the effective utilisation of available financial and infrastructural resources.

This report aims (i) to provide the specific context of the energy transition in India, including previous successes and lessons learned, and the potential challenges it faces both in economic development and decarbonisation; (ii) to introduce the Risk-Opportunity Analysis (ROA) approach to the policy context in India, which represents the flagship policy appraisal fundamental of the EEIST programme, and (iii) to present results from a modelling comparison exercise with both simulating and optimising models to explain the key differences and complementarities between existing and new modelling approaches¹ through model-specific information and data.

The report concludes that decarbonising the Indian economy does not come at a cost to its economic development aspirations. Renewable technologies like solar have already achieved cost-parity with coal. Moreover, India’s large economy means that it can leverage economies of scale to drive green technology costs down, as experienced by the success of past government programmes, such as aggregating the demand and bulk public procurement of LED bulbs.

The report also highlights the challenges and risks of India’s Net Zero strategy, including technology choices, system costs, existing grid infrastructure, power market structures, land availability, diverse stakeholder interests, challenges in mobilising finance, and labour market skilling programmes to support the transition of workers into green sectors. Policy appraisal tools like the ROA can play a key role as complementary tools to conventional analysis in guiding policy formulation associated with India’s energy transition.

The comparative analysis of modelling outcomes demonstrates their differences and complementarities: a conventional model (MARKAL), based on cost-optimisation and intertemporal equilibrium, and ‘new’ models (EPS and E3ME-FTT) that capture one or more aspects of the ROA approach, including the ‘learning-by-doing’ effects of technology deployment on technology costs that can create tipping points in technology transitions, **with the following insights:**

Policy questions	Key findings
What will the impact of decarbonisation be on electricity demand?	Decarbonising India’s power supply is critical given the projected growth in electricity demand. Electrification is central to India’s energy transition and net zero agenda. The three models diverge considerably in their assessment of India’s future electricity demand, ranging from 5400 to 9400 TWh in 2050, owing to different assumptions about economic growth, electrification rates and efficiency improvements over time. All three models project significant demand growth by at least 2.5 times between 2030 and 2050, representing the shift from fossil fuels to electrification in end-use sectors like industry, transport and buildings, despite significant projected improvements in energy efficiency.
What would be the most appropriate energy mix for India (in 2030 and 2050) for effective deep decarbonisation of the power sector, and which technology should be prioritised?	Planned phasedown in coal-based generation is key, but making choices about the technology mix and integration costs involve uncertainty. The decarbonisation pathways of all three models see the share of coal in electricity generation fall from 70% to below 50% in 2030 and to less than 10% in 2050. However, the modelling outcomes diverge in their mix of technologies to replace coal. The ‘learning-by-doing’ in E3ME-FTT results in dominance of solar coupled with battery storage in the electricity generation mix, reaching 61% in 2050. The MARKAL and EPS results identify a greater role for wind in India’s future energy mix, given its complementary generation profile to solar, reducing the intermittency of power supply. The difference in outcomes reflects uncertainty about the magnitude of grid integration costs and balancing technologies with the rising share of variable renewables in the energy mix; developing more granular models to represent the complexities of these interactions is an important priority.
What is the impact of decarbonisation on the labour market and just transition in India?	Investment in renewables has the potential to create net gains in employment, but mobilising green finance and just transition in the coal regions will be critical. Investment in renewables has the potential to create 3-6m net jobs by 2050, according to the EPS and E3ME-FTT models, outweighing the effect of a relative decline in fossil fuel and mining sectors. However, the additional investment requirements are significant, potentially amounting to 0.5% of projected GDP in 2030 and 1.5% in 2050. This indicates that mobilising green finance will be a key factor in enabling India’s energy transition. Moreover, mining and coal-dependent states will need to diversify their economies and reskill workers for new jobs in emerging green sectors.

¹ Barbrook-Johnson et al. (2023) New Economic Models of Energy Innovation and Transition: Addressing new questions and providing better answers

Introduction

India is the world's fifth-largest economy and has sustained an average post-COVID growth rate of 6.9%.² With growing industrialisation and urbanisation, India's greenhouse gas emissions have risen steadily over the last decade, from 1.8bn tons of carbon dioxide equivalent (BtCO₂e) in 2010 to 2.6 BtCO₂e in 2019.³ However, India still maintains remarkably low per capita emissions. To put this into perspective, at 1.9 tons they represent only about one-fifth of China's per capita emissions (8.73 tons) and a mere 13% of the US's (14.24 tons). But India is still in an early stage of its economic development – its energy demand continues to grow to fuel economic expansion and ensure energy security for its rapidly growing population. It is critical, therefore, that the country transitions into a new development paradigm that decouples economic growth from carbon emissions.

The challenges facing India on its path to sustainability are multifaceted. With an aspiration to become a US\$5tn economy by 2027-28,⁴ the country must further expand its renewable energy infrastructure, invest in energy efficiency and implement policies that encourage sustainable practices across industries. Additionally, addressing social security concerns, particularly in healthcare and education, is paramount to ensure that the benefits of growth are accessible to all segments of society. As the nation seeks to uplift its large and diverse population, it must simultaneously grapple with the pressing need to mitigate carbon emissions. This complex interplay of factors necessitates a nuanced approach that goes beyond mere traditional cost and benefit analysis and low-cost optimisation modelling.

This Economics of Energy Innovation and System Transition (EEIST) country report provides a crucial platform for comprehensively examining energy innovation and system transition in India. It goes beyond merely assessing the country's progress in decarbonisation and delves deep into the multifaceted challenges associated with this process. It also introduces policymakers in India to a new approach known as Risk-Opportunity Analysis (ROA), which aims to offer a more comprehensive and multidimensional understanding of the energy transition process, accounting for its dynamic nature and uncertainties. ROA serves as a powerful tool for researchers to elucidate the complexities involved which can provide Indian policymakers with research-based evidence and a well-informed decision-making process.

These insights are geared towards enhancing the effectiveness of future energy transitions in the country.

The report also compares and contrasts certain insights that emerge in the context of India's energy transition from the application of the ROA approach, as against conventional methods of policy appraisal, through a comparative analysis of select outcomes from three models: one conventional, based on neoclassical assumptions of equilibrium, marginality and homogeneous agents, and two that incorporate one or more elements of the ROA approach, such as representation of diverse agents, feedback loops, tipping points and uncertainty. In particular, the report aims to highlight the use of new approaches in complementing traditional approaches to provide a holistic view of the multi-dimensional nature of energy transition in India, necessary for effective policymaking to achieve India's climate targets.

The report proceeds as follows: Section 1 briefly outlines the progress of India's energy transition, identifying challenges and multi-dimensional considerations which policymakers need to take into account. Section 2 discusses the role of traditional approaches and cost-optimisation energy models and the complementarity of new approaches in informing policymaking in India's energy transition. Section 3 introduces the methodological framework and key policy questions of this report. The comparison of modelling results in electricity demand, electricity generation mix and the labour market and associated macroeconomic implications are presented in Section 4, followed by a concluding section on questions for further analysis in the context of India's energy transition.

² <https://www.worldbank.org/en/news/press-release/2023/04/04/indian-economy-continues-to-show-resilience-amid-global-uncertainties>

³ India, National Communication (NC). NC 3. | UNFCCC

⁴ <https://www.pib.gov.in/PressReleasePage.aspx?PRID=1875480#:~:text=In%20the%20same%20program%20he,held%20earlier%2C%20leaving%20Britain%20behind>

Section 1: India's energy transition: Recent experience

1.1 Background of the energy transition in India

At COP26 in 2021, India announced its aspiration to achieve net zero by 2070, with four additional goals to be achieved by 2030.⁵ These were:

1. Reducing India's total projected emissions until 2030 by 1bn tons
2. Reducing the carbon intensity of GDP by 45% compared to 2005
3. Sourcing 50% of India's energy requirements from renewable energy
4. Increasing non-fossil fuel power generation capacity to 500GW.

In an upward revision to its nationally determined contribution (NDC) targets for 2030, submitted to the UNFCCC in August of the following year,⁶ it included the target to reduce the emissions intensity of GDP by 45% from its 2005 level (compared to the earlier target of 33%-35%) and committed to

achieving 50% cumulative installed capacity of power generation from non-fossil fuel-based energy resources (compared to the earlier target of 40%). The targets demonstrate the country's continued commitment to the transition towards a low-carbon economy. Renewable energy generation, energy efficiency, electrification and deep decarbonisation are therefore four important pillars of India's energy transition.

India has already made progress towards its climate goals – now ranking 4th globally in its installed capacity of wind power, solar power and total non-fossil energy (including large hydro), totalling 172GW as of October 2022.⁷ Meanwhile, the energy intensity of India's GDP has declined by about a third over the past two decades (Figure 1), and the share of non-fossil fuel installed capacity has increased from 34% to 41% in the past decade (Figure 2).



⁵ Press Information Bureau (pib.gov.in)

⁶ <https://pib.gov.in/PressReleaseframePage.aspx?PRID=1987752#:~:text=In%20August%202022%2C%20India%20updated,enhanced%20to%2050%25%20by%202030.>

⁷ Year-End Review 2022 – Ministry of New and Renewable Energy (pib.gov.in)

Figure 1: Energy intensity of GDP (MJ/\$ 2017 PPP GDP) in India: Progress in the last two decades. Source: World Bank Development Indicators.

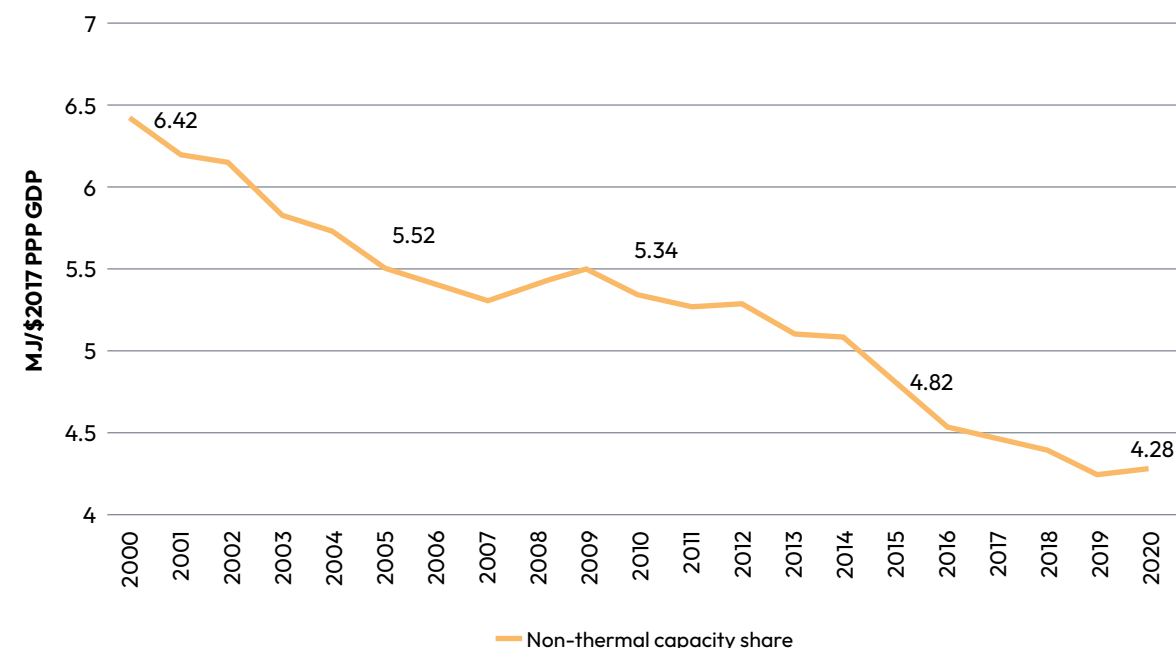
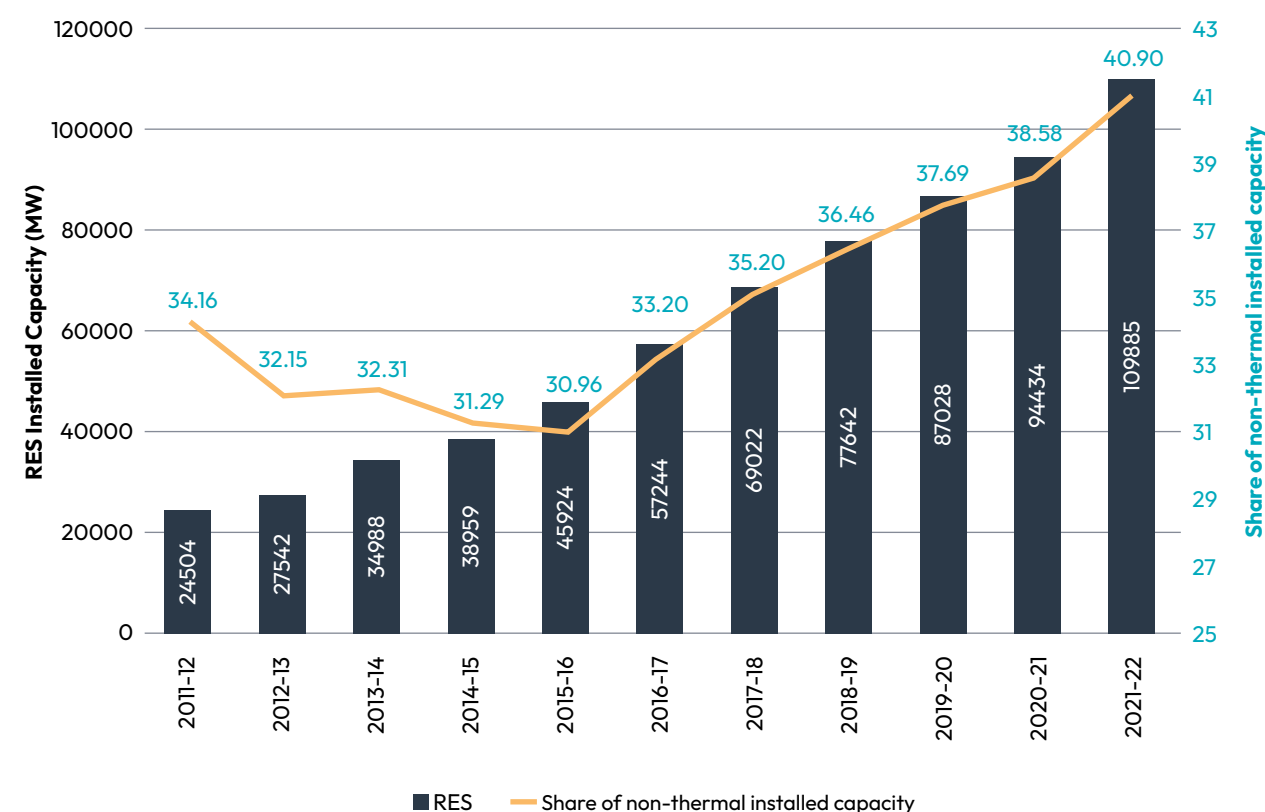


Figure 2: Renewable energy installed capacity (in MW) and share of non-thermal installed capacity in India. Source: Central Electricity Authority General Review 2023. Note: RES includes solar, small hydro projects, wind, biomass, biomass gasifier, and urban and industrial waste, while non-thermal includes RES, hydro and nuclear.



Box 1. Growth of solar power in India

With its rapid pace of growth, energy demand in India has progressively increased from 830,594 GWh in 2009-10 to 15,11,847 GWh in 2022-23.^[1] India has also managed to meet most of this excess demand itself and bring down its energy deficit from 83,950 GWh in 2009-10 to 7,583 GWh in 2022-23, reducing its reliance on import of fossil fuels, as well as emissions.

More significantly, clean or renewable energy forms an increasingly important component of the new capacity that India is adding to meet its energy needs. Generation of electricity from renewable sources (solar, wind, hydro and bio power) has increased from 193.5 TWh during 2013-14 to 306.3 TWh during 2020-21 – a compound annual growth rate of 6.8%. The share of generation from renewable sources (including hydro) in total generation increased to 22.2% during 2020-21.^[2]

Solar energy capacity in particular has seen phenomenal growth, from 2.6 GW in 2013-14 to 54 GW in 2021-22.^[3] The primary catalyst behind the increasing adoption of solar power is the diminishing cost factor. Solar energy costs have progressively dropped from INR 6.17 per kWh in 2014 to a mere INR 2.44 per kWh in 2018. Remarkably, solar and wind energy initiatives consistently secure contracts at more competitive rates than conventional thermal power projects.

These cost reductions have been achievable due to forward-thinking policy measures and spillovers from global cost reductions. In 2010, the Jawaharlal Nehru National Solar Mission (JNNSM) was launched, setting a target of 20 GW of solar capacity by 2022. This marked a significant milestone. In 2015, the government increased this target to 100 GW, underlining its commitment to clean energy. Through a combination of incentives, subsidies and competitive bidding processes, India managed to attract significant private investment into the solar sector.

Renewable Purchase Obligations (RPOs) introduced in the JNNSM have played a pivotal role in propelling the growth of renewable energy in India by de-risking the market. These mandates require certain entities – particularly power utilities and large consumers of electricity – to procure a specified percentage of their total power consumption from renewable sources. Additionally, the introduction of the Solar Parks scheme in 2014 facilitated the development of large-scale solar projects, making it easier for investors to navigate the complexities of land acquisition and infrastructure development.

A game-changer was the introduction of competitive bidding through reverse actions in solar project allocation, which drove down solar tariffs and boosted investor confidence. Subsequently, the Goods and Services Tax (GST) was rationalised for solar equipment, further reducing project costs. Furthermore, initiatives like 'Make in India' and 'Skill India' promoted domestic manufacturing and a skilled workforce, fostering self-sufficiency. The country continued its trajectory by launching the Production-Linked Incentive (PLI) scheme for solar equipment manufacturing in 2021, further strengthening its solar industry, by the end of 2023, had over 73GW of solar capacity, well ahead of its original target.

While significant progress has been made, challenges persist in furthering India to meet its full solar potential. The intermittency of solar energy is a significant hurdle, as in many other parts of the world. Integrating it into the grid requires careful planning and infrastructure development; sudden drops in solar generation due to cloud cover or storms can strain the grid, necessitating backup power sources to maintain stability. To mitigate this, storage solutions like batteries are needed. However, the cost of such large-scale energy storage systems remains a challenge.

India is a densely populated country with competing land uses for agriculture, industry and urbanisation. Finding suitable large tracts of land for solar power projects can be challenging, especially in states with high population densities. This scarcity of land can limit the development of utility-scale solar projects. Acquiring land for solar projects involves complex legal and administrative procedures. In a primarily agrarian economy like India, converting agricultural land for solar projects can lead to concerns about food security and livelihoods. Though the country has moved fast in this direction with policies, schemes and programmes such as the Grid Connected Solar Rooftop Programme (2017), Canal Bank & Canal Top Scheme (2014-15), and the Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyaan (PM-KUSUM) Scheme (2019). The success of such policies depends on a complex interplay of socio-technical and economic factors.

[1] Power Sector at a Glance ALL INDIA – Government of India – Ministry of Power (powermin.gov.in)

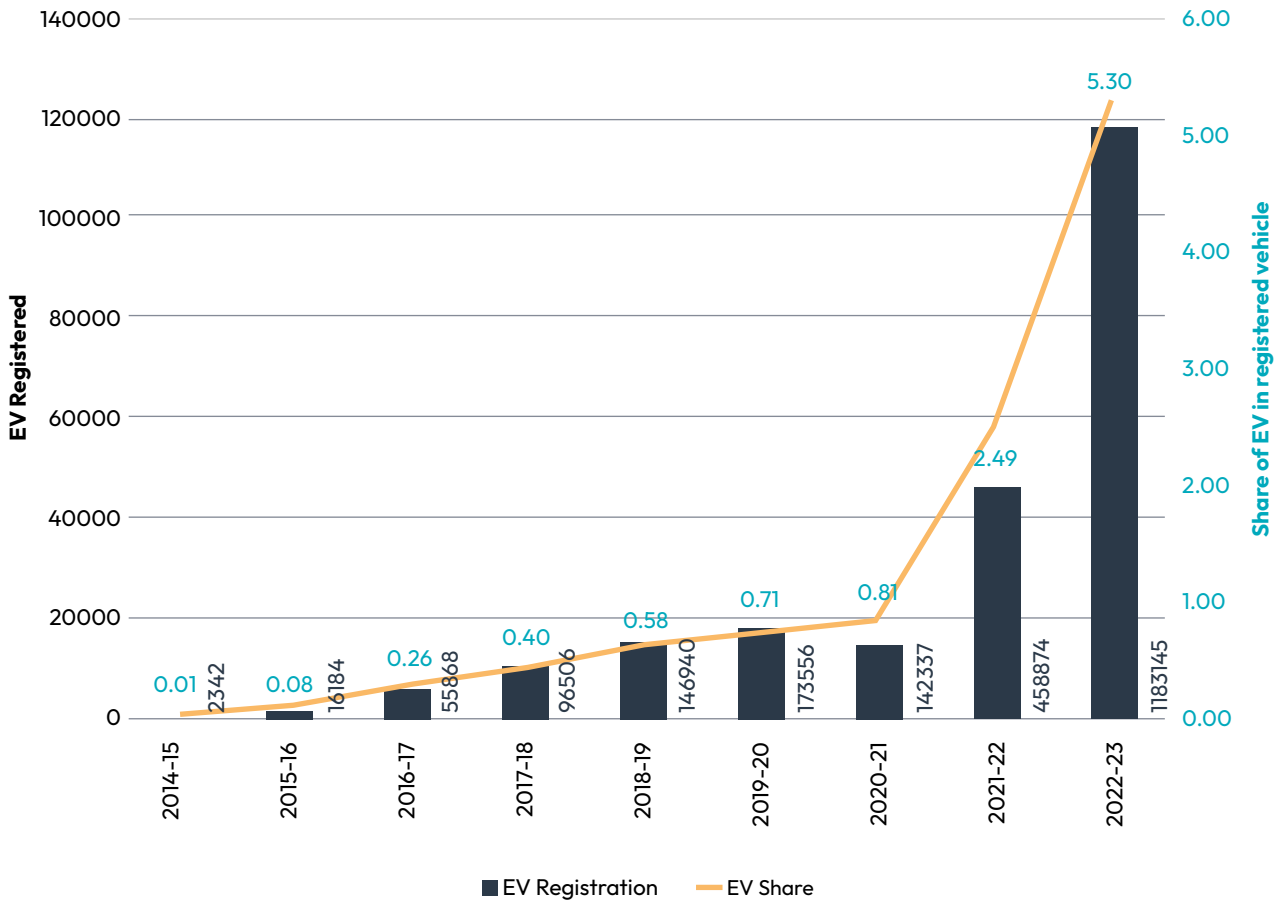
[2] MOP_Annual_Report_Eng_2021-22.pdf (powermin.gov.in)

[3] General Review Report – Central Electricity Authority (cea.nic.in)

India has further demonstrated its commitment to promoting energy efficiency in various sectors through the establishment of the Bureau of Energy Efficiency (BEE) in 2002. Among the effective energy efficiency schemes it promotes are the Energy Conservation Building Code, the Perform Achieve Trade (PAT) scheme for energy trading among energy-intensive industries, and the energy star rating and labelling system for electrical appliances.

Similarly, the electrification of India's vehicle fleet only began a decade ago but has already accelerated significantly. The Faster Adoption and Manufacturing of Electric Vehicles (FAME) subsidy scheme, introduced in March 2015, has led to electric vehicle (EV) penetration reaching 5.3% of total vehicles registered in India in 2022-23, compared to 0.01% in 2014-15 (Figure 3).

Figure 3: EV registration in India and its share in total registered vehicles (as per VAHAN dashboard).



India's ambition for net zero by 2070 has prompted both government and industry to launch a series of low-carbon initiatives such as the green hydrogen and green ammonia strategy (National Green Hydrogen mission),⁸ announced by the Ministry of New and Renewable Energy (MNRE) in 2022, and production-linked incentive (PLI) schemes that provide subsidies to promote the domestic manufacturing of green technology such as high-efficiency solar PV modules and advanced cell chemistry batteries.⁹

At COP26 in 2021, the Indian prime minister announced the 'Lifestyle for Environment' initiatives, which promote behaviour change towards sustainable and climate-resilient lifestyles such as use of sustainable transport and energy efficient goods.¹⁰ Along with the government, other stakeholders such as industry are voluntarily piloting decarbonisation technologies including Carbon Capture Utilisation and Storage (CCUS) and Carbon Capture and Storage (CCS).¹¹

⁸ <https://mnre.gov.in/national-green-hydrogen-mission/>

⁹ Indian PLI Schemes: Promoting Growth and Innovation (investindia.gov.in)

¹⁰ Life - NITI Aayog

¹¹ Carbon Clean provides India's first blast furnace carbon capture plant



1.2 Key challenges in India's energy transition

Achieving net zero by 2070 in India requires careful short and medium-term planning and consideration of the multifaceted challenges associated with the transition. Access to affordable clean energy, as well as ensuring energy security, are critical aspects. Justice and equity, including a consideration of trade-offs and co-benefits, also plays a pivotal role in shaping the transition's success, both directly and indirectly.

India's energy landscape is diverse, marked by variations in energy demand and supply across both regions and sectors. Moreover, the complex interlinkages between sectors and the presence of stakeholders with conflicting interests contribute to the intricacies of the transition process. Evaluating the transition's outcome from a multi-dimensional perspective is therefore imperative, transcending the confines of a simple economic cost-benefit analysis (CBA). The impacts of the energy transition extend well beyond the energy sector, intertwining with social, behavioural, political and non-energy sectoral factors. Therefore, the focus of analysis should not solely be on post-transition outcomes but also on determining pathways, the scale of the transition desired, and strategies to ensure its sustainability and inclusivity.

To gain a comprehensive understanding of the transition process, researchers and policymakers need to consider a broad spectrum of issues, including trade

and industrial competition, behavioural changes, the circular economy, job implications, stranded assets and financial aspects. This multi-dimensional analysis leads to the identification of a more comprehensive set of policies compared to those recommended by CBA alone. The following section gives brief details on each of these issues.

Equitable energy access and energy taxes

Achieving India's Sustainable Development Goals (SDGs) requires providing affordable clean energy to all its citizens. Despite significant strides in village electrification, rural areas grapple with unreliable power supply. Challenges persist in ensuring access to clean cooking fuels, hindered by factors like high LPG costs and inadequate supply chains in remote regions.

Fossil fuels play a critical role in meeting India's energy needs. Furthermore, taxes collected at different stages of fossil fuel production serve as a crucial source of government revenue, required to meet developmental needs.¹² However, heavy reliance on fossil fuels, also results in considerable environmental and health impacts. Therefore, ensuring long-term sustainability, while providing equitable and affordable access to energy, and sustaining public expenditure on development needs is needed.



Ensuring a fair transition to a greener economy

The transition away from fossil fuels in India is vital for decarbonisation and the impacts extend beyond the labour market in the fossil fuel sector. While the renewable energy sector offers opportunities, it requires distinct skills, posing challenges for labour markets. The geographical concentration of renewable energy potential in specific states in the western region exacerbates these challenges, as most coal production is concentrated in the eastern parts of the country,¹³ meaning the benefits of renewable jobs do not directly offset the losses from divestment.

The transition also has broader consequences, affecting consumers, employees, communities, regions and sectors. India's heavy reliance on fossil fuels, constituting 80% of its energy portfolio,¹⁴ exposes consumers and communities to transition vulnerabilities in sectors like coal, mining, power, manufacturing and micro, small and medium enterprises (MSMEs). The economic and social impacts on coal-dependent states, state revenue, the Indian railway and the workforce require comprehensive measures for retraining and reskilling. To ensure an inclusive transition, government initiatives like the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA)¹⁵ and Pradhan Mantri Kaushal Vikas Yojana (PMKVY)¹⁶ play crucial roles. Formalising engagement for informal workers, considering environmental and health standards, is essential.¹⁷ The shift toward a greener economy requires a balanced and equitable approach, addressing impacts on workers, communities, regions and the overall economy.

The challenge of stranded assets (whereby assets lose value prematurely) further complicates matters. A solution which meets the need for both decarbonisation and economic stability, by ensuring the impacts of asset value loss are mitigated against, is of prime importance in India and across the world.

Behavioural change and the circular economy

Behavioural change and the adoption of circular economy principles are integral to India's energy transition, as they lead to reduced energy demand

and positive outcomes like lower emissions and equitable energy-related benefits. Government initiatives such as the Perform, Achieve and Trade (PAT)¹⁸ programme and the Agricultural Demand Side Management programme (AgDSM)¹⁹ led by the Bureau of Energy Efficiency (BEE), focus on enhancing energy efficiency.

The promotion of energy-efficient appliances is a key area, with the challenge of initial high costs limiting widespread adoption. Efficient usage of appliances, especially air conditioners (ACs), could result in substantial savings. For instance, energy-efficient electrical appliances used in homes and businesses can save around 20,000 MW of power per year, saving INR 1.2tn (approximately US\$14bn-15bn) in capital investment on new power plants as well as transmission and distribution infrastructure (Economic Times, 2012). ACs are major energy consumers, especially for domestic users. The potential saving from energy-efficient AC units by households (five-starred appliance vis-à-vis less starred or no star appliance) can reach from 770 kWh to 890 kWh per annum respectively, which amounts to the range of INR 5,575 to INR 6,444 per annum.²⁰

India's Mission Lifestyle for Environment (LiFE)²¹ promotes a circular economy and individual behaviour changes to tackle climate change. Efficient use of AC, smart use of white goods, and sustainable transportation are among the behavioural changes encouraged. If adopted at a mass scale, LiFE initiatives have the potential to significantly reduce global CO2 emissions and save consumers billions globally. Another behavioural change is recycling and reusing discarded products, particularly critical minerals in energy-efficient appliances. India revised its e-waste and battery waste management rules in 2022, emphasising organised collection, integrated recycling infrastructure and setting targets for producers under Extended Producer Responsibility (EPR). This circular economy ecosystem has the potential to address critical mineral supply issues while promoting sustainability in production and consumption practices.

¹² Working paper on "Energy: Taxes and Transition in India" (prayaspune.org)

¹³ East and west: The parallel worlds of India's coal and renewable sectors (mongabay.com)

¹⁴ India Energy Outlook 2021 – Analysis – IEA

¹⁵ https://nrega.nic.in/MGNREGA_new/Nrega_home.aspx

¹⁶ <https://www.msde.gov.in/en/schemes-initiatives/schemes-initiatives-through-nsdc/pradhan-mantri-kaushal-vikas-yojana-pmkvy>

¹⁷ While MGNREGA aims to create employment with the notion of 'right to work', PMKVY has the objective to promote skill development through free training to interested youths.

¹⁸ <https://beeindia.gov.in/en/programmes/perform-achieve-and-trade-pat>

¹⁹ <https://beeindia.gov.in/en/programmesdemand-side-management/agricultural-demand-side-management-programmeagdsm>

²⁰ <https://www.teriin.org/event/behavioural-dimensions-indian-power-sector>

²¹ <https://www.mygov.in/life/#:~:text=In%20this%20context%2C%20the%20concept,towards%20E2%80%9Cmindful%20and%20deliberate%20utilisation%2C>

Financing the transition

Developing nations may need around 4.5% of their GDP to be allocated to green finance, and India's decarbonisation efforts will similarly require substantial investments. The country faces a significant financial challenge, requiring an estimated average of US\$160bn annually until 2030 and a colossal US\$10.1tn in cumulative investment to achieve its 2070 net zero target.²² Similarly, to achieve its renewable energy targets, about US\$500bn will be required over the next decade, primarily directed towards wind and solar infrastructure.²³ Green hydrogen production is also vital for industrial decarbonisation, but it is capital-intensive, requiring significant upfront investments. India's green hydrogen policy aims to domestically produce at least 5 million metric tons (MMt) annually by 2030, necessitating additional renewable energy capacity and an estimated cumulative investment of US\$1.5tn. This initiative is expected to generate employment for 0.6 million people, reduce annual greenhouse gas emissions by 50 MMt and cut fossil fuel imports by US\$1tn by 2030, while positioning India as a global hub for hydrogen and ammonia exports.²⁴ A recent EEIST case study found that green hydrogen in India can lead to huge benefits in terms of improved security of power supply and system resilience, as well as improved affordability.²⁵

To meet the investment needs for a transition towards a low-carbon energy and green hydrogen production economy, international climate finance is vital due to scant domestic resources, risk-averse domestic investors and the overwhelming reliance on commercial banks for debt financing. While private sector investments have dominated climate finance, specialised green financing institutions are crucial for bridging funding gaps for low-carbon developments in India. Various global green financing mechanisms, such as green bonds, carbon taxes and carbon markets, are available in India but still remain in a nascent stage.

In conclusion, India's journey towards a sustainable and decarbonised future is fraught with challenges, yet it is marked so far by significant progress and strategic initiatives. Aiming for net zero by 2070 demands meticulous short and medium-term planning, acknowledging the diverse energy landscape and intricate interlinkages between sectors. Justice, equity and the consideration of multi-dimensional factors are instrumental in achieving this ambitious climate goal.



²² https://asiasociety.org/sites/default/files/2022-09/ASPI_Getting%20India%20to%20Net%20Zero_Report.pdf

²³ <https://ieefa.org/articles/ieefa-global-capital-mobilising-indias-500bn-renewable-energy-infrastructure-opportunity#:~:text=%E2%80%9CWe%20estimate%20that%20striving%20for,%24150%20billion%20on%20expanding%20and>

²⁴ <https://pib.gov.in/PressReleasePage.aspx?PRID=1888547>

²⁵ <https://eeist.co.uk/wp-content/uploads/2023/11/081-EEIST-India-Policy-Brief-AW.pdf>

Section 2: Risk-Opportunity Analysis – what it means for India

2.1 Energy modelling in India to date

India is now at a unique intersection, facing the dual challenge of meeting its growing energy demand while also transitioning towards sustainable energy sources. The application of energy modelling in India is, therefore, essential to inform decision making and strategic planning to achieve a balanced, sustainable and secure energy future. This section compares the similarities and differences between modelling approaches and discusses the importance of choosing an analytical framework that effectively evaluates the energy transition policies in question.

Energy models serve as key tools in assessing the potential impacts of energy transition policies. In India, examples of such models with economy-wide coverage presently include MARKAL,²⁶ EPS,²⁷ SAFARI,²⁸ and there are also several sectoral models, such as for the power and transport sectors. The use of energy models in India began in the late 1970s and early 1980s to address the country's growing energy demand and to ensure energy security. They were seen as valuable tools to assess various scenarios and/or formulate strategies to optimise energy production, consumption and distribution with available resources. However, until 2004, they focused on individual sectors and lacked a comprehensive, integrated framework.

The Integrated Energy Policy Committee (IEPC), formed in 2004, aimed to provide a roadmap for India's energy security, considering various energy sources, technologies and policy measures. The committee recognised the interlinkages between energy, economy, environment and social development, so the methodology emphasised cross-sectoral integration. As part of its efforts, the IEPC used energy models to project energy demand, assess resource availability and explore different energy mix options to meet the country's long-term energy needs. This is the earliest example of evaluating risks and opportunities associated with different energy choices. This included evaluating geopolitical risks related to energy imports, technological risks of new energy sources, and the economic opportunities tied to domestic resource utilisation and technological advancements. The recommendations from this framework helped shape India's energy policies and strategies over subsequent years.



²⁶ Market and Allocation (MARKAL) is used by The Energy and Resources Institute (TERI)

²⁷ Energy Policy Simulator (EPS) is used by the World Resources Institute (WRI)

²⁸ Sustainable Alternative Futures for India (SAFARI) model, developed and used by the Center for Study of Science, Technology and Policy (CSTEP)

2.2 Conventional and new approaches to policy appraisal and modelling

Energy modelling is crucial for guiding policy decisions, setting targets for renewable energy deployment, informing energy infrastructure investments and achieving India's commitments under international agreements. The turning point, marked by the 2015 Paris Agreement and the IPCC's Special Report on Global Warming of 1.5C, has elevated the significance of energy models in addressing the need for net-zero emissions by around 2050. The urgency stems from the realisation that delivering the goals of the Paris Agreement necessitates a transformational change, and energy models should be adapted to this more stringent context.

Traditional models are rooted in neoclassical assumptions, emphasising single equilibrium, marginality, and homogenous agents and focus on finding the most efficient solutions based on a set of predefined parameters. However, the complexity of the green transition in India requires a wider range of energy models, that can go beyond existing optimising frameworks to address unique challenges and uncertainties that the country faces in its energy sector.

As a novel and complementary approach, Risk-Opportunity Analysis (ROA) considers the inherent uncertainties, vulnerabilities and potential benefits associated with complex energy systems. It draws upon complexity theory and systems thinking, incorporating diverse preferences of economic agents, feedback loops and tipping points. Thus, applying ROA principles to energy modelling in India can provide a more holistic and adaptable approach to energy planning. This is particularly important in a dynamic and rapidly changing energy landscape, where uncertainties are inherent and decisions have long-term implications. Some of the factors that make ROA relevant for India are discussed below.

1. Complexity and uncertainty: India's energy landscape is complex, with a mix of fossil fuel-based and renewable energy sources and rapidly rising energy demand in a context of wide differences between different regions and consumer groups, and technological uncertainties. Optimisation models may not adequately capture the complexities and uncertainties of the Indian energy sector, leading to suboptimal solutions. An ROA framework allows for a more comprehensive assessment of various risks and potential benefits under different scenarios.

2. Vulnerabilities and resilience: India is exposed to a range of energy-related vulnerabilities, including power supply disruptions, price fluctuations and environmental threats. A risk-based approach helps identify vulnerabilities and assess the resilience of the energy system to external shocks. By considering potential risks, decision makers can develop strategies to enhance the system's resilience and minimise adverse impacts.

3. Renewable energy integration: India has ambitious targets for renewable energy deployment, but its variable nature introduces uncertainties into the energy system. ROA can assess the challenges and opportunities of integrating renewable energy sources. These may include addressing grid stability and back-up capacity requirements, and exploring the role of energy storage solutions and production of green hydrogen at times of electricity oversupply.

4. Policy and regulatory uncertainties: The energy sector is influenced by evolving policies, regulations and international commitments. A risk-based approach helps model the impacts of different policy scenarios and regulatory changes on the energy system. This is particularly important in India, where policy shifts can have profound implications for energy planning and investment decisions.

5. Climate change and sustainability: Climate change and environmental considerations are critical factors in energy decision making. An ROA framework can guide policymakers in developing resilience of the energy sector to the impacts of climate change, and evaluate the opportunities associated with low-carbon and sustainable energy pathways.

6. Socioeconomic factors: Energy decisions have socioeconomic implications, and an ROA framework can assess the potential social and economic outcomes of different energy strategies. This includes analysing the distributional impacts of energy policies on various segments of the population.

7. Technology and innovation: Emerging technologies and innovation introduce uncertainties on the way to transformational change of the energy system. Rather than relying on measuring existing assumptions about costs and benefits, ROA can provide a more holistic approach to policy appraisal by accounting for dynamic features such as technology learning, feedback loops and tipping points and associated non-monetary benefits of the energy transition.



Section 3: Methodological framework

This report compares selected outcome indicators, mainly with respect to power sector decarbonisation from three energy transition models in India that differ in their structure and assumptions. These can broadly be categorised into the following:

1. Traditional neoclassical assumptions of single equilibrium, marginality and homogenous agents
2. New approaches, informed by complexity theory and systems thinking and incorporating one or more elements of the ROA approach, such as, internalising diverse preferences, feedback loops and tipping points.²⁹

The comparative analysis aims to demonstrate how two approaches represented by different models can answer the policy questions and explore their complementarity.

²⁹ More information on the differences between existing and new approaches to be found in the EEIST report. The New Economics of Innovation and Transition: Evaluating Opportunities and Risks > EEIST.

3.1 Policy questions

While exploring net zero pathways for India, energy models often attempt to identify the policy measures required to decarbonise the power sector for a net zero by 2070 scenario. Given its significance, deep decarbonisation of the power sector is required well before, and in this study, we assume by 2050. We focused on the following policy questions for India's energy transition through the lens of the two different but complementary approaches:

1. What will the impact of deep decarbonisation be on electricity demand?
2. What would be the most appropriate energy mix for India (in 2030 and 2050) for effective deep decarbonisation of the power sector, and which technology should be prioritised?
3. What is the impact of decarbonisation on the labour market and just transition?



3.2. Overview of the models

This study uses three models to present a comparative assessment of outcomes with respect to the policy questions outlined above: MARKAL, E3ME-FTT and EPS. While MARKAL is an example of a well-established model that follows the traditional approach based on cost-optimisation and intertemporal equilibrium principles,³⁰ the

E3ME-FTT and EPS are examples of approaches which assume that the economy would evolve irreversibly (non-equilibrium), in non-optimal circumstances.

Table 1 summarises the basic features of each model. For details on assumptions of each of the three models, refer to Annex 1.

Table 1: A few basic features in MARKAL, EPS and the E3ME-FTT framework are given below:

	MARKAL	EPS	E3ME-FTT
Sector	Purely an energy sector model	Economy-wide model with detailed representation of the power, industry, transport and buildings.	A model for entire economies, comprising various sectors
Method	Linear programming model	A recursive-dynamic model based on the systems dynamics approach	Econometric and evolutionary model
Socioeconomic detail	No presence of socioeconomic factors like employment	Includes several socioeconomic outputs like employment, government accounts, air quality and water-use	Socioeconomic factors are present
Representation of GDP	GDP is exogenous	Change relative to an exogenous baseline GDP trajectory is calculated within the model	GDP is estimated within the model
Representation of supply and demand	Demand-supply interaction is the primary determinant	Supply-side responses are primary determinants of economic outcomes	Effective demand is the major determinant
Key output	The lowest-cost configuration of the energy sector	A ‘what-if’ scenario representing simulated effects of chosen policy actions on a range of different outcome indicators, without optimising for any one indicator	The most likely scenario, which is usually not the lowest cost

³⁰ With the term intertemporal partial equilibrium on energy markets, we indicate that the quantities and prices of the various fuels and other commodities in the MARKAL model are in equilibrium, i.e. their prices and quantities in each time period are such that at those prices the suppliers produce exactly the quantities demanded by the consumers. As a result, this equilibrium has the property that the total surplus is maximised over the whole horizon, and that investments made at any given period are optimal over the horizon as a whole.



Section 4: Exploring risks and opportunities for India's energy transition: A comparison of models

Decarbonisation options are often contingent on availability of natural resources in a country or region. In India's case, its own unique stock of natural endowments offers a possibility to pursue various energy options, ranging from nuclear and hydro to solar, wind and biofuels, providing a unique advantage for the decarbonisation of its power sector. Consequently, a significant challenge for the country lies in identifying the most suitable low-carbon energy mix, while ensuring energy security and equity for its rapidly growing economy.

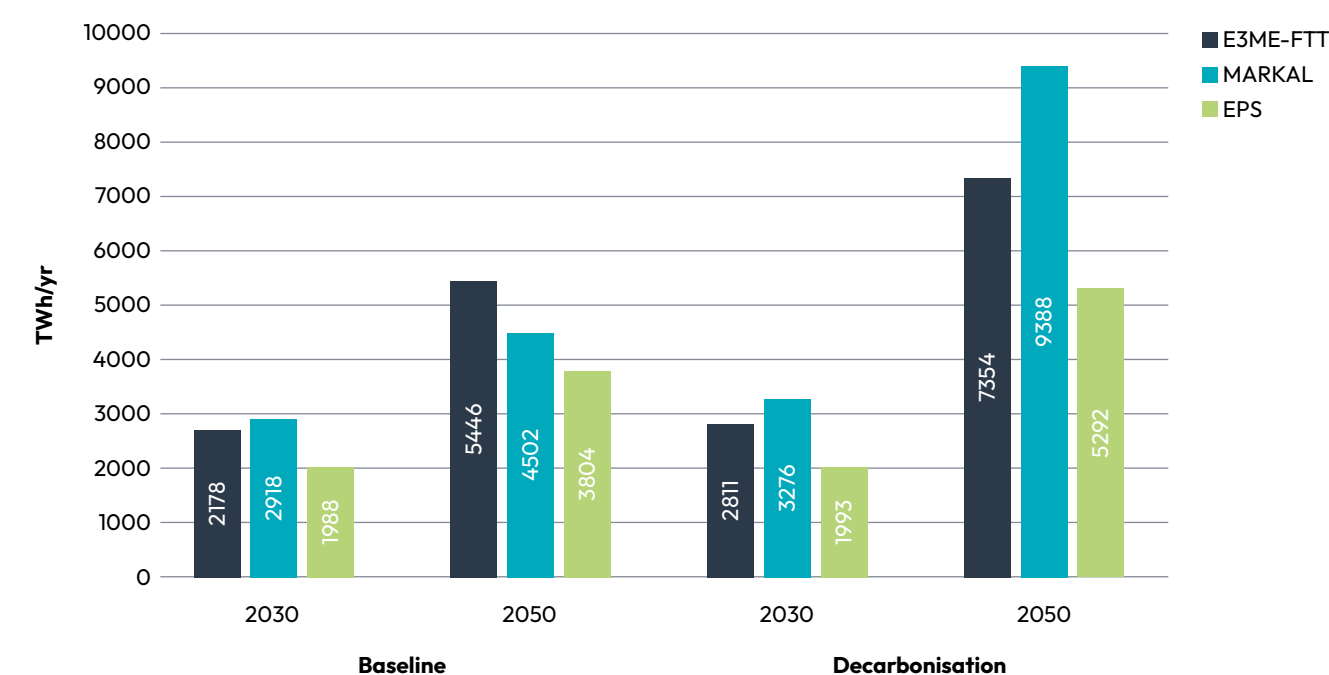
This section undertakes a comparative analysis of modelling outcomes of MARKAL, E3ME-FTT and EPS in relation to the policy questions outlined in Section 3, specifically in the context of India's net zero goals. The modelling results are discussed against two key scenarios. First, a baseline scenario, which projects past trends in data and assumes that only the existing policy measures will remain in the future. Second, a decarbonisation scenario, which assumes that new policy measures and technological solutions can be undertaken to facilitate the achievement of India's net zero target.

4.1 Electricity demand

India's electricity demand has been growing rapidly, with about a 6.8% increase in peak demand from 2022 to 2023.³¹ However, there is significant variation across seasons, regions and sectors, making forecasting challenging. The increasing penetration of appliances, implementation of energy efficiency

and demand control measures further exacerbate uncertainties in electricity demand. This is reflected in a wide variation in modelling results about future electricity demand. Figure 4 presents changes in electricity requirements in 2030 and 2050 across baseline and decarbonisation scenarios.

Figure 4: Comparison of total electricity demand across models and scenarios. Note: The EPS baseline was adjusted for the COVID-19 shock, whereas the baselines of the other two models are not adjusted for COVID-19 and assume a higher rate of economic growth, hence project a relatively higher electricity requirement.



While projected estimates differ across models, all models suggest an increase of at least 1.5 times in electricity demand between 2030 and 2050 in the baseline scenario owing to India's growing population, urbanisation and economic output. The decarbonisation scenario, which considers additional electrification in end-use sectors to decarbonise these sectors, sees a sharper increase, with electricity demand surging by at least 2.5 times across all models between 2030 and 2050.

Even though electrification of end-use sectors is necessary for decarbonisation, it is insufficient to

achieve the net zero target. The rapid and continuous increase in electricity consumption makes decarbonisation of the power sector central to India's energy transition. Complementary policies should also include energy efficiency and promote instruments such as the Energy Conservation Building Code,³² Perform Achieve Trade (PAT)³³ and star rating,³⁴ and labelling would need to be scaled up to reduce future electricity demand. Similarly, behaviour change interventions and the adoption of circular economy principles, such as in Mission LIFE,³⁵ can reduce energy demand.

³¹ Power Sector at a Glance – ALL INDIA | Government of India | Ministry of Power (powermin.gov.in)

³² <https://beeindia.gov.in/en/energy-conservation-building-code-ecbc>

³³ <https://beeindia.gov.in/en/programmes/perform-achieve-and-trade-pat>

³⁴ <https://beeindia.gov.in/en/star-label>

³⁵ <https://www.mygov.in/life/#:::text=In%20this%20context%2C%20the%20concept,towards%20%E2%80%9Cmindful%20and%20deliberate%20utilisation%2C>

4.2 Suitable electricity generation mix

Given the scale and sheer complexity of India's physical, energy and industrial infrastructure and logistics, a single optimal electricity generation mix is challenging to define, as it depends on technology choices, technical constraints and associated issues. The choice of technology relies on factors such as the cost trajectory of alternative options, availability of domestic energy-related R&D, global technological developments, technology transfer possibilities and technical challenges of integrating intermittent renewables and availability of energy storage.

Exogenous assumptions about cost trajectories can influence current and future technology choices, and different models have their own cost trajectories that significantly affect technology choices and the optimal energy mix. However, there are areas of convergence across models that can help policymakers allocate limited funds effectively and provide suitable incentives for the promotion of specific technologies (for more details, see EEIST's Ten Principles report).³⁶

Coal phasedown.³⁷ The analysis of the change in energy share between baseline and decarbonisation scenarios, presented in Table 1, reveals critical insights into the transition dynamics across different models. The focus is on coal phasedown, the evolving shares of solar, wind and biofuel, and the impact of grid energy storage considerations on the electricity mix. In all models, there is a notable phasedown in coal-based generation in the decarbonisation scenario. In this scenario (Figure 6), MARKAL and EPS indicate a very sharp phasedown between 2030 and 2050 compared to the baseline scenario (Figure 5), whereas E3ME-FTT doesn't have a large difference between the two. This divergence is due to the fact that FTT is more optimistic about the future cost reductions that can be expected in renewable energy, and therefore of its penetration, even in the baseline.

Solar energy and the learning curve effect. In the decarbonisation scenarios, solar emerges as the single largest technology in India's electricity mix by 2050, reaching more than a 40% share in total

generation in all three models (Figure 6). In the FTT model, it reaches over a 60% share, and emerges a clear technology winner. According to FTT, due to global learning-by-doing, solar is expected to become significantly lower cost than all available alternative technologies. This suggests that a preference for policies on solar scale-up can help India achieve cost-effective decarbonisation in the long run.

Role of wind energy. While the FTT model envisions solar to play a key role, with a minimal share of wind, MARKAL and EPS see a much greater role for wind in the energy transition, which reaches around a 35% share in electricity generation in the decarbonisation scenarios of both models. The reason is that grid battery energy storage emerges as a constraint in both models, given the nascency of this technology in India, while FTT assumes that solar and wind are coupled with energy storage. Due to their complementary generation profiles (solar during the day and wind largely at night), a more balanced mix of solar and wind reduces the intermittency of electricity supply and reduces the need for grid flexibility provisions such as battery storage capacity. India having a coastline of about 7,600km has good prospects of harnessing offshore wind energy in the future.

Role of transitional fuels and importance of energy storage. Another consequence of a storage-constrained future is the emergence of a role for transitional fuels such as natural gas for grid stabilisation as coal is phased down in all three models. In the MARKAL model, nuclear and biofuels are projected to play a greater role in the electricity mix than in the decarbonisation scenario. MARKAL envisions a well-balanced (between solar and wind) and diverse energy system (with significant presence of nuclear, hydro and biofuel). On the other hand, a more optimistic outlook on battery storage technology scale-up in the FTT sees solar emerge as a clear technology winner – the dominance of one technology in this case results in greater economies of scale, leading to lower costs compared to a more diversified technology mix.

Figure 5: Comparison of electricity generation mix in baseline across models.

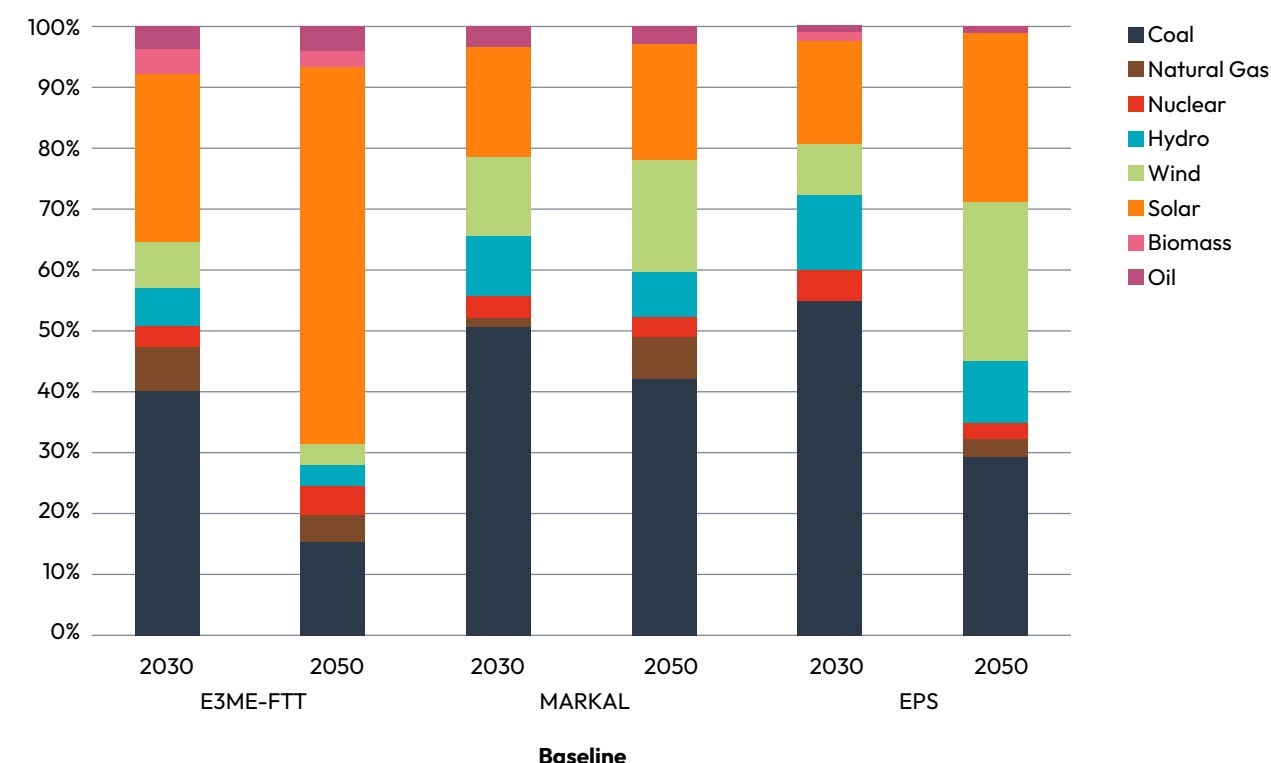
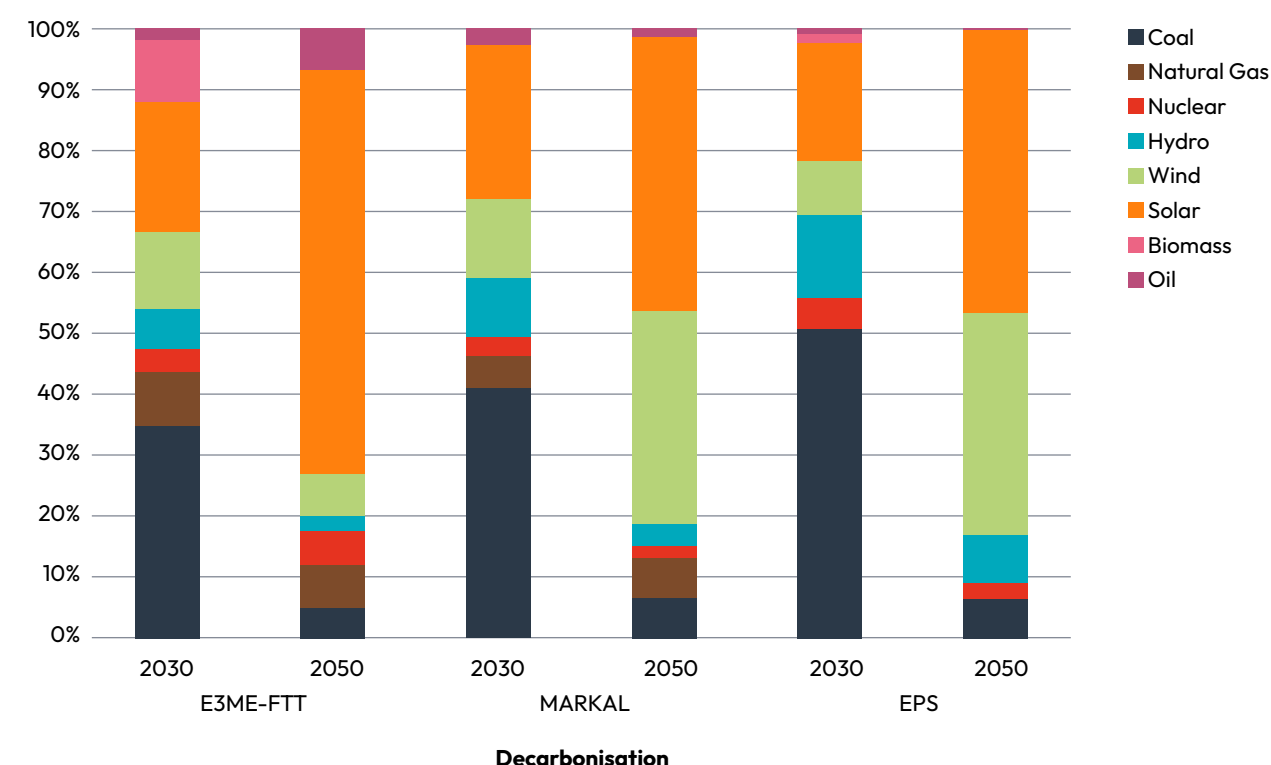


Figure 6: Comparison of electricity generation mix in the decarbonisation scenario across models.



³⁶ Anadon, L. D., Jones, A., & Peñasco, C. (2022) Ten Principles for Policymaking in the Energy Transition: Lessons from Experience. <https://climatestrategies.org/publication/ten-principles-for-policymaking-in-the-energy-transition-lessons-from-experience/>

³⁷ Indian policies have a focus on growth of non-fossil fuel share in the power generation, rather than clear indication of coal phasedown.

Box 2. Emission reduction potential and enabling policies in India

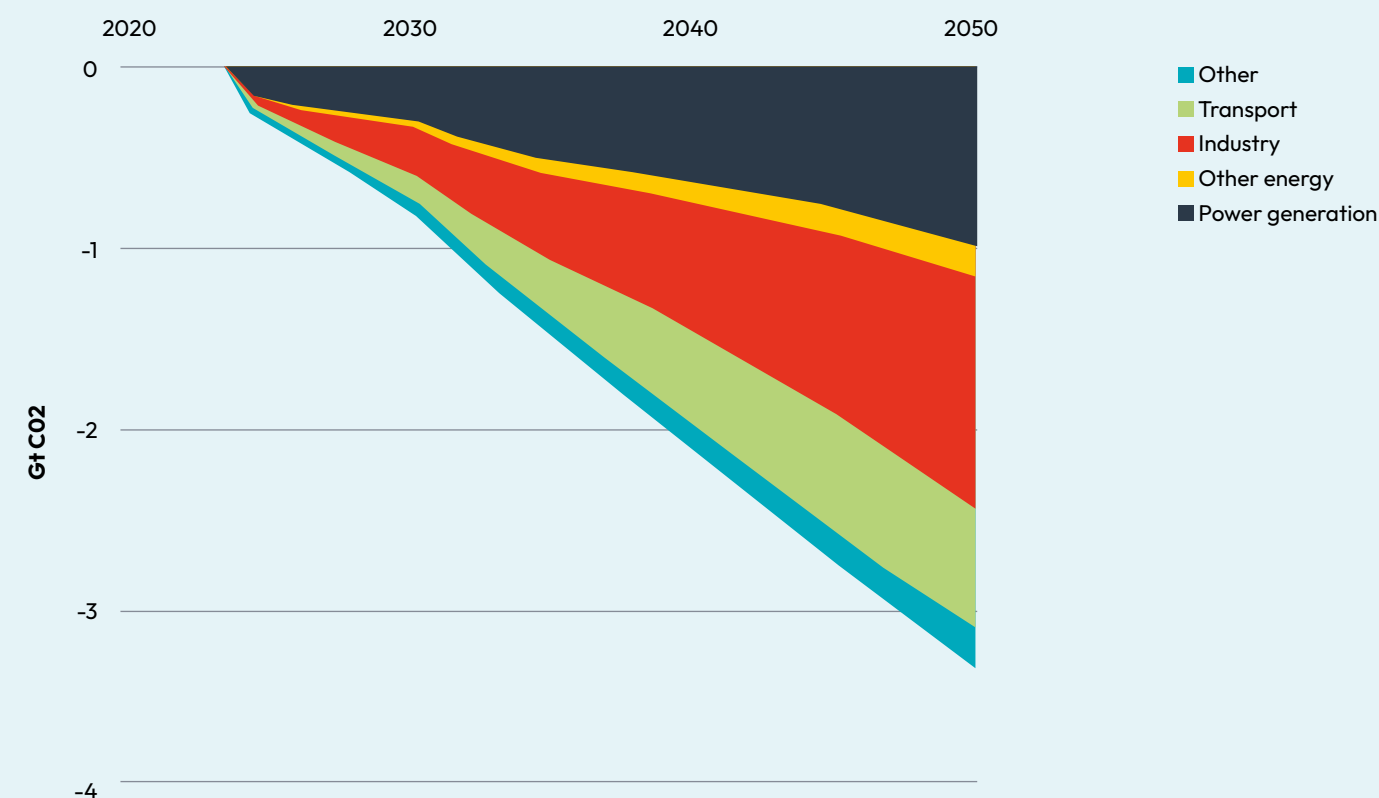
Emission trajectories across the three models

Emission trajectories also depend on the technology mix and technology choice decisions. Compared to the baseline scenario, the decarbonisation scenario shows an emission reduction potential in the range

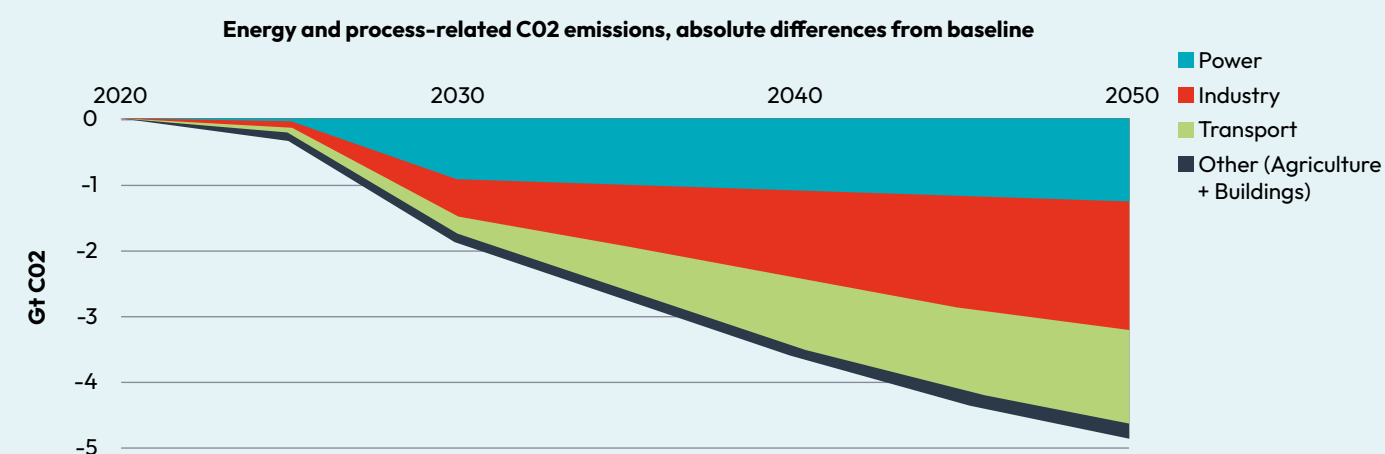
between 3.4 and 4.81 Gt CO₂ in 2050. Most of this reduction is expected to be achieved in power generation and industry.

Figure 7. Change in sectoral emissions compared to the baseline in E3ME-FTT, MARKAL and EPS

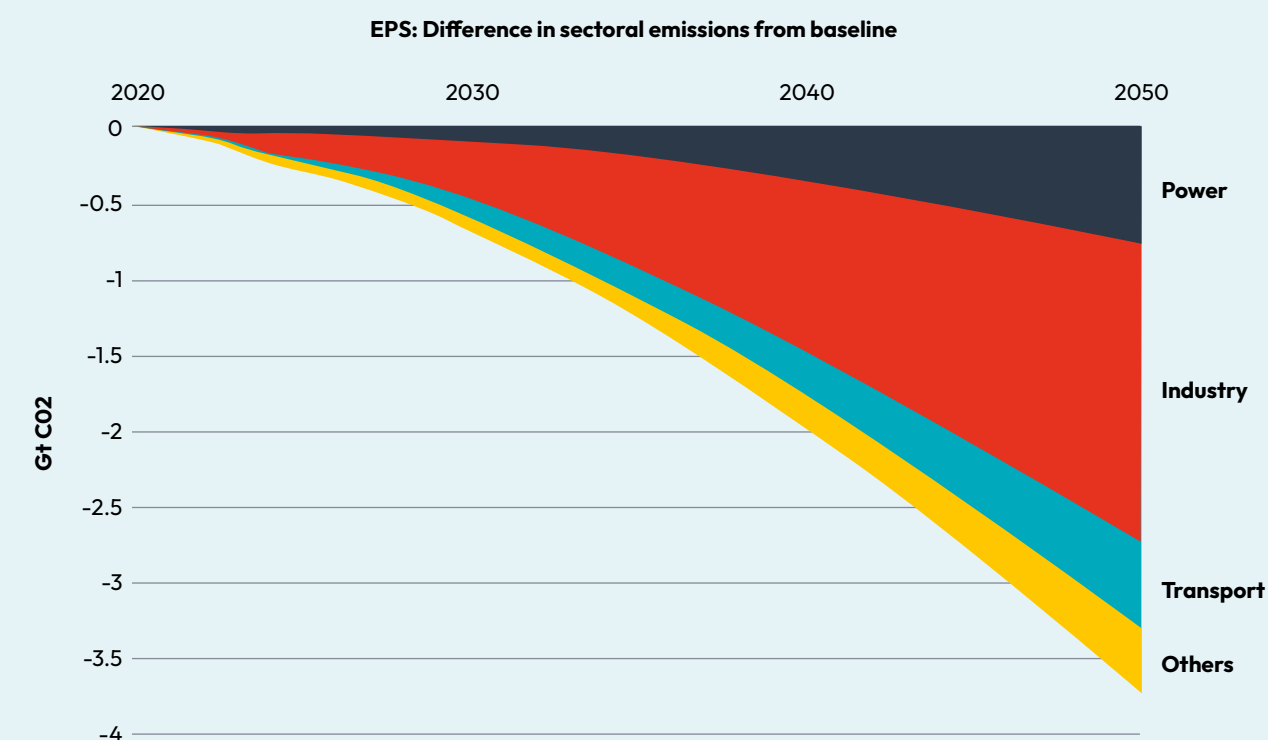
(a) E3ME-FTT



(b) MARKAL



(c) EPS



Emission reduction policies

A recent study by the World Resources Institute (WRI) India using the Energy Policy Simulator model also looked into the measures responsible for emissions reduction and identified mandates for energy efficiency, electrification and green hydrogen uptake in industry, together with a phased carbon tax that reaches US\$50/tCO₂ (in 2018 prices) in 2050, to be the key enabling policies. In the power sector, mandates for carbon-free electricity generation and phased retirement of coal power are key

policies – the reduction in the cost of renewables due to technology diffusion, initially a result of these mandates, in turn, drives further capacity addition of renewables, which reduces costs, exceeding the policy-mandated requirements over time. In the transport sector, the primary policy lever is electric vehicle sales mandates. For the freight transport segment, where electrification potential is limited, mode switching (from road to rail) and fuel efficiency standards also play a key role.³⁸

³⁸ Pathways for Decarbonizing India's Energy Future: Scenario Analysis Using the India Energy Policy Simulator | World Resources Institute (wri.org)

4.3 Impact on the economy and employment

Energy transition in India will also have an impact on the labour market and, more broadly, economic growth and structural change in the economy, as covered in the EEIST case studies.³⁹ Unlike MARKAL, a conventional cost-optimisation model, new models such as EPS and E3ME-FTT offer the possibility to address those issues.

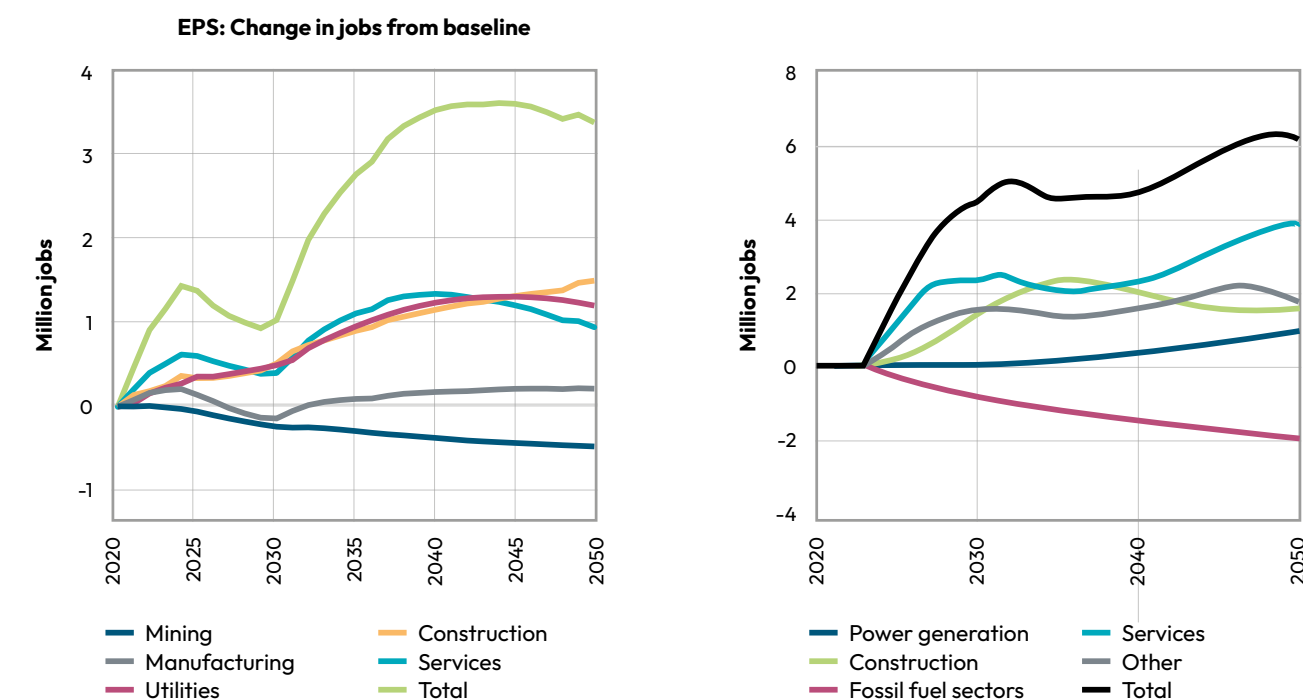
Analysis from EPS⁴⁰ and E3ME-FTT indicates that decarbonising the economy can create net benefits. The decarbonisation scenario in both models sees a slight increase in GDP relative to the baseline as well as 3m-8m more jobs by 2050 (Figure 10). Both models identify electricity utilities, construction and services as the three major sectors that will create new jobs. However, fossil fuel and mining sectors see a relative decline in employment, implying that mining and coal-dependent states will face the need to diversify their economies and retrain workers to enable them to transition to new jobs in emerging sectors.

The E3ME-FTT modelling case study⁴¹ found a positive impact from India's decarbonisation on employment. However, employment opportunities are not evenly distributed across sectors and the transition away from fossil fuels. In the case of coal, huge employment losses will affect related sectors, with more than 2m jobs at risk as a result of the

phaseout of fossil fuels. The results suggest that the energy transition in India will lead to a net benefit of 8.4m jobs generated by 2070, with new jobs to be mostly observed in renewable power generation, followed by the construction sector. Employment generation in these sectors will have a cascading effect on the economy through income generation and related demand creation.

The EPS modelling case study⁴² projects that a net zero scenario delivers a GDP that is 2.3% higher and generates 3.4m more jobs⁴³ by 2050.⁴⁴ The drivers for economic growth and employment are supply-side effects – while the overall demand for energy and materials reduces as a result of efficiency improvements in the net zero scenario, investments to decarbonise supply (along with associated indirect and induced effects) drive the growth in the economy. The additional annual investment compared to the baseline amounts to around US\$28bn (2018) (~0.5% of projected GDP) in 2030, and rises constantly thereafter as renewable energy infrastructure, EVs, battery storage and green hydrogen production is ramped up, to reach US\$247bn (~1.5% of projected GDP) in 2050 in the decarbonisation scenario, pointing to the fact that availability of green finance will be a key factor in enabling India's energy transition.

Figure 8: Impact of decarbonisation on jobs



Note: Change in direct and indirect jobs excluding the agriculture sector

Box 3. Co-benefits of decarbonisation

Cleaner air

A recent study by TERI shows that India's decarbonisation can effectively address air pollution, with the estimated emissions of different pollutants decreasing after 2030 under low-carbon scenarios.⁴⁵ Improvements in emission control technologies in power plants and the introduction of strict emission control norms conducted under decarbonisation leads to significant reduction in PM10 emissions, while increased penetration of clean cooking fuel and energy-efficient cooking systems leads to a reduction in CO emissions. However, the study found that, while the current decarbonisation measures in India can reduce SO₂ emissions (due to reduction of emissions from the power sector), the control of NO_x is not satisfactory because of a lack of stringent policy.

In terms of environmental co-benefits, the EPS net-zero scenario sees particulate matter (PM_{2.5}) emissions cut to almost half by 2050, potentially helping avoid 5.8m premature deaths due to air pollution over the period 2022-2050, compared to the baseline.

Enhanced water availability

Another study by TERI identified another co-benefit of India's energy transition: improved water availability.⁴⁶ It found that the move away from water-intensive thermal to renewable generation technologies could deliver a decline on water consumption of around 30% from the current level. As per EPS, transition of power sector from coal to renewable energy can result in a net saving of 12tn litres of water from the present through 2050.

⁴⁰ New economic models of energy innovation and transition: Addressing new questions and providing better answers > EEIST

⁴⁰ Macroeconomic Impacts of Long-Term Decarbonisation in India: Implications for a Just Transition | World Resources Institute (wri.org)

⁴¹ Case study: Economic Impacts of Net Zero in India by 2070 (EEIST, 2023)

⁴² Case study: Decarbonising the Indian Economy: Policies and Impacts (EEIST, 2023)

⁴³ These include direct jobs (created due to enacted climate policies) and indirect jobs (created within industries that supply to directly affected industries) excluding the agriculture sector.

⁴⁴ Macroeconomic Impacts of Long-Term Decarbonization in India: Implications for a Just Transition | World Resources Institute (wri.org)

⁴⁵ https://www.climate-solutions-explorer.eu/story/india_air_pollution_transition/

⁴⁶ https://www.climate-solutions-explorer.eu/story/india_water_transition/

4.4 Summary of comparison of model results

The three models converge in their assessment of India's electricity demand growing by at least 2.5 times between 2030 and 2050, in spite of significant improvements in energy efficiency in their respective decarbonisation scenarios. This is because of energy demand shifting from fossil fuels to electricity as end-use sectors like industry, transport and buildings electrify over time, making decarbonising India's power generation instrumental to its net zero ambition.

Decarbonising the electricity supply implies a sustained phasedown in coal-based generation, which comprises nearly a 70% share of the current electricity generation mix. The decarbonisation scenarios of all three models see the share of coal reduced to less than 50% by 2030 and less than 10% by 2050. However, the scenarios diverge in their mix of technologies to replace it – the E3ME-FTT places emphasis on solar coupled with battery storage, relying on economies of scale to drive down costs, with generation from wind not seeing any increase between 2030 and 2050. On the other hand, MARKAL and EPS are less optimistic about the fall in grid integration costs of variable renewable energy and identify a greater role for wind in India's future energy mix, given its complementary generation profile to solar to reduce intermittency of supply and thereby reduce grid integration costs (see Table 2).

Finally, the new models offer the opportunity to answer labour market and broader macroeconomic policy questions, which MARKAL is not developed for such analysis. Both E3ME-FTT and EPS indicate that investment in renewables has the potential to stimulate additional economic growth and employment relative to the baseline, counteracting the effect of a relative decline in the fossil fuel and mining sectors, as well as reduced demand for material and energy in the economy due to efficiency improvements. Both models identify electricity utilities, construction and services as the three major sectors that will create new jobs. E3ME-FTT suggests that employment generation in these sectors will have a cascading effect on the economy through income generation and related demand creation. EPS concludes that harnessing these macroeconomic opportunities will require significant additional annual investment, close to 0.5% of projected GDP in 2030 and 1.5% in 2050, pointing to the fact that availability of green finance will be a key factor in enabling India's energy transition.

Table 2: Comparison of MARKAL, FTT and EPS results for baseline and decarbonisation scenarios:

Parameter	MARKAL	FTT	EPS
Impact of enhanced efficiency – annual final energy demand reduction in the decarbonisation scenario compared to baseline	4.8 PWh/year or 24% by 2050	2.4 PWh/year or 10% by 2050	2.4 PWh/year or 10% by 2050
Annual reduction in CO2 emission in the decarbonisation scenario compared to baseline	3.5 Gt/year or 57% by 2050	3.4 Gt/year or 81% by 2070	3.8 Gt/year or 64% by 2050
Total electricity generation – baseline projection	Nearly 3,000 TWh/year by 2030; 4,500 TWh/year by 2050	Nearly 2,700 TWh/year by 2030; 5,500 TWh/year by 2050	Nearly 2,000 TWh/year by 2030; 3,800 TWh/year by 2050
Coal generation – baseline and decarbonisation scenario	Baseline: 1,500 TWh/year in 2030; 2,000 TWh/year in 2050	Baseline: 1,100 TWh/year in 2030; 800 TWh/year in 2050	Baseline: Nearly constant at 1,100 TWh/year from 2030 through 2050
	Decarbonisation: 1,300 TWh/year in 2030; 600 TWh/year in 2050	Decarbonisation: 900 TWh/year in 2030; 400 TWh/year in 2050	Decarbonisation: 1,000 TWh/year in 2030; 400 TWh/year in 2050
Generation from solar PV – baseline and decarbonisation scenario	Baseline: 500 TWh/year in 2030; 800 TWh/year in 2050	Baseline: 600 TWh/year in 2030; 3,300 TWh/year in 2050	Baseline: 300 TWh/year in 2030; 1,100 TWh/year in 2050
	Decarbonisation: 800 TWh/year in 2030; 4200 TWh/year in 2050	Decarbonisation: 600 TWh/year in 2030; 4800 TWh/year in 2050	Decarbonisation: 400 TWh/year in 2030; 2500 TWh/year in 2050
Generation from wind – baseline and decarbonisation scenario	Baseline: 400 TWh/year in 2030; 800 TWh/year in 2050	Baseline: Nearly constant at 200 TWh/year from 2030 through 2050	Baseline: 200 TWh/year in 2030; 1,000 TWh/year in 2050
	Decarbonisation: 400 TWh/year in 2030; 3,300 TWh/year in 2050	Decarbonisation: 350 TWh/year in 2030; 500 TWh/year in 2050	Decarbonisation: 200 TWh/year in 2030; 2000 TWh/year in 2050

Conclusion

India has made considerable progress towards its climate goals, now ranking fourth globally in installed capacity of both solar and wind power. Over the last decade the energy intensity of the country's GDP has declined by about 20%, while the share of non-fossil fuel installed capacity has increased from 34% to 41%. However, India is still an emerging economy, with its per capita energy consumption and income being about one-third and one-fifth of the respective global averages. As its energy demand continues to grow to fuel economic expansion and ensure energy security for its growing population, it is critical for the country to transition into a new development paradigm that decouples emissions from growth to achieve its target of becoming a net zero emissions economy by 2070.

The EEIST project has provided a platform for addressing the sheer complexity of India's energy transition through the lens of Risk-Opportunity Analysis (ROA) to provide evidence-based policymaking directed towards transformational change. This report compares the outcomes of models from a conventional model, MARKAL, based on cost-optimisation and intertemporal equilibrium, and 'new' models, EPS and E3ME-FTT, that capture the ROA principles, including the 'learning-by doing' effects of deployment on technology costs that can create tipping points in specific technology transitions.

Overall, our analysis indicates that decarbonising the Indian economy does not represent a trade-off with its economic development – the transition away from fossil fuels has the potential to cut energy prices and create net economic growth and additional employment opportunities, as well as deliver co-benefits of cleaner air and substantial water savings. India is uniquely endowed with a variety of natural resources encompassing nuclear, hydro, solar, wind and biofuel, and possesses a diverse range of options for decarbonising its energy supply. Consequently, a key policy question pertains to the choice of non-fossil sources for its future electricity mix.

The modelling outcomes conclude that a single optimal electricity generation mix is challenging to define, as it hinges on multiple factors. These include the estimated scale of future energy demand to ensure security of energy supply, estimated cost trajectories of different technologies, domestic R&D capabilities, global technology learning and technology transfer possibilities, and a multitude of technical constraints and associated challenges. These include mobilising concessional finance for upfront investment needed for capital-intensive technology transition, ensuring availability of land for scaling up land-intensive solar and wind capacity, addressing technical challenges of integration of intermittent renewables into the electricity grid, and the socioeconomic impacts of a transition away from coal.

Need for evaluating potential land constraints

The inter-model comparison shows solar emerging as the single largest technology in India's future electricity mix with a massive projected scale-up in generation. However, meeting land requirements for large-scale renewable deployment, especially solar installation, is a major challenge for Indian policymakers due to competition for scarce land given India's projected growth in food and feedstock demand, urbanisation, and biofuel and afforestation targets. Currently none of the above three models consider the marginal cost of land in estimations of the future energy mix. Doing so might change the results and is an important next step to consider through interlinkage of energy and non-energy sectors.

Need for technology prioritisation

Due to limited public finance, prioritisation of technology choice can help policymakers utilise the available resources more effectively and provide suitable incentives for promotion of that technology to build economies of scale (for more details see EEIST's Ten Principles report⁴⁷). The Indian government has previously used this to great effect to promote the use of both LED bulbs and compressed natural gas.⁴⁸ Technologies of interest include battery storage, green hydrogen or offshore wind, or specific deployment models for proven technologies – for example, rooftop solar.

Need for developing a better understanding of system costs

The model comparison also indicates that the system costs of integrating variable renewable energy is an important consideration in the choice of the future technology mix. A comprehensive evaluation of the potential and associated costs of the different options for grid flexibility, including different storage options (pumped hydro, battery, hydrogen), demand response policies and cross-border electricity trade⁴⁹ can play an important role in determining the energy mix.

Need for understanding impact on trade dynamics and energy security

Moreover, an energy transition in India will profoundly affect the country's trade dynamics and energy security. While its import sources for fossil fuels are geographically diverse,⁵⁰ the same is not true for raw materials for renewable energy and storage technologies,⁵¹ which are poised to become the cornerstone of the country's energy system.

Domestic availability remains a challenge, as does the competitiveness of local products, perpetuating import dependency on solar technology and related raw materials. The potential of raw material recycling through circular economy, and geographic diversification of imports, remain open questions for further assessment. Green hydrogen coupled with cheap renewables is considered a potential solution, particularly for hard-to-abate sectors, but the technology is in a nascent stage in India and requires significant upfront capital investment.

Need for new approaches in policy evaluation

Traditional approaches to policy appraisal work well in situations of marginal change. However, for questions relating to structural and transformational change, such as the transition from a fossil fuel-based to a low-carbon energy system, they need to be complemented with new approaches. We have presented Risk-Opportunity Analysis and dynamic non-equilibrium models as examples of approaches that can help to identify positive tipping points, providing critical insights to policymaking.⁵²

Need for domestic capacity-building and training

To ensure that new approaches to policy appraisal are used effectively, domestic capacity should be built across policy advisers and modelling practitioners on the governmental and state level. Improved access to and quality of data will also be instrumental in unlocking the full potential of the new models and ensuring an adaptable evidence-based policymaking process.

⁴⁷ Ten Principles for Policy Making in the Energy Transition > EEIST

⁴⁸ LED case study, in The New Economics of Innovation and Transition: Evaluating Opportunities and Risks > EEIST

⁴⁹ Chaudhury, S., Bose, R., Samanta, D., & Anbumozhi, V. (2023) Renewable Energy Transition in South Asia: Role of Regional Energy Trade. Renewable Energy Transition in South Asia: Role of Regional Energy Trade (eria.org)

⁵⁰ High-quality coal comes from countries like Indonesia and Australia, crude oil is predominantly imported from Iraq, the US, Nigeria and Saudi Arabia, and natural gas primarily arrives from Qatar, UAE and Saudi Arabia.

⁵¹ More than 90% are imported from China.

⁵² Barbrook-Johnson et al. (2023) New Economic Models on Energy Innovation and Transition: Addressing new questions and providing better answers. EEIST D4 Report



Appendix: Model assumptions

Assumptions of MARKAL:

MARKAL is an energy sector model designed to specifically address demand-supply interactions in the energy system. It covers energy demand from various energy-consuming sectors and integrates those end-use energy demands with available alternative supply options, including energy export/import. It is a dynamic model which optimises the energy system cost with the presence of constraints like maximum generation capacity. It measures the optimal energy mix in the economy, along with sectoral and total emissions (CO₂ equivalent) from the energy system, and uses linear programming techniques to solve the optimisation problem.

Basic assumptions of the MARKAL model:

- GDP and population, which are the primary determinant of sectoral and total energy demand, are exogenous to the model.
- Scenarios depict different decarbonisation paths where, based on the growth of demand and/or supply of energy sectors, alternative energy mixes and emissions are estimated.
- Cost of technology/prices are estimated outside the model framework and provided as inputs.
- As an energy sector model, socioeconomic implications are not estimated.

Assumptions of EPS:

The India Energy Policy Simulator (EPS) is an open-source model with economy-wide coverage based on an integrated 'input output-systems dynamics' approach. The model divides the economy into the power, industry, buildings, transport and land sectors and allows users to simulate different scenarios of climate change mitigation policies enacted within these sectors through 2050. It offers many environmental, economic and social outputs that can be compared across scenarios. The structure, approach, data sources and assumptions of the India EPS are explained in a technical note available online,⁵³ with a few key points noted below:

- Baseline energy demand is exogenous to the model and taken from respective sectoral demand trajectories in the India Energy Security Scenarios (IESS) by NITI Aayog.
- The model uses a least-cost logic to determine choice of technologies to construct supply to meet a given demand, subject to meeting any specified policy mandates.
- Prices are simulated by combining exogenous projections of technology (and fuel) costs with the effects of specified pricing policies (taxes or subsidies) in a scenario. The model also uses an endogenous learning curve to account for

the 'learning-by-doing' effects of local technology diffusion on technology costs in the case of emerging technologies, namely solar, wind, battery storage and hydrogen.

- The model simulates effects of policies at an aggregate spatial (national) and temporal (annual) scale, which precludes the assessment of distributional implications of policies across regions and population subgroups.
- Indirect and induced economic impacts in the model are calculated based on transaction relationships between industries in the economy per India's input-output (I/O) tables as of 2015, which are assumed to hold over time.

Assumptions of E3ME-FTT:

The Economy-Energy-Environment Model (E3ME) is a macro-econometric modelling approach. It integrates the interactions between economic activities, energy consumption and emissions for a given region or system. E3ME is often run in combination with the Future Technology Transformation (FTT) suite of models, an evolutionary family of models targeted to different sectors (i.e. power, transport, steel). E3ME-FTT features the dynamics of transition based on learning-by-doing and investors' choices. Its basic propositions are as follows:

- E3ME's fundamental structure is based on post-Keynesian economic theory, which postulates that effective demand is the key determinant

of economic performance. The economy may not operate at full capacity because the level of output is determined by the level of aggregate demand. Thus, the observed level of output could be less than the level of potential output. FTT models technological transformations, including those in the power sector. A key feature is the positive feedback between technology deployment and prices via learning-by-doing.

- E3ME and FTT are linked with a two-way feedback: the electricity demand calculated in E3ME is given as an input into FTT, which returns a price, fuel use and investment for replacements and new generators as parameter updates for E3ME.
- The combined E3ME-FTT model features complexity dynamics in the economy – i.e. past behaviours influence future decisions, leading to path dependency and technology lock-in (both from the econometric relationships in E3ME and experience curves in FTT).
- Rather than traditional 'rational behaviour' of economic agents, E3ME and FTT assume that agent behaviour is subject to many real-world influences and is not fully 'rational'. For example, in FTT, technological diffusion is based on decisions by a heterogeneous group of investors, who decide based on prices and historical preferences.

⁵³ A Tool for Designing Policy Packages To Achieve India's Climate Targets: Methods, Data, and Reference Scenario of the India Energy Policy Simulator | World Resources Institute (wri.org)

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Economics of Energy Innovation and System Transition

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change. By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.



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