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India's pathway to net zero by 2070: status, challenges, and way forward

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Abstract

The announcement of India's 2070 net-zero target has demonstrated the power of a credible policy signal and changed the course of India's climate debate. While the Government of India (GoI) has not specified whether this target refers to carbon-dioxide or all greenhouse gases, the announcement has been a watershed moment in India's climate policy. From questions related to whether and at what pace should India decarbonize its economy, various actors in India are now aligned towards this target. An important contribution to inform India's net-zero journey has

come through various modelling assessments undertaken by India's institutions and researchers. While a few economy-wide net-zero modelling assessments are available, a comprehensive and integrated picture woven collaboratively by India's climate experts is conspicuously missing. It is critical to complement quantitative modelling-based assessments with insightful perspectives of experts on India's climate policy. Together, modelling based quantitative assessments and insightful qualitative perspectives of climate experts would be an instrumental force that will ensure that the country achieves its net-zero target by understanding synergies and trade-offs, harnessing opportunities, and avoiding risks along the way. This collaborative article discusses various aspects of pathways towards India's net-zero goal to address the gap in literature by looking at broad and inter-related dimensions of '*national and sub-national perspectives*', '*sectoral and technological transitions*', and '*enablers*' needed for India's transition. While the larger net-zero debate relates to all greenhouse gases, we focus on carbon dioxide in our current effort. The assessment aims to inform not just India's policy makers and stakeholders, but various researchers, practitioners and governments around the world for them to be better aware of the various aspects of India's net-zero debate. It weaves the perspectives of experts from 24 institutions across the three broad dimensions to give a comprehensive view of a roadmap towards India's net-zero future.

Contents

1. Introduction

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The 26th Conference of Parties (COP26) will always stand out as a milestone in India's decarbonisation journey. At COP26, India's Prime Minister announced that India would become a net-zero country by 2070. While the Government of India (GoI) has not specified whether this target refers to carbon dioxide or all greenhouse gases, and more deliberations are needed in this regard, the announcement was significant, as this was the first time India had signed on to an absolute emissions cap. The 2070 net-zero goal includes an implicit acknowledgment that India's fast-growing emissions would have to peak in absolute terms sometime during 2040–45 to achieve the net-zero goal [1]. The announcement in 2021 was followed by formal submission of updated nationally determined contribution (NDC) [2] and Long-Term Low Emissions Development Strategy (LTS) [3] to the United Nations in 2022. This has since been followed up by a host of policies and actions in terms of domestic policies, including game changing initiatives like India's domestic greenhouse gas (GHG) emissions trading scheme [4].

India's total GHG emissions in 2019 [5], excluding land-use, land-use change, and forest (LULUCF) emissions stood at 3.13 Giga-tonnes of carbon dioxide equivalent ($GtCO_2e$). Of these, carbon dioxide emissions from energy and industrial processes and product use (IPPU) accounted for 2.48 $GtCO_2$, while removals from the LULUCF sector accounted for 0.49 $GtCO_2$. Of the energy sector and IPPU related carbon dioxide emissions, the power sector accounted for almost half, while road transport accounted for 11.1%, the rest being mainly the industrial sector emissions. The fastest growth in emissions between 1999 and 2019 was observed in the waste sector, followed by the energy sector. The bulk of non-CO_2 emissions, at 0.42 $GtCO_2e$, were emitted from the agriculture sector.

In terms of future emissions in the business as usual (BAU) scenario, most modelling studies published between 2017 and 2021 show [6] that India's energy sector carbon dioxide emissions in 2050 would range between 5.6 $GtCO_2$ to 7.7 $GtCO_2$ in 2050, though three studies also project 2050 BAU emissions to be as high as 11.8–14.1 $GtCO_2$. The wide range shows the uncertainties associated with a fast-growing economy, pace of decline in the cost of low carbon technologies, as well as pace of adoption of energy and resource efficiency measures across sectors. Various combinations of these variables along with how investors and consumers respond to these underlying combinations lead to vastly different emission futures for India. In terms of the 2070 net-zero scenarios, however, there is a clear lack of modelling-based assessments for India. The only two assessments [7, 8] that evaluate and present 2070 net-zero scenarios for India in our knowledge show that the strategy has to depend on solar based electricity as well as nuclear on the supply side. On the end use side, electrification of end use sectors as well as energy efficiency has to play a major role, along with the use of hydrogen in sectors like steel and fertilizers. While modelling is important and provides critical insights for policy makers, decision makers and stakeholders have to also account for various other perspectives of sector and climate experts to understand and inform India's roadmap towards a net-zero future. Broadly speaking, we categorise these perspectives into three broad dimensions (figure 1).

The first dimension relates to *national and subnational perspectives*. Equity is at the heart of India's climate policy debate. India, like any other developing economy, has the right to develop and needs adequate carbon space for the same, while ensuring that intra-country energy inequity is not exacerbated. Equity has to go hand in hand with economic growth. On the macroeconomic front, the debate on the impact of the net-zero transition on gross domestic product (GDP) is not settled, while there are some clear gains like lower oil import bill. It is imperative that there are no shocks to the macro-economy. The net-zero target is not just a climate change imperative, it is about economic transformations across sectors, and this economic transition has to be just. The challenge of just transition is immense, and deliberations on this issue are gaining momentum at the highest policy levels, particularly at the level of Indian states. States are powerful actors in India's federal system and their decisions related to energy and land use change are path defining, and the challenges at this governance level matters. Cities, on the other hand, are centres of economic growth and energy demand, and the way we build and operate cities would have a strong bearing on decarbonisation efforts. Increasingly, the profile of urban areas in India's decarbonisation debate is increasing. Co-benefits, as a theme, resonates strongly in India's climate policy at the national as well as subnational level.

The second dimension relates to *sectoral and technological transitions*. Energy demand and supply sectors- power, industry, buildings, and transport- will have to witness deep transformations given that bulk of India's emissions are from the energy sector. Understanding challenges related to the energy sector is key. More specifically, meeting the exponential

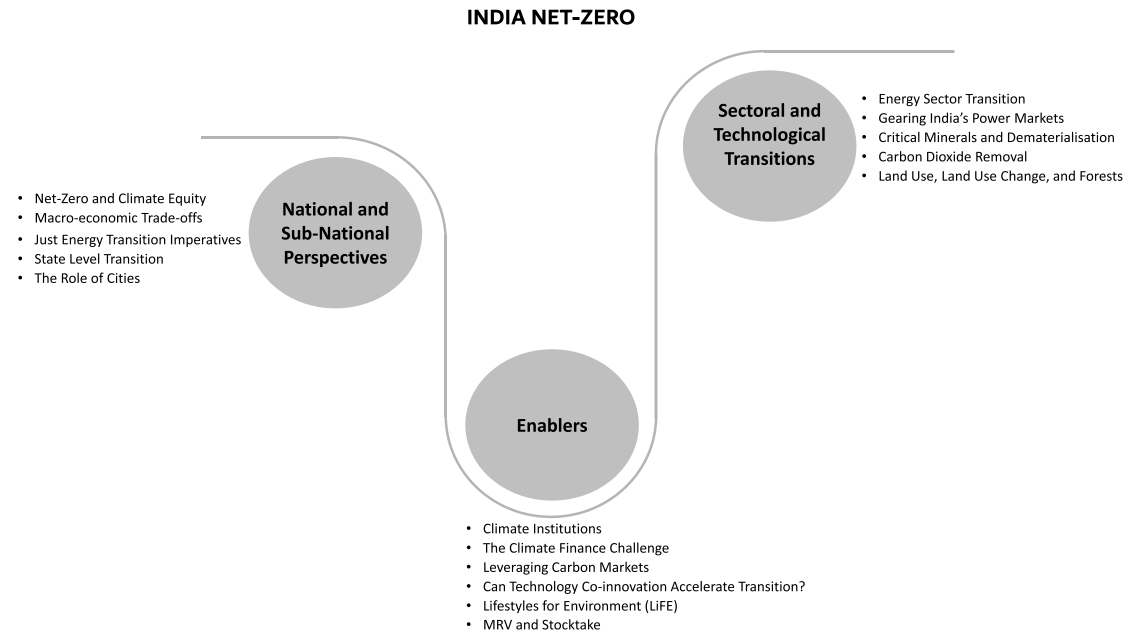

Figure 1. Framing India's net-zero debate.

rise in power demand through variable renewable energy (VRE) would require India's power market to undergo an overhaul in purpose and design. The design of India's power markets, entangled in vestiges of the past, has to be future ready. The debate on technological transition within the power sector cannot be blind to the conundrum related to batteries, needed for high VRE share but dependent on short in supply critical minerals. India's critical mineral supply chains are inadequate to meet the ambitious solar, hydrogen, wind, and battery energy storage goals, and this key vulnerability needs to be addressed. Discussions around carbon dioxide removal (CDR) in India are at an early stage, and their development will take a separate course as compared to developed economies. In addition to the various transitions in the energy sector, emissions from land-use, land-use change, and forest (LULUCF) sector have to be addressed. This sector is very different in nature compared to the energy sector. Conservation and restoration of existing forests and land use systems, along with soil carbon enhancement of agriculture lands, and reducing GHG emissions from land use systems is an important wedge.

The third dimension relates to that of enablers, which are important to accelerate the transition towards a net-zero future. Climate institutions are important enablers, and whether the current institutions will deliver or a fundamental rehaul is needed is an important question. Along with 'soft' institutions, India needs to scale up 'hard' climate finance massively to facilitate its mitigation ambition, given the fiscal challenges of a developing economy. Big bang reforms in international climate finance and access to low-cost capital would be a key enabler for the transition. A successful channel for international climate finance for the developing world has been carbon markets, that also minimize the aggregate cost of mitigation by enabling the lowest cost mitigation opportunities to be harnessed. While carbon market is expected to spur innovation, it is not an alternative to dedicated investments in research and development that has traditionally lacked in India. Co-innovation, defined as a collaborative and iterative approach involving multiple partners across the value chain, could emerge as a compelling process to overcome the limited success of climate technology transfer. Along with innovation, sustainable lifestyles are a key enabler. LiFE (Lifestyles for Environment) is an Indian initiative that seeks to mobilize individuals, communities, private sector, and policy makers to shift individual and collective behaviour towards '*mindful and deliberate utilisation, instead of mindless and destructive consumption*' and needs to be promoted. Finally, India is strengthening its monitoring, reporting and verification (MRV) capabilities of its domestic programmes and initiatives and continuous progress in this direction would also be an important enabler to accelerate the transition towards a net-zero future for India.

We assemble this article with a motivation to understand the key dimensions of India's net-zero debate in a comprehensive way. This assessment presents the perspective of experts from 24 institutions across the three broad dimensions to give a comprehensive view of a roadmap towards India's net-zero future. While the net-zero debate is about all greenhouse gases, this India specific discussion focuses only on carbon dioxide emissions from India's energy and land use sector, given that it accounts for a bulk of India's emissions story. This article is written with the intent of informing not just India's policy makers and stakeholders, but various researchers, practitioners and governments around the world for them to be better aware of the status of various aspects of India's net-zero debate, understand the high-level issues and challenges related to the transition, and think about way forward for the same.

2. National and sub-national perspectives

2.1. Net-zero and climate equity

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Status

Equity is at the heart of the climate debate. Since 1850, globally 2495 GtCO2 has been emitted—wherein shares for US, EU and China stand at 24%, 17% and 14% respectively [9]. Consequently, only a small carbon budget, 320 GtCO2 for below 1.5 °C target and 1160 GtCO2 for below 2 °C world (>50% probability) [10], between 2020 and 2070 is available for the world going ahead.

While global GHG emissions need to peak this decade to meet the carbon budget constraints, emission peaking timelines differs across countries, and developing countries may take longer to peak due to late start of their developmental cycles (Article 4.1)[26] [11]. Global emissions are projected to reach net zero between 2050 and 2070 in 1.5 °C scenarios and after 2080 in 2 °C scenarios [12]. Most European countries peaked during 1990s and USA in early 2000s. They have committed to NZ by 2050 -time gap of almost 50 years between peaking and NZ years. India has not yet peaked and is likely to peak post 2040s due to developmental deficit [8, 13]. An equitable carbon space is required to support development policies as indicated by various effort sharing assessments [8, 14], and with time gap of 30 years net-zero 2070 is an ambitious target for India [15].

Climate equity needs to be ensured not only across countries but also within the country. India has high variability in energy consumption and GHG emissions across regions and economic strata. As of 2022, India's HDI was 0.633. Historically countries with relatively high HDI consume around 70–100 GJ/capita/year final energy consumption (FEC). In contrast, India's average FEC is around 19 GJ/capita/year. This average hides the large internal inequality ranging between 6–91 GJ across states and union territories (2019). FEC of 40–55 GJ/capita/year would be required to achieve a HDI of 0.7–0.9 in 2070 [8]. Providing energy and electricity to the population without access is a priority for India, while safeguarding energy and climate security.

The Paris Agreement highlights the need for sustainable finance to ensure equitable transition. However, currently global climate financing is inequitable at sectoral and regional level. It is observed to be skewed towards transport, renewable energy and energy efficiency related technologies. While industry, building, land, water, waste, and agriculture sectors that emits significant GHGs and employ over 50% workforce but do not get adequate financing. During 2010–22, around 63% investment in early stage climate technologies by venture capitalists during 2010–2022 went to the USA and Europe, 25% to China, 3% to India and 9% to rest of the world [16]. For equitable transitions, the global total of green investment must increase along with increase in the share of investments flowing to developing countries across all sectors in the next few decades.

Current and future challenges

Assessments suggest that the US, the EU and China would consume almost 45% and 91% of the 1.5 °C carbon space by 2030 and 2050 respectively whereas India's 2070 net-zero pledges mean 59% less emissions than China, 58% less than the US and 49% than the EU cumulatively (1850–2100) [17]. For the carbon space distribution to be equitable, firstly, there needs to be a discourse on the subject with a common global understanding on equity. Currently, there exists no commonly accepted definition of equity. Studies have explored fairness in the carbon budget allocation across countries [18–20]. However, the political outcomes under the UNFCCC processes do not reflect a global agreement on 'equity' in the context of carbon budget allocations.

A bigger challenge arises due to the geopolitics of climate. The developed world is consistently pushing to dilute the core principles of UNFCCC which include equity, historical responsibility, and common but differentiated responsibility with respective capabilities (CBDR-RC). An honest reflection by the developed world on the core principles of UNFCCC may lead to additional responsibility, which is a big challenge in any agreement on the climate equity debate.

The energy sector makes up for 75% of the total GHG emissions from India, with electricity production comprising 40% [21]. Coal is one of the main sources of domestic energy. As India moves to NZ,

[26] Some examples of effort-sharing approach: equal cumulative per capita emissions, contraction and convergence, grandfathering, greenhouse development rights and ability to pay (https://link.springer.com/article/10.1007/s10584-019-02368-y).

the challenges would be in dealing with stranded assets, employment transition, revenue generation alternatives and energy prices. Currently there is little research that investigates the implications of India's NZ pathways on social costs and disproportionately higher risks for vulnerable communities. One of the challenges in undertaking such studies is lack of data availability.

From the equity perspective, financing the transition activities of the informal sector—medium, small and micro Enterprises (MSMEs) is a huge gap. The MSMEs contribute almost 30% of India's GDP, 45% of exports, and employs 110 million workers—the second largest employer after agriculture [21] and had a GHG footprint of 110 $MtCO_2e$ during 2015–16 [22]. A key obstacle in accessing finance is the lack of consistent and comparable or a 'common ground' taxonomy that helps to identify activities that could be considered 'green' and 'sustainable'.

Way forward for policy and practice to address challenges

A global dialogue on equitable allocation of carbon space is need of the hour. Parties to the UNFCCC and Paris Agreement need to come to a consensus on the operationalization of equity principles in global carbon budget allocation to ensure timely achieving the Paris goals.

NDC and LT-LEDS are living policy documents [3, 23]. Every cycle needs to build climate equitable actions (policy measures) to correct the injustices caused and avoid future unfairness. India needs to build its own body of research on inequity implications of NZ transitions. This includes the need to investigate not only on the impact of fossil fuel phase down on each of the sectors (directly and indirectly) through socio-economic, technological transformations, but also focus on development, geography-based, temporal, inter-generational, and gender-based inequities in a comprehensive manner. Technology drivers such as digitalization have ensured successful targeted policy implementation in the last decade. These advancements allow governments to verify quality, monitor performance, and regulate financial transactions. It also provides a window to obtain and analyse data at scale and speed that enhances opportunities for economic, environmental and social action [24].

If climate change is the greatest calamity of 21st century, nobody should try to generate extraordinary profits through solution provision. Lack of technology availability and low-cost finance makes the transition process incredibly challenging for developing countries. Only access to technology and finance would help in make climate transitions equitable. Therefore, technologies that promote transitions should be made accessible to developing countries. Common ground green taxonomy could be agreed internationally—for about forty transition technologies[27] anywhere in the world. This would allow easier and equitable transition finance [25]. Multilateral and bilateral institutions should facilitate low cost and grant based financing. Some countries lack capability to attract finance due to poor credit profile, lack of robust institutions and high debt to GDP ratio. Call-in capital[28] for multilateral development banks (MDBs) and blended finance[29] options should be encouraged to get the funds flowing,

Concluding remarks

A global understanding on equitable distribution of carbon space to meet developmental deficits of countries is the need of the hour. Socio-technical transitions to mitigate and adapt to the impacts of climate change pose complex, multi-dimensional challenges at spatial and temporal levels. An equitable transition requires high capital investments and transaction costs, international financial support in addition to access to desired technologies. The Government of India has emphasised the principle of ***Vasudhaiv Kutumbakam***—one world, one family, one future, where no one is left behind, a theme adopted by India for its G20 presidency[30] [26]. As the most populous developing economy in the world, dealing with climate inequities aggravates the current social-economic-political-cultural inequalities due to its size, geography, and limited resources (energy, minerals, technology and finances). India may need to select sub-optimal technologies to harness high-impact transition opportunities. Low-cost finance is a must for all such transitions. Last but not the least, in addition to educating the society, India needs to nurture entrepreneurs and integrators in every field (social, political, technology, finance, climate) that not only address the issue of social and climate equity but also drive these transitions at large scale.

[27] This includes battery storage, green hydrogen, CCUS, recycling of critical minerals, and nuclear energy.

[28] Call-in-capital/callable capital; constitutes an obligation for or promise by shareholder governments to provide capital if ever needed, thus accounts for about 60%–90% of each MDB's capital.

[29] Blended finance is the strategic use of development finance for the mobilisation of additional finance towards sustainable development in developing countries (OECD).

[30] 'Vasudhaiva Kutumbakam' or 'One Earth One Family One Future' is drawn from the ancient Sanskrit text of the Maha Upanishad. The theme considers the value of all life of all kinds (human, animal, plant, and microorganisms) and their interconnectedness on the planet Earth and in the wider universe.

2.2. Macro-economic trade-offs

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Status

Since 1991, the Indian economy has experienced an average annual growth rate of 7%–8%, with the agricultural sector decreasing from 42% to 17% and the services sector increasing to 53% [27]. This economic transition is unfolding along with an energy and climate transition. According to [28] climate change could reduce India's GDP by 0.42% in 2030, and 3% by 2100, even if the global temperature rise remains below 2 °C, under an unmitigated scenario it might increase potentially up to 5% by 2050. As demonstrated in [29] the long-run impact of 2 °C global warming on India's GDP is projected to cost around 6.4% per year, with a cost of around 10% per year in 3 °C scenario.

Limited research exists on macro impacts of deep decarbonization and net-zero pathways for India, which analyses employing macro-economic models and approaches to deepen India-specific understanding (e.g. [30, 31]). As far as the impact on GDP is concerned, Indian researchers have varying narratives on low-carbon transitions. Chaturvedi and Malyan [32] suggest that the early net zero targets will require higher costs. A net zero in 2050 would imply that economic losses as a percentage of GDP in 2050 would be 6.9%–7.2% if CCS is unavailable and 4.2%–4.5% if CCS is accessible. If 2070 is the net zero year, economic losses in 2070 vary from 2.8 to 4.4% across all technology availability scenarios. It is important to acknowledge the fact that delays in mitigation may lead to increased long-term costs (37% increase compared to immediate mitigation) and risks in containing climate change impacts is also considerable [33]. Whereas, it is demonstrated in [34] that the overall effect of the low-carbon transition on India's economic growth is positive. The GDP in 2050 is projected to be higher than the reference scenario by US$406 billion in the Net Zero Scenario (2018 prices). The positive impact due to investments, reduced energy costs, and increased demand from consumption and employment, act as an enabler to the smooth transition.

Considering energy sector jobs, net zero might be promising for India since green investments would likely fuel economic growth and create jobs. The estimates, diverge ranging from 3.4 million additional jobs [35] to 43 million additional jobs [36] in 2050.

Transition to cleaner fuels reduces fossil fuels dependency and import bill, that further keeps foreign debt under control at the cost of lower household consumption. Regions with economic activity reliant on fossil fuels may require economic diversification programs and reskilling of workers [31].

Current and future challenges

Decarbonisation regulations require capital reallocation, shifting investments to expensive low-carbon alternatives for climate change mitigation measures, if the pace of transition is not managed [6]. On the other hand, when accounting for environmental damages via taxation or credit trading, the cost of low carbon technologies might be cheaper than their fossil equivalent. Moreover, the cost of technologies such as energy storage, including batteries, is rapidly decreasing, while its capability is increasing [37]. The falling costs of clean energy technologies, such as LED bulbs, solar and wind, and electric buses, offer an opportunity for an economically viable transition [38].

Indian economy is grappling with unemployment and steep fall in economic growth amid post-COVID-19 pandemic. For instance, distribution companies are facing potential revenue losses of 8%–10% due to a 25% decrease in demand since the start of the lockdown [38]. These uncertainties present further challenges in defining policy strategies. The key challenges in net zero transition through the lens of macroeconomics are discussed below.

Upfront capital investment requirement: Large scale renewable energy (RE) penetration requires a lot more upfront investment in electricity generation. While the levelized cost of electricity (LCOE) is lesser for renewables compared to fossil fuels but the upfront cost for the renewable power projects remains high especially in a low-income economy such as India. India might face significant capital mobilisation related challenges for renewable capacity, transmission infrastructure, and energy storage technologies [39].

Loss of tax revenue, royalties and coal sector jobs: India imposes certain taxes on fossil fuels, which further translates into an effective carbon tax rate [38]. Indian states, like Chhattisgarh, Jharkhand and Odisha may face financial difficulties due to loss of revenue from the coal sector. Over half a million coal mining employees may be required to find alternative employment, retrain in other energy industries, or receive severance compensation if industry closure occurs, that creates an aggravate macroeconomic imbalances [1].

Import dependence in RE segment: energy transition using modern RE technologies may create increased dependence on critical minerals imports particularly if India relies on domestic manufacturing

[40]. India lacks sufficient domestic resources of critical minerals, so low-carbon energy systems may lead to increased import dependency, thus threatening energy security [39].

Pass through impact of carbon prices: carbon prices, driven internationally or domestically, may lead to increasing energy costs for household and industries that may lead to negative welfare effects and loss of economic value in the country. Hence equitable revenue recycling will ensure the balancing of distributional effects while implementing carbon pricing.

Supply shocks to GDP: concentration of critical mineral supply chain, essential minerals utilised in the RE and clean transportation sectors [1], in the hands of any one nation could lead to supply shocks for India's GDP even if it might not be a huge import bill like oil import bill.

Stranded assets: finally, higher investment in fossils that may become stranded before its financial life would lead to loss of economic value and such investments should be avoided.

Way forward for policy and practice to address challenges

RE investment surged in the past decade, driven by economic growth, rising fossil fuel prices, technology advancements, policy support, and citizen demand for cleaner environments. Over 2019/2020, solar projects in India received the largest financial investment of rupees 54 thousand crores, accounting for 41% of total finance flows to the clean energy sector, implies that there is an opportunity for the general public to invest [41].

Additional policies and international support are required to complement climate measures in order to maximise economic opportunities and minimise potential shocks. While recycling carbon revenues and leveraging other tax-raising mechanisms are important potential funding mechanisms for green investments. Policies that encourage reskilling and upskilling of the Indian workforce will also enable employees to take full advantage of new job possibilities created by a low-carbon economy [42].

Identifying compensatory methods for increased costs in decarbonisation efforts, analysing approaches, and implementing policies can help address trade disruptions, skill demand, employment losses, and income inequality. So, analysis on income inequality by including the household classification based on income in the economy-wide model is critical particularly in the context on India where there is widespread income disparity [43]. Unabated coal phase-out regulations, are particularly successful at producing considerable emissions reductions in the long term, but they can be expensive due to the high expenses of government compensation for stranded assets. Market-based tools, on the other hand, are likely more successful than regulation due to stronger societal support for these policies in the industrial and residential sectors, particularly in the longer term when no regulatory measures are in the pipeline. As a result, a comprehensive package containing a combination of regulatory and market-based interventions that is customised to sector characteristics is required [42].

Policymaker's judicious decisions can help to achieve high growth and a low-carbon economy simultaneously. Technology transfer is crucial for India's growth, as economy's shift from agriculture to industries and services [31]. Low-carbon growth requires structural changes in energy systems, including renewables, reduced demand, and clean coal technology deployment [44].

There is an urgent need to address these challenges by developing a 'hybrid' tool that can provide the inputs on national climate policy based on the macroeconomic assessment of the mitigation and development pathways [45]. Model setup can incorporate non-standard specifications for different sectors, like energy and non-energy, to control the interface between top-down and bottom-up models for assessing macroeconomic trade-offs and informing policy makers.

Concluding remarks

This chapter elucidates the significance of the macroeconomic assessment of the low-carbon pathways for India. There is a clear lack of agreement in the current literature on whether, at the aggregate level, the transition will hit the economy negatively or will it provide an economic fillip. Indian context is different from that of other countries in terms of economic structure, dependency on fossil fuel imports, economic growth, and emphasis on manufacturing in the recent years. The net zero targets and other commitments on NDC for UNFCCC are likely to impact the macroeconomic situation, so it is critical to investigate the energy-economy implications of mitigation pathways. There are several challenges in modelling the macroeconomic indicators particularly the consistency issues on soft-coupling the two different modelling approaches: top–down and bottom–up [46]. With focus on data collection, realistic assumptions, modelling constraints and macroeconomic closure rules, it is possible to derive useful inputs for the policy makers so that they can make policies that achieve the mitigation and development targets simultaneously.

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2.3. Just energy transition imperatives

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Status

In recent years, the Government of India (GOI) has made significant announcements at various national and international platforms and undertaken important policy measures that has underscored the country's commitment to transitioning to clean energy systems and building a low-carbon economy in the coming decades. At the same time, there is a growing emphasis on just transition in the context of energy transition to strike a balance between 'energy security, environmental sustainability and socio-economic development' [47].

Deliberations on just transition at the highest policy levels are gaining momentum as it is well recognised that the transition away from fossil fuels will have major social and economic consequences for workers and local communities. It will also have implications for government revenue at the national and state levels, and social sector investments [48]. Therefore, building a low-carbon economy requires a deep understanding of the socio-economic and political consequences of the transition and developing measures to minimise disruptions in the economic and social systems [49].

In India, the national and the state governments are rising to the challenge. For the country, just transition is not just being viewed as an issue of transitioning the fossil fuel-dependent workers and communities, it is considered as a process of achieving sustainable development outcomes and inclusive growth. Under India's G20 Presidency, therefore, the Government has been repeatedly emphasising on 'just, affordable, and inclusive energy transitions', as a mean of enabling 'secure, sustainable, equitable, and inclusive growth' [50].

Institutional mechanisms at the national and state levels are also being initiated to support just transition. For example, the Ministry of Coal has set up a 'Sustainability and Just Transition Division' to address sustainability and transition issues of the coal sector and the coal regions. At the state level, India's first 'Sustainable Just Transition Taskforce' has been set up by the Government of Jharkhand, one of India's key coal-dependent states.

Therefore, as the momentum grows, it becomes important to understand the challenges and complexities of just transition in India, and the policy and planning aspects that need attention to ensure a well-planned and well-managed transition process.

Current and future challenges

Four key challenges are essential to consider for ensuring a just transition in India. These include, the geographical scale of the transition, the workforce distribution, the socio-economic vulnerabilities of fossil fuel-dependent regions, and the financial requirements for implementing just transition measures.

There are at least 120 districts that have a significant reliance on fossil fuel sectors and fossil fuel-dependent industries (primarily large; if medium, small and microenterprises are considered the number is higher) including, coal mining, oil and gas production, thermal power plants, steel, cement, automobile, refineries and fertilizer (urea) [51]. Considering the imperative for a fossil fuel transition to meet the climate goals, and develop a net zero economy, these sectors will need transition planning in the coming decades. However, In the immediate future, districts that are particularly at risk is where old and economically unviable mines and old power plants are concentrated. For example, in states like Jharkhand, West Bengal, Chhattisgarh, Madhya Pradesh and Maharashtra, many such mines are primed for transition [48]. For power plants, about 9% of the country's coal-based capacity (about 207 GW) is 21–30 years old, 11% is 31–40 years old, and 2% is 41–57 years. Many units of the old units will be retired by 2030 due to economic and environmental concerns [52].

For workers, at least 20 million people engaged formally or informally in the various fossil fuel industries will be impacted by the transition. Experiences from top coal districts show that the informal workforce is a major concern, as they are predominant in sectors such as coal mining and coal-based power [51]. Besides, there is high informality in the SMEs. For example, in the brick sector, which employs about 11 million workers, over 80% are informal [53].

The vulnerability of the workers is further enhanced by limited alternative economic opportunities in these regions. For example, in many coal districts over 50% of the district GDP is dependent on coal mining and coal-dependent industries [48]. The poor status of social infrastructure further undermines the adaptive capacity of the local community. An assessment of multidimensional poverty indicators (exhibits the status of healthcare, education, and living standards) shows that nearly 69% of the coal districts have more than 25% of the population who are multidimensionally poor, which is the India average [54].

Finally, the fossil fuel transition will have significant impact on government revenue. Coal, oil, and gas collectively contribute about 18.8% and 8.3% of the total revenue receipts of the central and the state government(s) respectively [55]. Besides, a large sum of money will be necessary to support various just transition measures. Therefore, planning for revenue substitution and securing finances for just transition remain crucial [56].

Way forward for policy and practice to address challenges

Five key factors will be essential to ensure a just transition in India considering the context of the fossil fuel industries and regions.

To begin with, economic diversification of fossil fuel-dependent regions will be one of the most important interventions to ensure economic and social vitality of the impacted regions [57]. Measures should include investments in green industries and green energy, harnessing the potential of local resources (such as forest and agri-based) to strengthen SMEs and improve income opportunities from these sectors, among others.

A closely related issue to economic diversification is the repurposing of land and energy infrastructure. Over 0.4 million hectares of land is available with operational coal mines and power plants in various states and districts. Reclamation and repurposing of the land provide massive scope of creating immediate and long-term economic opportunities, including the development of green industries and green energy infrastructure [51].

Reskilling the existing workforce and providing transition support to the impacted workers will be another essential intervention. There is a massive need to invest in skilling programmes and institutes (including for higher order skills) and foundational education to improve employability and income opportunities of both formal and informal workers, including women, and develop the workforce for the low-carbon economy [58].

Beside measures of workforce transition, poor socio-economic indicators in many fossil fuel-dependent districts necessitate investments in social infrastructure to improve local communities' adaptive capacity during transition and achieve long-term developmental goals. The convergence of various developmental programmes operational at the district and state levels is an immediate opportunity to support such measures.

Responsible environmental practices are also equally important to ensure well-being of the local communities. Many of the coal and industrial regions have been identified as 'critically' or 'severely' polluted areas by the Central Pollution Control Board [59]. Therefore, the new economy should be planned in a manner that the pollution problems are not exacerbated. Besides, reduction of material and resource use, and reuse of the same, must be ensured through circular economy practices [60].

Finally, the central and the state government(s) will need to plan for revenue substitution and also mobilise resources for just transition. Early planning for economic diversification will be crucial for diversifying and substituting revenue sources of the government(s). Besides, the central government will have a key role in mobilising public and private finances from domestic and international sources to support transition measures.

The above-mentioned factors should be considered for instituting policies and developing plans and investment measures. Besides, strong institutional mechanisms must be developed at the central and state levels. Among others, a dedicated just transition department at the national level, and an office of just transition at the state level will be required for interdepartmental coordination, facilitating the development of policies and plans, fostering stakeholder engagement and monitoring the implementation of just transition measures.

Concluding remarks

Considering the scale of the fossil fuel transition in the coming decades, along of nature of workforce and socio-economic realities of various fossil fuel-dependent regions, developing just transition policies, plans and investment measures for India will require a holistic approach underpinned by a development agenda, including a major focus on green growth and jobs.

Overall, just transition must be planned as a strategic development intervention. A road map must be developed for the coming decades, aligning with the country's energy transition ambition and net zero targets, and considering the opportunities in hand, to usher a transformative change that is inclusive, just and viable.

2.4. State level transitions

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India has announced the goal of net zero emissions by 2070, and in its updated NDCs has committed to reduce emissions intensity of its GDP by 45% from 2005 and achieve 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030. India's progress on the NDC targets has largely been driven by national policies, but the success of its net-zero ambition will depend on how well low-carbon options are woven into the development and economic frameworks of states as default options. The diversity of Indian states, which necessitates multiple pathways, will determine the larger national low-carbon transition.

The role of states in India's low-carbon transition is implicit in the ambition itself. Many of the sectors that are key to the discourse fall either within the legislative jurisdiction of states (e.g. agriculture) or are concurrent (e.g. power, transport, forests) in the Constitution of India. Many of these are further devolved to urban and rural local governments guided by the principle of subsidiarity. Further, the extent and nature of vulnerabilities call for location and region-specific adaptation and resilience measures. States as laboratories of policy innovations have been instrumental to India's energy transition. For example, early initiatives by Gujarat and Rajasthan on solar, and Maharashtra and Tamil Nadu on wind, have contributed significantly to renewable energy uptake at the national level. India's achievements of its 2022 target for 175 GW renewable energy offer some insights into the importance of sub-national action. While it achieved a significant portion of the target, only Gujarat, Rajasthan, Karnataka, and Telangana surpassed their individual targets. Four states, Maharashtra,Uttar Pradesh, Andhra Pradesh, and Madhya Pradesh, on the other hand saw considerable shortfall in achievement of targets [61].

Thirty-four States /Union Territories (UTs) have prepared, and some have updated their State Action Plan on Climate Change (SAPCC) in line with National Action Plan on Climate Change. SAPCCs have served as the primary policy and programmatic framework for short-term climate action at the sub-national level. Analyses of the SAPCCs point to some common institutional, financing, and capacity challenges discussed in the next section. Increasingly cities are at the forefront of strengthening climate-sensitive urban development. Many states are also developing village-level climate action plans which involve local communities in identifying climate risks, vulnerabilities, and adaptation strategies. States are also beginning to prepare long-term climate-resilient and low-carbon development strategies.

Current and future challenges

From the experience of states in developing SAPCCs and more recently, long-term strategies, several common challenges stand out. A key issue relates to inadequate detailing and prioritization of interventions, and clear linkages to accountable agencies/departments and alignment with development plans and budgets. Another concern is the weak inter-departmental coordination for mainstreaming and monitoring climate action across sectors. While several institutional mechanisms have been put in place under the SAPCCs, the process is mostly led by the Environment/Forestry Department, or Pollution Control Board, which have limited authority or levers within state governments to influence other departments for mainstreaming SAPCC. Limited capacity within and outside the government is often a constraint in the design and implementation of localized programmes and projects based on long-term strategies.

An issue that often does not get adequate attention relates to availability of credible, adequate, granular, and consistent data as the basis for scientific assessment of future emission scenarios and climate risks, including sector-specific impacts. Inconsistency in data collected from different sources is another challenge. Where information is available, lack of local capacity may still restrict its analysis and dissemination.

There are also practical challenges thrown up by the federal structure of India. About 30% of India's installed thermal capacity is owned by central PSU's which can pose a challenge for a state in dealing with net zero ambition. Similarly, an approach would need to be evolved to account for emissions from inter-state road transport, especially freight, and centrally controlled modes of transportation such as railways. Physical constraints such as land, water and natural resource can limit the ambition of low-carbon pathways- for example competing demand for land from agriculture, forests, industry and urban development can affect the solar potential that states are able to effectively harness.

Indian states will have to find their unique development pathways that balance multiple imperatives-decarbonizing their economies and funding related capital expenditures, and enabling equitable economic development, particularly by expanding access to affordable, secure energy- in the face of compounding climate risk. A state like Bihar, with over 75% of its large population dependent on agriculture [62] would need a different strategy than a Tamil Nadu that has the largest number of persons engaged in factories [63]. These tailored policy roadmaps will have to be internalized in sectoral policy and budgetary frameworks, within an overarching policy and governance framework that enables the required economic, financial and behavioural transformation.

Way forward for policy and practice to address challenges

Three elements will be critical in shaping states' climate response.

First, governance approaches are needed which ensure that climate action—mitigation and adaptation—is embedded in development aspirations at the highest level and steered by political and executive leadership such that it percolates into the long-term vision across sectors, as well as translates tangibly into programmes, policies, and budgets. For instance, Jharkhand, India's largest coal-producing state, established a Task Force for Just Transition in November 2022 to create a roadmap for a transition to cleaner energy [64]. The Task Force comprises 17 institutions, including different government departments, and is working on seven thematic areas—livelihoods, energy transition, coal transition, electric mobility, decarbonisation of industries, climate finance and capacity building.

Coordination is also necessary to enhance opportunities for co-benefits including ancillary and nonmarket benefits, and limits maladaptation and tradeoffs. These include mitigation actions that increase exposure and vulnerability to climate change or adaptation action that undermines mitigation efforts.

States will have to focus on creating capacity to understand and respond to challenges and opportunities thrown up by climate change across departments, tiers of governance, and stakeholder groups. State-level training institutions will need significant strengthening in this respect. As an example, the Kerala Institute of Local Administration (KILA) has internalised training on Ecosystem-based Disaster Risk Reduction into various livelihood guarantee schemes [65]. At the same time, capacities would need to be strengthened in States to access multilateral funding.

Most critically, net zero pathways will need to be backed by adequate finance. It would be important for states to better leverage national and international public climate finance to unlock private capital from banks, investors, and capital markets. Tamil Nadu, for example, has established the Tamil Nadu Green Climate Company (TNGCC) as a special-purpose vehicle to implement three key missions related to climate, afforestation, and wetlands. The not-for-profit company has an equity of INR 50 million from the state government and can get funding or grants from any source, including the Government of India and international agencies. The recent steps by the Government of India towards a domestically regulated carbon market are significant for mobilizing private capital. Given India's estimated urban infrastructure investment deficit of USD 827 billion for the period 2012–2031 [66], it is also important to highlight the role of national support programs for financing green infrastructure that are tailored to help municipalities cover additional investment costs. Underscoring all these policies is the need to ensure that climate mainstreaming is reflected in state budgets across departments. Initiatives such as the Green Budget of Bihar can facilitate this process [67].

More than anything, the 2070 net zero goal needs to be viewed as multi-trillion, multi-decade investment opportunity by the states.

Concluding remarks

It is encouraging that several Indian states have set ambitious climate goals or initiated significant efforts in the energy and mobility sectors, among others. The economic transformation required to achieve netzero emissions must be seen as an economic opportunity with social and economic co-benefits in terms of inter alia health, livelihood, and conservation of natural capital. It is an opportunity for states to take advantage of cutting-edge technologies across almost all sectors. At the same time, states need to invest in understanding and planning for long, medium and short-term risks of climate change. Governance, capacity and finance will be critical aspects of this transformation. This is especially relevant given the long-term net-zero targets, which necessitate institutionalized governance and monitoring mechanisms that also allow for integration of the fast-evolving technological ecosystem. As the world prepares for the next round of NDCs by 2025 in line with the outcomes of the global stocktake of the Paris Agreement [68], there is a clear need for a review of ways and means to enhance efforts on climate action where sub-national governments can shine the light on translating intent into action.

2.5. The role of cities

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The sixth assessment report of the Intergovernmental Panel on Climate Change shows that cities can get to net zero greenhouse gas emissions by reducing emissions within and outside the city boundary [69]. Unlike other large developing countries (China, Brazil, South Africa), India has a relatively low share of urban population (34%) however, this is expected to exceed 50% by 2050 [70]. Key drivers of emissions-urbanization, population and income are expected to grow over the coming decades influencing the demand and patterns for urban housing, transport and infrastructure.

Road transport, energy use in buildings and methane emissions from waste and wastewater are the highest emitting sectors in Indian cities. Transport emissions mainly from fossil fuel-based vehicles are expected to grow as travel distances increase due to spatial sprawl. Energy use from buildings is increasing by 8% annually [71]. Urban residential floor space per capita is projected to increase by over three times and the commercial sector floor area will increase tenfold between 2020 and 2050 [72]. This would imply a substantial increase in electricity demand for cooling, lighting and appliances; and for building materials-cement, steel and bricks. Switching away from conventional to alternate construction materials could save between 180–600 $MtCO_2$ in 2050 [73, 74].

India's long term low carbon strategy identifies urban design, low-carbon transport, energy and material efficiency in buildings and solid waste management as key elements in achieving net zero targets [75]. The Smart Cities mission highlights the importance of a sustainable environment and digital solutions to deliver core infrastructure and provide a decent quality of life to urban residents. Many sectoral mitigation solutions have been successfully adopted in cities however, climate change is not always a key priority for local governments. Many initiatives are implemented in a project mode funded through international finance and often supported by external agencies. A variety of plans exist (e.g. climate action plans, urban development or sectoral plans) but these are disjointed. Overall, climate action remains incremental, lacking in ambition or poorly implemented.

Energy and emissions are unevenly distributed across households. The energy and material consumption patterns (electricity, LPG, residential floor area) of wealthier urban households is significantly higher than that of the large number of low income households who live in slums with unmet housing and infrastructure needs [76]. Urbanization needs to address simultaneous challenges of reducing energy and material demands while also improving the quality of life of poorer households.

Current and future challenges

The gap between projected emissions from the BAU and ambitious mitigation scenarios is sizeable [77]. A net zero pathway implies a transformative shift away from BAU towards a sustainable pathway. Some of the challenges are highlighted below:

1. Limited capacity of local governments: cities lack adequate skilled staff resulting in limited capacities for developing and enforcing plans [78]. Only a fraction of the thousands of staff positions required at the local level are officially sanctioned. The working strength is even lower, with vacant positions ranging between 15 and 50%. A number of Indian cities lack Master plans to guide urban development. Poor urban planning has resulted in haphazard sprawl and resource intensive growth. Following existing trends will intensify environmental and social challenges including traffic congestion, air pollution, urban flooding, loss of green spaces, urban biodiversity and inequality.
2. Challenges to financial flows and access: significant upfront investments for infrastructures are needed. Indian cities do not have a significant source of generating their own revenue and largely rely on national or state government funding. In addition to the steep demand-supply gap, barriers include limited capacity to utilise available resources and to develop innovative financing models.
3. Managing growing demand: growing income will lead to changing lifestyles and higher consumption of floor space, personal vehicles, appliances, etc. Poorly insulated buildings will lead to a high demand for electricity during summer months especially on hot days. Meeting thermal comfort needs without a steep rise in emissions will be a major challenge. Similarly, the growing demand for building materials and associated process related CO_2 emissions of cement production is challenging, as low-cost alternative options are not yet readily available.
4. Inadequate data and technical capacity: few cities have reliable local data on climate and sectoral energy consumption, or an updated emissions

inventory which are key to developing local climate action plans. Limited technical expertise and capacity within urban local governments could result in weak implementation and a higher reliance on external actors and agencies for support.

5. Lack of autonomy: India's existing system allocates higher powers to central and state governments. The 74th Amendment of the Indian Constitution (1992) was intended to facilitate decentralisation by granting autonomy to local governments. However, this was left to state governments' discretion and was not fully implemented, as a result city governments lack adequate powers to execute mandated functions [79]. The presence of multiple agencies at different levels and siloed planning further limits the abilities of cities to undertake ambitious action.

Way forward for policy and practice to address challenges

The first step to achieving net zero emissions is a robust emissions inventory starting with direct emissions and progressively building data to include indirect emissions occurring outside city boundaries. Different types of cities (megacities/ million-plus cities/small towns, etc.) can then develop their own targets and roadmaps that align with their capabilities and development priorities.

Substantial investments in public transport infrastructure complemented by demand side measures to restrict the ownership and use of private vehicles will enable a sustainable transport transition. These include improvements in road design and public transport infrastructure, increasing service quality, affordability, and improved information on public transport, using digitalisation to integrate transport modes especially including public transport and para transit (3-wheelers) modes which will remain a key mode in the near-future.

Electrification and shift to renewables will be a major lever for decarbonisation. This will require a systemic approach. For example, ambitious EVs targets complimented with changes in building regulations, rooftop RE targets, grid augmentation, net metering, time of day pricing, etc. will encourage private investments in charging and renewables.

Digitalization, shared and on demand mobility are quickly transforming the landscape for urban mobility by improving access and affordability of public transport modes. Urban planning guidelines, and municipal bye laws need to ensure compact and mixed-use development and more green spaces. There is a need to raise the ambition in existing building regulations and providing incentives towards achieving high efficiency standards, lowering the cooling load, and improving existing construction practices. Policies and infrastructure, when complemented with appropriate information on benefits, and incentives to public can enable behaviour change and reduce lifestyle consumption.

Investment estimates for India's net zero transition are not insignificant. It will be challenging for cities to undertake ambitious net zero actions without dedicated funding, especially for medium and small cities. Such funding could include a combination of public finance (states and centre), international finance and the private sector. Multilateral banks and city networks can support cities in developing innovative financing models and leveraging international and domestic climate finance. Market based mechanisms (tax rebates, incentives) and public private partnerships encourage adoption and upscaling.

Targeted efforts by the central and state governments are needed to build technical capacity to collect appropriate sectoral data, prepare emissions inventories, develop net zero pathways, assess costs and benefits of actions, and develop climate action roadmaps. These would require specialised trainings, city-to-city learning for transfer of good practices, better coordination across agencies and engagement with non-state actors.

Concluding remarks

An urban net zero transition is possible however, this requires a massive shift in the existing urban planning and governance model. Such shifts are not easy and changing status quo requires overcoming technological, socio-economic and political barriers. Steep emission reductions can only be delivered through ambitious policies, strong political will and behavioural change. Building urban capacities to push the necessary projects with increasing quality standards through the planning and permission process pipeline needs attention. Significant and concerted efforts for catalysing finance are needed, particularly for the small and medium-sized cities. Future urban plans and infrastructure investments would need explicit consideration of climate change to avoid locking-into carbon intensive infrastructure and lifestyles.

A sustainable urban net zero transition, besides delivering ambitious emissions reductions, will support a cleaner, less material intensive development and the wellbeing of millions of residents.

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3. Sectoral and technological transitions

3.1. Energy sector transition

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Status

India has adopted a net-zero emissions goal to be achieved by 2070, despite a formidably increasing energy appetite driven by the growing economic and social energy needs. The present emissions landscape of the nation is dominated by its energy sector contributing to about 75% of the total GHG emissions. Figure 2 illustrates sector-specific emissions in energy sector, highlighting electricity as the dominant contributor with a 40% share [80]. India has an installed electricity generation capacity of 416 GW, of which 179 GW (43%) is from non-fossil fuels [81], though about 73% of electrical energy is still produced by coal [82]. Figure 3 shows the capacity and energy mix in FY 2022–23 and YOY addition of RE [83]. As part of its NDC (2021–30), the government has committed to increase the share of non-fossil fuel-based energy resources in total installed capacity to 50%.

There has been a positive trend of the energy and emissions intensity of India falling over the last two decades, primarily on the strength of energy efficiency improvements mandated under the Energy Conservation law. From 2005 to 2016, the emissions intensity of India's GDP declined by 24%. The energy intensity of India decreased from 0.2801 MJ/₹ in 2012–13 to 0.2245 MJ/₹ in 2021–22 at a CAGR of −2.43% [84].

Figure 4 exhibits the total energy supply mix in India, highlighting the dominant roles of coal (45%) and oil (24%). In this light, the government has taken a few positive measures to promote energy transition through mandates for energy saving, RE use, fuel blending, and efficiency norms. Most noteworthy mandates are RE purchase obligations for DISCOMs, 40% RE generation obligation for generation companies, amending the Energy Conservation Act to mandate minimum use of RE in designated industries, and compulsory 100% procurement of power from waste-to-energy plants. *Perform, Achieve & Trade* scheme aims to reduce energy consumption in energy-intensive industries. *Building Energy Efficiency Program* is designed to implement energy-efficient measures in government buildings. *Unnat Jyoti by Affordable LEDs for All* initiative aims at providing LED bulbs to consumers at subsidized rates. Promotion of EVs in public transport system is being supported through a subsidy scheme of *Faster Adoption and Manufacturing of Hybrid EVs*. Phasing out subsidies for petrol and diesel have been a major policy shift towards a market oriented fiscal policy in the energy sector. A domestic carbon market has been put in place for trading of carbon-denominated energy units and assist industry in meeting their energy consumption targets.

Current and future challenges

The key challenges could be understood from both the demand and the supply side. India's total electricity demand would be about 5500–6000 TWh by 2050 [85], implying significant ramp up in power supply. Even with the lower variable costs, additional investments are likely to be in the range of $223 billion between 2022–2029 to meet the stated solar and wind capacity targets alone [86]. There is additional need of almost 125 GW of RE capacity and 60–100 GW of electrolyser production by 2030 just to meet the goals of the National Green Hydrogen Mission which targets yearly production of 5 MT by 2030 [87]. Mobilizing finance for these investments is a critical challenge.

India has a declared target of installing 500 GW of non-fossil fuel-based capacity by 2030. RE capacity additions are daunted by acute financial distress of DISCOMs caused by inflexible energy subsidies, outdated infrastructure, high AT&C losses, and cross-subsidization of energy. Furthermore, the grid must be equipped to store surplus RE energy given that grid integration of intermittent RE is a critical challenge. Scaling up provision of bio-energy is challenging due to cost incurred in the supply chain as well as food security related challenges.

Energy demand for space cooling is rising at a rapid rate in urban segments. Air-conditioners expected to contribute to 50% of total space cooling demand by 2037–38, up from 7%–9% currently (2021), which will change the shape of load curves. Pushing and integrating higher RE in a high electricity growth scenario with rapidly changing load curves is a challenge that no country but India is witnessing.

Community and business participation in solar rooftop has been muted largely on issues related to high upfront capital cost and lack of sufficient incentives. Off-shore wind, which has large potential, is very costly. The progress on nuclear has also been slow due to high cost and environment concerns.

On the demand side, inducing behaviour change is a critical challenge. With rising incomes, people are moving towards private mobility and the share of public transport has been declining. Faster implementation of building codes has been a challenge due to split incentives in the system.

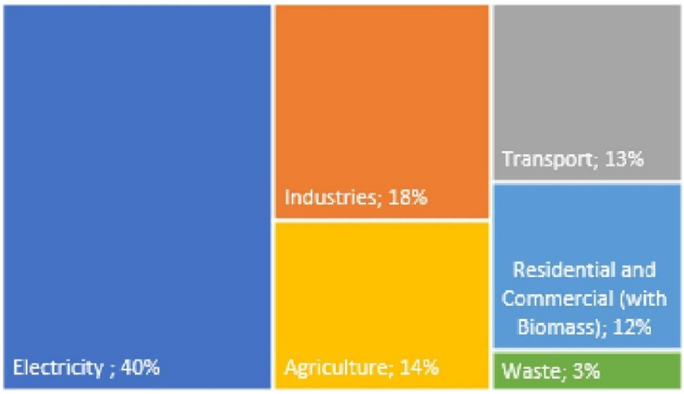

Figure 2. GHG emissions in energy sector.

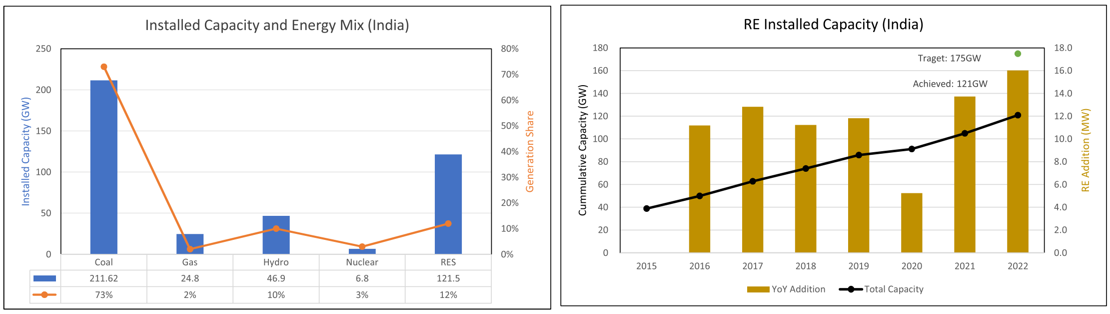

Figure 3. Capacity and energy mix in FY 2022–23 and YOY addition of RE.

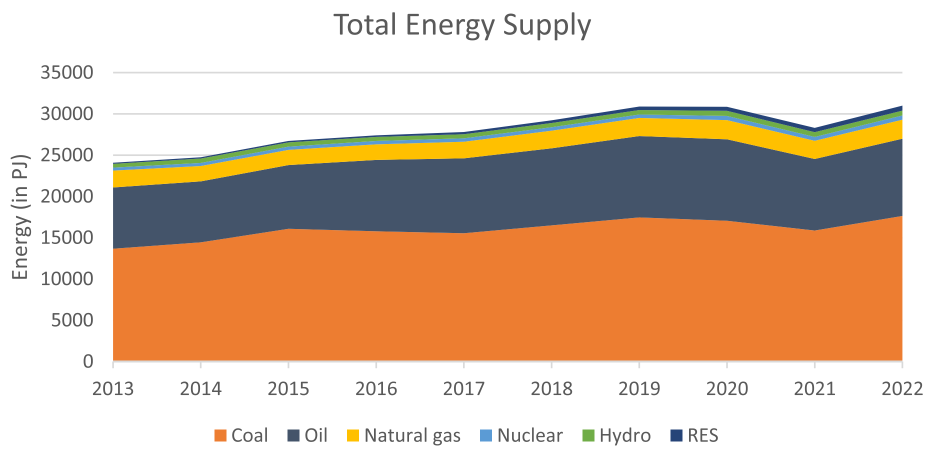

Figure 4. Total energy supply in India.

The transition in heat-intensive industries (large and MSMEs) such as cement, steel, chemical, petrochemical, and metallurgical industry, and internal combustion-based transport, which together contribute to 45% of total emissions, will be equally difficult in the absence of innovative technologies. Research and technology development that increase energy efficiency, reduce emissions, and enhance the overall sustainability of industries is a pressing concern.

Way forward for policy and practice to address challenges

India has put forward a low emission development strategy for 2070 to reach net-zero target by 2070. This envisages transition in six economic sectors: power, transport, habitat/buildings, industries, and forests. However, the roadmaps for transition in each sector are yet to be prepared. The government has also made a commitment to reduce the projected CO_2 emissions by 1 billion tons by 2030.

If the RE share in generation has to go up, RE capacity needs to be coupled with grid-scale energy storage to support grid balancing and ancillary services. BESS, CSP, and PSP appear to be most scalable and cost-effective technologies necessitating investment and thoughtful policy formulation. Pilot storage projects with various battery chemistries and experimentation with emerging technologies (e.g. compressed air, gravity storage, and hydrogen) are also imperative. Awareness campaigns, consumer subsidies and regulatory support are essential to increase penetration of rooftop solar. Additionally, energy banking for industrial consumers, encouraging captive wind farms, and initiating offshore wind power development are crucial steps to boost wind energy adoption. Improvement of DISCOMs' financial health is key to future RE integration and would depend on energy market reforms, solutions to the problem of stranded assets and eventual phase out of cross-subsidy.

To stabilize the rising energy demand, it is crucial to implement building energy codes across all municipal jurisdictions and include the enforcement of appropriate Minimum Energy Performance Standards (MEPS) for all appliances as a key component of broader energy efficiency measures [88]. Integrated approaches combining passive building design and affordable energy efficient technologies to accelerate access to thermal comfort for all must be promoted. Indian SMEs can be incentivised or mandated to use the new and simplified standard, or ISO 50 005. Their involvement in efficiency measures could be promoted through (i) policies for higher energy and material efficiency, (ii) energy audits, and (iii) programme for motor replacement (IE class 3 or above).

In the hard-to-abate sector, policies to promote resource efficiency, electric arc furnaces in secondary steel production and hydrogen or gas-based steel production, battery based EVs, and innovations in carbon capture use and storage technologies are critical to reduce industrial emissions intensity. Integrated mobility plans and policy support are critical for success of cost-effective public transport systems are necessary. In addition, financial and policy support for the development and use of alternative fuels in the energy intensive sectors and phased decarbonisation must also be prioritized.

Concluding remarks

India has to not just undertake energy intensity reduction and fuel switching measures, it has to do so while providing energy to millions of energy poor households. Development aspirations are paramount. Within this context, transforming India's energy systems to achieve net-zero emissions by 2070 is economically challenging but technologically feasible. The crucial questions that need to be addressed in the medium term are primarily about doubling the scale of current investments in RE capacity expansion and making the process of RE integration in the grid sustainable through reliable and durable energy storage systems. In the long term, emission reduction from fossil fuel intensive sectors is possible if energy market reforms are undertaken, social impacts of fossil fuel phase down are addressed, and technological innovations become the basis for future investments. The pace and scale of transition in various sectors of the economy will depend on the sectoral transition roadmap that has to be drawn up as part of the long-term low emission growth strategy.

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3.2. Gearing India's power markets

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Status

India's stride towards becoming a Net Zero Economy by 2070 will be marked by two key trends: rapid end-use electrification of a growing economy, and near-complete decarbonisation of power generation [7]. Meeting this exponential rise in demand through VRE would require India's power market to undergo an overhaul in purpose and design.

The current market structure is a result of several design shifts over the past three decades in response to changing socio-economic context, policy priorities, and international developments. The decades of 1990 and 2000 saw unbundling of the generation, transmission, and distribution segments, the opening-up of generation and transmission sectors to private players, and the establishment of the central transmission utility and electricity regulatory authority. The landmark Electricity Act of 2003 enabled non-discriminatory open access to the transmission network and bilateral trade of power culminating in the opening up of two national power exchanges in 2008 [89].

These developments aimed to attract investments and enable competition in the sector for enhanced access to reliable and affordable electricity for the growing economy and population. Market reforms backed by policy measures have been successful to a good extent. The generation capacity grew six-fold from 64 GW to 370 GW between 1990–2020, with nearly half of it now owned by private players [90, 91]. More than 70 distribution companies connected with an integrated national grid are servicing ∼290 million electricity connections [91]. These achievements have made India the third-largest electricity system in the world today.

The past decade has seen another wave of policy and market reforms to support deployment of RE and increase the efficiency of the wholesale market. These include financial incentives for RE deployment and integration, competitive auctions to discover market-reflective prices, the introduction of new electricity trading platforms such as the real-time market (RTM), green day ahead market (GDAM), and expanding the scope and framework for procurement of ancillary services. As a result, India has installed 122 GW of RE capacity with its share in generation rising to 14% (in May 2022), and nearly 12.5 BUs of electricity traded in the national market [91–93].

Notwithstanding the range of reforms, India must overcome several challenges to integrate the rising share of renewables with the grid and realise its Net Zero vision, as discussed below.

Current and future challenges

We list key challenges for India's power markets here.

Gaps in mechanisms to ensure adequate resources availability to meet energy and peak demand. These include variations in methods employed by states to forecast load and an insufficient accounting of supply and demand-side resources, which in turn is linked to the limited institutional capacity. As a result, India had an estimated surplus capacity of 35 GW in 2020 [94].

Inefficiencies in procurement, sharing, scheduling and dispatch of resources. Power distribution companies (discoms) in India rely heavily on bilateral power purchase agreements, many of which have rigid provisions like high take-or-pay levels, strict minimum loading conditions, and lack of termination dates [89]. Inflexible contracts, lack of supply in the market, deviation from merit order dispatch, and limited sharing of surplus resources across states lead to inefficient resource use and burden the discoms with expensive power [95–97]. The systemic cost of these inefficiencies is exorbitant. India could have saved ∼USD 5 billion annually in fixed costs through measures to avoid overcapacity and timely resource sharing [94].

Illiquid wholesale electricity market. During 2021–22, only about 7% of total electricity was procured from the power exchange, despite the latter being in operation for ∼15 years [93]. Legacy PPAs are the primary cause. Additionally, the fragmented market structure is responsible for multiple trading platforms operating in silos (e.g. DAM, GDAM, RTM) [89]. Recently, India split its DAM into a low and high-price segment with pre-defined, and narrow tariff bands. Such a 'diversified' market with low depth presents price volatility risks and restricts cost-effective integration of RE [89, 98].

The poor financial health of public discoms. Most public discoms are stressed with high losses despite many reform packages. In 2020–21, the all-India aggregate loss stood at 21%, around thrice the world average [99]. This is due to high power purchase costs, gaps in tariff design (cross-subsidies, static and non-cost-reflective tariffs), and inefficiencies in energy accounting, billing, and revenue collection [100]. These operational and financial constraints limit discoms' willingness and ability to comply with renewable purchase obligations, facilitate open access or invest in infrastructure and capacity upgrades essential to scale RE.

Absence of a retail market for flexible resources. Cost-effective integration of VRE would require enhanced flexibility, with a significant contribution from demand-side resources. However, limited policy push and discom capacity, along with regulatory, technological, financial and behavioural constraints have hindered the development of a market for flexible resources [101].

Way forward for policy and practice to address challenges

India's electricity system must transform to become efficient, reliable and decarbonised. We discuss key reforms necessary in this pursuit.

First, implementing robust resource adequacy (RA) framework to guide investments in flexible, clean technologies and transmission infrastructure. The Government of India has proposed integrated resource planning guidelines [102]. It must now equip states with simulation tools, expertise, best practices, and institutional coordination mechanisms to help them conduct RA exercises that account for emerging risks and uncertainties. While India has seen limited transmission congestion so far [89], more evidence-based planning and pricing reforms must guide transmission expansion. For instance, stakeholders must review the relevance of continuing transmission charge waiver for renewables, and assess the change in power flows and new congestion hotspots with increasing VRE. A robust generation and transmission planning must precede the wholesale market design reforms (discussed next).

Second, rethinking market design to enhance liquidity and attract investments in essential flexible resources. This requires multiple interventions. One, innovative mechanisms to restructure legacy PPAs and allow economic dispatch of the system while honouring existing contracts and incentivising new entrants. For example, the pilot on Security Constrained Economic Dispatch (SCED) has contributed to higher utilisation of cheaper inter-state coal power plants in India [103]. Two, supporting states for timely resource-sharing, for example, through the proposed national portal for trading surplus power. Three, regulators must focus on consolidating the spot market, devising new short-term trading avenues, evaluating possible capacity market designs and introducing financial derivatives market, while ensuring robust systems for regulation against price volatility [104, 105].

Third, preparing discoms for a clean energy future—financially sound, efficient and dynamic. Indian government's Revamped Distribution Sector Scheme is at aimed at supporting discoms' financial turnaround through investments in advanced metering infrastructure and robust energy accounting and management. A consumer-centric approach to the scheme's roll-out, and strengthening discoms' capacity to leverage this infrastructure would be crucial to ensure the scheme's success [106]. In parallel, states must reform the governance structure to decouple the sector from politics and embed a culture of change such that discoms can respond to the changing demand-supply context. Finally, regulators and discoms must collaborate to unlock the power of grid-edge innovations (e.g. distributed solar, battery storage, smart meters and sensors) through pilots, smart tariff design, and regulatory innovation to enable new business models [107]. This would be fundamental to establishing retail electricity market essential for cost-effective management of demand-supply variations.

Concluding remarks

In pursuit of its Net Zero Goals, India needs to chart a unique journey of decarbonising an expanding electricity system, which is already the world's third largest. Success of this transition would rest on India's ability to pivot its power market to serve a renewed purpose albeit within enhanced system constraints.

A systemic approach would be essential to integrate an increasing share of VRE in an expanding and modernising grid. This would require parallel efforts to develop resource adequacy plans at national and sub-national levels to inform generation and transmission planning, redesigning of wholesale markets, creation of new markets for distributed and flexible resources, and importantly, a revamp of the distribution sector.

Many progressive steps are underway, but much more is needed. Here, it is important to highlight that electricity is a concurrent subject under the Indian Constitution, implying shared roles and responsibilities of central and state governments in the sector's governance. Thus, centre-state alignment through periodic dialogue on seminal policies and regulations would be the key to India's sustained progress towards a Net Zero power sector. For this, policy makers must guide the system actors to collaborate, innovate and upgrade to shape a new electricity future.

3.3. Critical minerals and dematerialisation

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Status

Critical minerals (CMs) are integral to renewable technology, electric vehicles (EVs), hydrogen, and digitalisation. They are poised to play a crucial role in achieving net zero by 2070. CMs include lithium, copper, nickel, cobalt, rare earth elements, silicon, and many other materials. India's CMs supply chains are inadequate to meet the ambitious solar, hydrogen, wind, and battery energy storage goals.

With energy independence within the ambit of the Government of India (GoI) and various reports discussing energy independence or net-zero transition by 2050 [108, 109], the installed capacity of solar and wind is expected to be around 3076 GW [110] and 500 GW [111], respectively. Every megawatt of installed solar capacity requires 7 tonnes of silicon, 7 tonnes of copper, and 14.4–37.4 kg of silver [112, 113]. Likewise, onshore (offshore) wind requires nickel, copper, and rare earth. Corresponding figures are ∼10.5 (49.5), 1.74 (381), and (0.640) tonnes/MW, respectively [111].

India's transport sector contributes nearly 14% of the total GHG emissions. The transition to battery powered EVs will reduce these emissions significantly. A 60 kWh nickel-manganese cobalt (NMC622) car battery requires 6 kg of lithium, 11 kg of cobalt, 32 kg of nickel, 10 kg of manganese, 50 kg of graphite, and 19 kg of copper [114].

India plans to produce 5 million tonnes of green hydrogen (GH2) by 2030, and it is projected to increase approximately 5–6 times, reaching 28 million tonnes by 2050 [115]. A polymer electrolyte membrane electrolyser requires 0.3 kg MW^{-1} of platinum, 0.7 kg MW^{-1} of iridium, and 500 kg MW^{-1} of titanium [116]. It is very clear from these estimates that, going forward, the demand for CMs will grow exponentially to meet net-zero goals. The critical material required in each sector is expected to change based on the technology upgrade or advancement with time.

The Ministry of Mines, GoI, has identified 30 CMs, out of which lithium, cobalt, nickel, vanadium, niobium, germanium, rhenium, beryllium, tantalum, and strontium have 100% import dependency [117]. Rare earth elements have 100% import dependency, and 94% of the global supply of heavy rare earth elements is controlled by China, which is essential for permanent magnets used in EVs. Solar photovoltaics (PV) requires CMs such as silicon, silver, indium, arsenic, gallium, tellurium, and germanium, none of which are domestically produced. Solar PV is expected to play a crucial role in decarbonisation, but domestic production has been impacted because of high production costs, lack of supportive policies, access to low-cost finance, and low-priced exports.

Curbing import dependency, managing supply chain management, finding suitable substitutes, and adopting a circular economy will be crucial going ahead. Figure 5 depicts circular economy adoption in the life cycle of minerals for enabling the transition.

Current and future challenges

In the ongoing clean energy transition, India is facing the following challenges:

(1) **Supply and import dependency risk:** insufficient CM reserves to meet domestic demand and import dependency on countries such as South Africa, Congo, and China are escalating the supply risk for India [118].
(2) **Cost risk**: higher inflation is being driven by the overwhelming demand for CMs, and the near monopoly of China and some Western countries regarding CM reserves is creating a higher cost risk for India. The dollar denomination in international trade practices is further accelerating the prices of CMs.
(3) **Environmental risk:** formal means of recycling have limited applicability for some CMs, and certain CMs are not adaptable to recycling, resulting in garbage accumulation instead of fostering reusability for future demand. Electronic consumer goods recycling by the informal sector is a perfect example of an environmental threat.
(4) **Controlled supply risk:** china is investing in overseas cobalt and lithium mines, which can create controlled supply risk [119, 120]. In 2019, 70% of the global cobalt demand was met by Democratic Republic of Congo, a majority of which was supplied to China—a leading

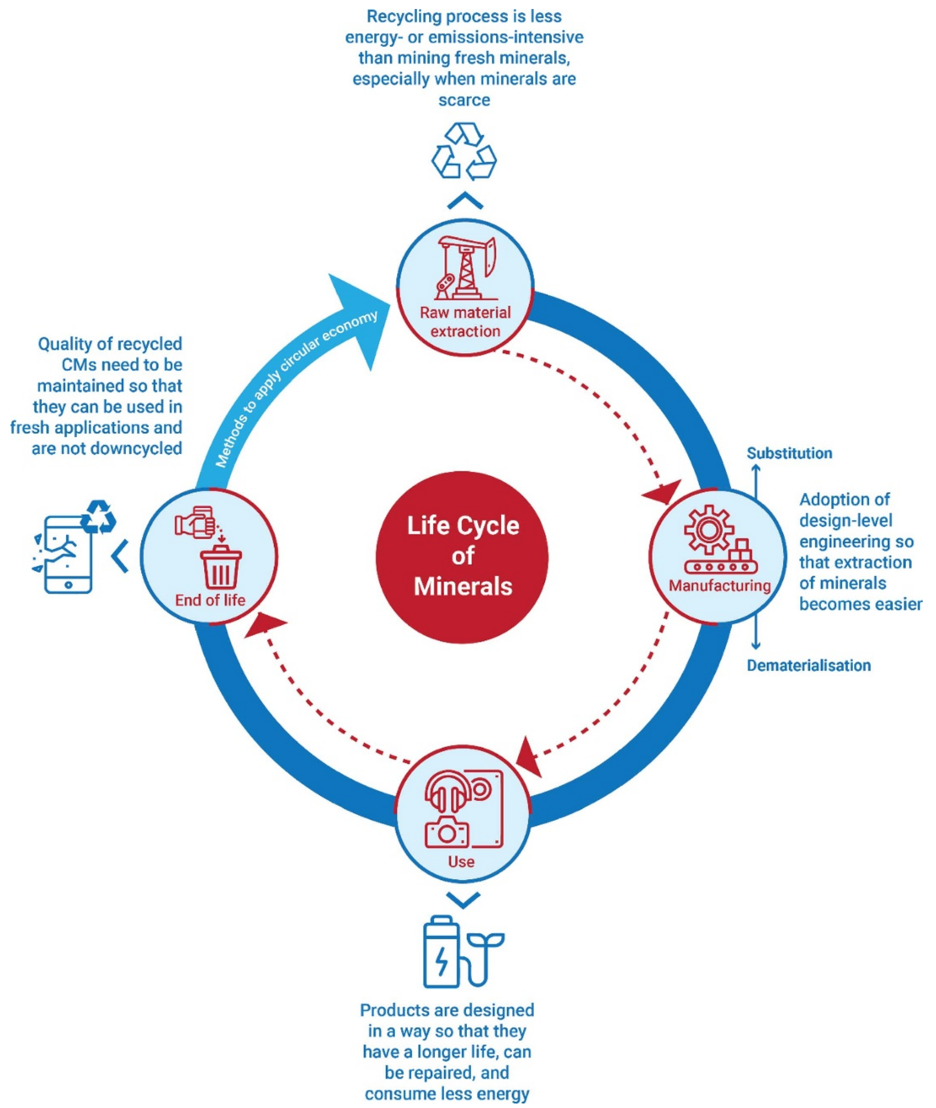

Figure 5. Application of circular economy at each stage of the mineral life cycle. Dematerialisation or substitution is applied at the initial stage.

importer of mined cobalt and exporter of processed cobalt [121]. This will lead to near monopoly or duopoly in the supply of CMs.

(5) **Limited data availability:** limited availability of literature that discusses the demand projections of CMs in different renewable, clean energy, and energy storage sectors in the Indian context.

(6) **Geophysical and geochemical mapping:** India lacks detailed geophysical and geochemical mapping [121] for a more accurate classification of resources and reserves. As per the Ministry of Mines, GoI, only 4% of the total land mass has been assessed through geochemical surveys sand less than 40% of the total land mass has been evaluated through geophysical surveys [122].

(7) **Low recycling and substitution rate:** India's low recycling and substitution rates lead to resource scarcity risk. Currently, recycling in India is mainly handled by informal sectors and unskilled labour, and they use energy-intensive recycling methods. India lacks significant recycling capacity for CMs, except for copper, iron, and aluminium [123].

(8) **Technology innovation and research and development (R&D) initiative:** there is a lack of technology advancement and domestic R&D initiatives for exploring terrestrial (green-zoned) CM reserves.

India must overcome various challenges for a sustainable and resilient supply of CMs. As per the International Energy Agency, CM prices are skyrocketing because the current and planned production of CMs is insufficient to meet the demand for lithium and other CRMs.

Way forward for policy and practice to address challenges

Science and technology will be crucial in making India self-reliant on CMs and finding suitable substitutes for some CMs used in green technology. Indigenous R&D is one such area that requires further push and increase the rate of reuse and recycling as evident from EU practices [124]. Rare earth elements (REE) processing through Japan is an instance where India collaborated with Japan to meet its permanent magnet need despite being resource sufficient in monazite ore [122]. It is not only creating an extra cost burden but is also time-consuming.

In the coming years, the following technology/policy options have the potential for significant advancements:

- India's participation in CMs mapping initiatives (CMMI) [121] and CMs mapping initiatives will aid in locating new reserves and enhancing our comprehension of existing and potential mineral reserves. The transition towards a circular economy, encompassing raw material extraction to end-of-life product management, will prove useful in mitigating supply risk associated with CMs. Additionally, finding a suitable substitute for CMs will also be helpful.
- Investment in overseas mines and domestic currency denominated international trade participation will subside cost associated risk of CMs at greater extent.
- Adopting urban mining [125] will help recycling of CMs from the electronic waste of urban landfills, scrapyards, and dump yards
- Recycling critical minerals can help address supply challenges and reduce environmental impacts. Policies can be crucial in addressing the rapid increase in waste volumes by incentivizing the recycling of end-of-life products, supporting efficient collection and sorting activities, and funding research and development for new recycling technologies.
- To form Organization of Petroleum Exporting Countries (OPEC) like organization or to be the part of such organization will help India as well entire globe of smooth supply of CMs.
- Encouraging educational research activities in premier institutes and think tanks will lead to the creation of a larger database, which could help in sustainably managing the supply of critical minerals.
- Design-level engineering of products for sustainable application of circular economy will enhance the recycling rate at a lower cost. Further investment in R&D will help in identifying suitable substitutes for CMs.
- Technology transfer, academic collaboration, and a skilled workforce will aid R&D infrastructure.
- A technology assessment framework can also be used for deciding the best-suited technology to achieve net-zero goals in different sectors [126].
- Quadrilateral Security Dialogues (QUAD) and Indo-Pacific Economic Framework (IPEF) is an existing GoI initiative for meeting CRM needs while a strategic alliance with Central Asian neighbours e.g. Kazakhstan, Uzbekistan etc., will give extra leverage in minimizing the import risk.

Reducing the import duty is another area where the GoI can support domestic healthcare manufacturers. CMs used in medicine, EVs, and renewable energy technology could be on the 'no import duty' list. The Production Linked Incentive Scheme [127, 128] is another good initiative by the GoI in the battery and renewable sectors.

Concluding remarks

The sustainable use of CMs will decide countries' success in cutting down carbon emissions to net zero. India has a lesser share of the total CM reserves in the world but is a mega contributor of carbon emissions followed by United States and China. India can achieve its net-zero targets by dematerialisation and the adoption of a circular economy. The supply risk of CMs will be a bigger threat in mission net zero. Ongoing R&D in the areas of solar, EVs, hydrogen, and wind technology will further reduce the use of CMs and make India self-reliant. India can critically benefit from investing in areas such as plastic electronics and PVs, magnesium-based batteries, and solid-state refrigeration.

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3.4. Carbon Dioxide Removal (CDR)

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Status

The IPCC Sixth Assessment Report indicates near-essential deployment of CDR technologies if global temperatures are to be constrained to 1.5 °C by 2100 [129]. This consensus around CDR has developed since the mid-2010s, as modelling has demonstrated that emission reductions alone will not be adequate in reaching the Paris Agreement goals. For instance, under 1.5 °C scenarios without overshoot, the scale of engineered CDR deployment is projected to be 2.5–7.5 Gt-CO_2/year globally in 2050 [129]. Even as CDR technologies are anticipated to be a key component of net-zero economies, their required scale is dependent on the rate of emission reductions in the near-term.

Several CDR platforms are reliant on nature-based solutions, such as afforestation/reforestation and biochar sequestration. Others are heavily engineered and include direct air capture (DAC) of CO_2 [130]. Finally, bioenergy with CO_2 capture and storage (BECCS) and enhanced weathering (EW) are hybrid platforms which fuse engineering and nature-based solutions to produce negative emissions and value-added products.

India's historic cumulative GHG emissions have been low, and as such, equity-based analyses of global CDR requirements show low uptake of these approaches here. For instance, one study estimates that cumulative CDR allocation to India based on share of cumulative emissions through 2100 would be less than 1 Gt-CO_2, while they may increase to >100 Gt-CO_2 under pathways solely focus on cost minimization [131]. The Government of India has indicated that CDR may be a part of the decarbonization portfolio in its recent long-term low-carbon development strategy [132].

To our knowledge, there has been no unified assessment of CDR in India. But estimates have been published for different technologies (table 1). For instance, the government's Paris INDC itself commits to creation of forest cover that would sequester 2.5–3.0 Gt-CO_2 by 2030—to this end, over $27 million was invested in 2022–2023 financial year [133]. There is a similarly large potential for biochar utilization as existing crop residues may be converted to sequester >200 Mt-CO_2 annually [134]. Coupling BECCS with enhanced oil recovery can remove CO_2 at $20–40/t-$CO_2$ in western India [135]. India also has large basalt deposits, where EW may be viable. Because of the large costs, DAC has not been considered in the Indian context, although upcoming indigenously developed technologies such as those with UrjanovaC may offer scalability and low-cost [136].

Current and future challenges

CDR approaches are impeded by a variety of technological, economic and regulatory challenges. Engineering-heavy technologies are currently expensive, with cost of avoidance being well above $100/t-$CO_2$ without additional co-product revenue or government support [130]. Nature-based solutions such as afforestation/reforestation and biochar are generally cheaper. However, the accounting of carbon fluxes in these cases is often more challenging and their permanency uncertain.

Potential assessments on CDR deployment generally are emphasize the role of BECCS and DAC, which are technologies that require low-cost geologic CO_2 storage. Various estimates pit the geologic storage potential of CO_2 in India at 100–614 Gt-CO_2 [141–143]. However, these estimates have been published with limited data availability. In India, subsurface characterization of aquifers has largely been done at shallower depths with the interest of exploring groundwater reserves for human use. However, aquifers suitable for CO_2 storage are generally at depths of 1000–3000 m, where there has been little-to-no characterization. This may be framed as the most critical challenge to CDR in India [144]. Capturing CO_2 from flue gas is also an expensive process with costs of avoidance of $50–80/t-$CO_2$ from most point sources in India [145]. These costs have inhibited CO_2 capture across the world, with most existing CCS facilities globally being limited to capturing high-purity CO_2 sources (e.g. ethanol fermentation) [146]. Recent progress on CCS in Indian context includes initiation of project for CO_2 capture at a coal-fired power plant and its reaction with green hydrogen to produce methanol. For translating this progress into CDR, such capture must be initiated where biomass is co-fired. That said, co-firing biomass is more expensive and less efficient than coal, which requires more sophisticated technologies such as gasification that are at a lower technological readiness level in India, as compared to combustion [139].

Nature-based solutions, while less costly, have challenges pertaining to carbon accounting. Emissions inventory in the agricultural and land use, land-use change and forestry (LULUCF) sector as per

Table 1. State-of-the-art for CDR in India (Indicated TRLs are country-specific).

Technology	Country-specific status	Key states/regions	Costs	References
Afforestation/ reforestation	High: TRL-9. Government of India intends to sequester 2.5–3.0 Gt-CO_2 and has allocated $27 million last year in this area.	Rajasthan, Madhya Pradesh, Karnataka, Andhra Pradesh, Odisha, West Bengal	$4–25/t-$CO_2$	[137]
Biochar sequestration	Medium: TRL 3–6. Detailed estimates and protocols published. Lab analyses carried out.	Uttar Pradesh, West Bengal, Bihar, Chhattisgarh, Andhra Pradesh, North Eastern States	$20–50/t-$CO_2$	[138]
Enhanced weathering	Moderate: TRL 3. Lab characterization carried out.	Andhra Pradesh, Maharashtra, Jharkhand, Bihar	$80–180/t-$CO_2$	[139]
BECCS	Low: TRL 3. Proof-of-concept analysis carried out.	Gujarat	$200–250/t-$CO_2$ (without EOR), $20–40/t-$CO_2$ (with EOR; but may undercut carbon removal)	[135, 140]
DAC	Very Low: TRL 1	—	$225–600/t-$CO_2$	[139]

India's existing institutional arrangements is carried out using Tier-1/2 methodology [144]. This induces a much higher uncertainty than most energy-related activities. If CDR is adopted at a large scale, this could fail to appropriately incentivize carbon removal unless site-specific emission factors are developed. This is particularly true because these forms of CDR approaches are temporary. For example, only about 50% of the gross carbon sequestered in Indian shrublands is anticipated to be retained over a 200 year period [146].

Way forward for policy and practice to address challenges

Indian technology developments have largely focused on CO_2 utilization based on the existing government policy directives. CO_2 capture technologies—both for point sources and DAC—are at a less advanced stage than global counterparts [139]. India is a participant in the Mission Innovation program, wherein a number of countries are collaborating for technology development. This creates a mechanism for enabling technology transfer for CO_2 capture that can also propel the scale-up of CDR in India.

As discussed earlier, BECCS and DAC at scale may not be established without detailed characterization of geologic formations. Thus, funding provision is needed for effective assessment of sink availability. Here, targeting data collection in eastern India may be most viable due to close proximity of coal, shale and basalt formations, while that in the western India may be favoured by the occurrence of depleting oil and gas fields and saline aquifers. Drilling new study boreholes will be required to collect adequate information for a robust geologic inventory. The quantum of funding for such activities may be matched with funds like the Global Environment Fund (GEF). It is notable that past developments in the coalbed methane industry in this region were greatly accelerated through the GEF [147].

As technologies reach higher readiness (TRL 7–9), funding would need to be diversified to the Global Climate Fund and other sources such as low-cost financing from MDBs. MDBs provided $81 billion globally in climate funding in 2021–22, and this may facilitate commercial stage deployment [145]. The Asian Development Bank also has demarcated CCUS funds where only select countries, including India, could be eligible to receive finances. As green finance develops, sustainability-linked loans are anticipated to receive more traction which would be linked to the environmental, social and corporate governance metrics of individual companies. As such, improving the quality of such disclosures for Indian companies relevant to CDR development is necessary.

Finally, measurement, reporting and verification (MRV) protocols need to be developed in the next five years to reduce uncertainty in net carbon sequestration. This is particularly true for afforestation/reforestation where an improved focus on carbon dynamics via remote sensing and *in situ* methods is necessary [148]. At the same time, there is a need for developing more transparent and accessible methods for maintaining spatial and temporal carbon dynamics for long-term MRV in this domain.

Concluding remarks

Discussions around CDR in India are at an early stage, and their development will take a separate course as compared to developed economies. Specifically, there may be a greater focus on bio-based technologies, where protocols are necessary to account for carbon dynamics. For more engineered technologies, pilot data availability is critical before commercial scale development could be undertaken. Funding availability and technology transfer need to be catalysed for India to develop CDR in the next 5–10 years. There is an opportunity to pursue CDR development in India such that is accompanied by several co-benefits such as employment, ecological conservation and economic growth. In terms of co-benefits, both biochar and EW can improve soil health and agricultural productivity, while afforestation could potentially aid in flood management and soil conservation. BECCS can help with farm employment. Some configurations of DAC can be carried out with water harvesting. Similarly, BECCS conversion processes can improve management of waste biomass feedstock. Ultimately, the choice of CDRs is likely to depend several regionally differentiated factors such as costs, resources, and socio-political acceptability.

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3.5. Land use, land use change, and forests

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Current status

In the year 2016 about 15% of the national CO_2 emissions were sequestered by the Land Use, Land Use Change and Forest (LULUCF) sector. Old growth and new forests, trees outside forests (ToFs), and agricultural soils contributed to much of the sink in the sector [80]. At the twenty sixth conference of parties (COP26) of the United Nations Framework Convention on Climate Change (UNFCCC) in Glasgow India committed to Net Zero (NZ) goal for the year 2070. A review of quantitative national studies ($N = 34$) on long-term emission pathways captures the uncertainties associated with India's NZ goal [6]. The review finds that despite best efforts, and most favourable assumptions, still a large emission gap ($\sim$2 $GtCO_2$ yr^{-1} in 2050) would remain. Future state of LULUCF sink/source would thus substantially affect this emission gap, underpinning LULUCF sink's critical role in India's NZ strategy.

Figure 6 outlines the universe of possible LULUCF sector mitigation strategies[31]. Most important mitigation strategies are highlighted below. Indian forests currently hold about 30 billion tonnes of CO_2 [149], thus **conservation of existing forests**, ecosystem functions and biodiversity that maintain their carbon stock, remain the singular most valuable strategy towards long-term sustainability of forest sinks in India. Amidst these existing forests, reside some of the hottest hotspots of biodiversity on this planet. Second most important strategy is the **restoration of impaired (degraded) forests. Forest and tree cover expansion along roads, railways, water bodies, wastelands, grasslands, and settlements**, in an environmentally sustainable and socially just way constitutes the third most important strategy. Detailed analysis of the second and third strategies are available in FSI (2019) [149]. Expansion of ToFs/agro-forestry on croplands, along with **soil carbon enhancement in croplands is considered to be the fourth most important strategy** [150, 151]. Here we argue that ToFs on croplands should be viewed as an opportunity to restore degraded and marginal croplands, contributing to land fertility and farmer's well-being.

Despite high population density India has generally done well in forest conservation space since 1980s, still some level of deforestation and forest degradation continues in specific parts of the country including in some of the biodiversity hotspots [152]. Many of the LULUCF sector mitigation strategies listed above have received strong policy support in India. Examples include, India's Long-term Low Emission Development Strategies (LT-LEDS) [75], forest and tree cover related goals in India's Nationally Determined Contributions, and the Bonn Challenge. Additional policy push is required for easing out constraints on implementation, especially access to finance, for scaling up the restoration projects.

Current and future challenges

For each of the four mitigation strategies, the key challenges along their timeline of project life cycle are listed here (figure 7).

At the planning stage one of the key challenges is identification of priority areas for mitigation actions [151, 153]. Fleischman *et al* [154] added social dimension to the land based mitigation debate, and argued that land use priorities should not be decided by the top–down approach rather such priorities should arise as result of a dialogue and negotiation among different stakeholders. Land-based projects often have multiple stakeholders with varied and many a times contrasting interests. Reconciling the interests of different stakeholders while safeguarding the interest of the most vulnerable entities is a challenge [154].

Implementation of mitigation action on the ground faces a multitude of problems, especially as these projects interact strongly with communities and their livelihoods. Lack of guidelines/protocols for selection of areas and practices for restoration, availability and access to 'mitigation technologies and protocols', availability and access to specialised nurseries, and the availability and policy mainstreaming of verification mechanisms for mitigation projects constitute key challenges at this stage. Land-based projects are often cost-intensive, in some cases wasteful expenditure has been highlighted as a concern [155], in others especially for scaling up of restoration projects, lack of funds is identified as a key bottleneck [156].

While mitigation actions are planned and implemented with best intentions, how do these actions fare in the long run and interact with the environment and society across scales, is an important research challenge in context of India's NZ transition in the LULUCF sector. India is experiencing developmental transformations, along with rising incomes and food

[31] From emissions accounting perspective (Good Practice Guidance, 2006 and 2019 amendment) Bioenergy is not accounted as part of the LULUCF sector. It covers emissions from biomass and soil pools of the key landuse categories (figure 6 outlines the universe of possible LULUCF sector mitigation strategies, to drive home this point). As such discussion on Bioenergy is not included in this chapter.

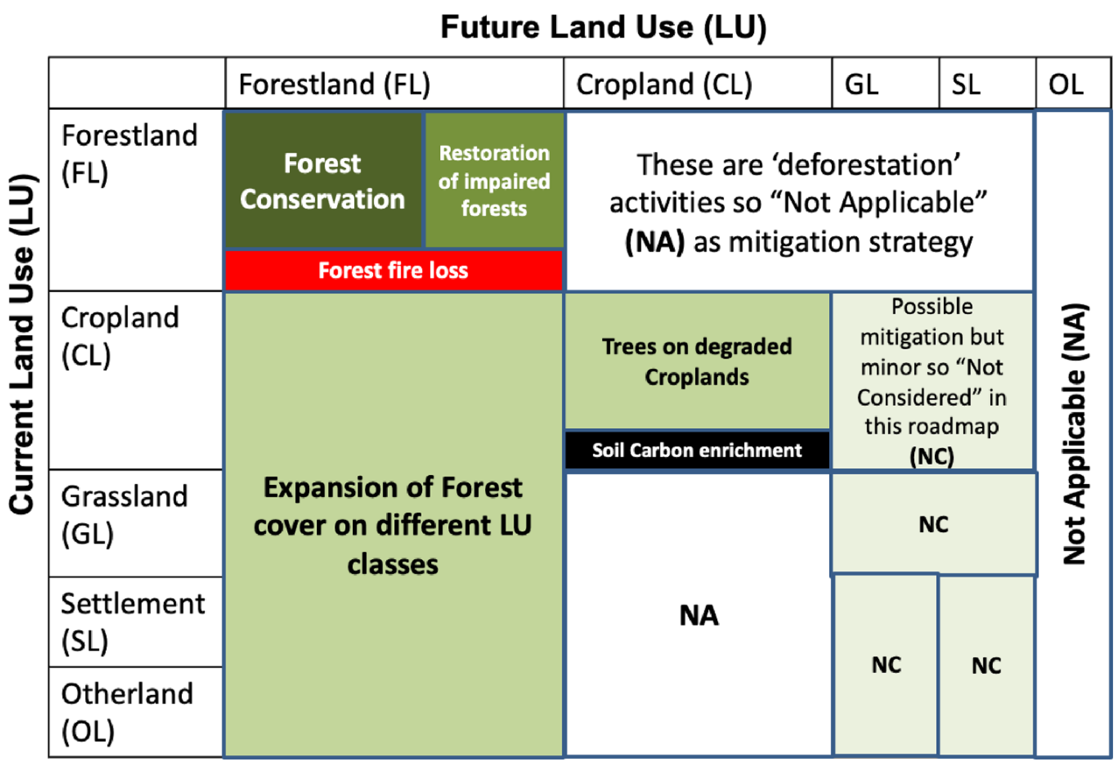

Figure 6. LULUCF change matrix describing possible strategies for carbon storage/ sequestration in the sector *[Note:* This matrix imagines different LU and LU Change (LUC) possibilities from today to 2070, e.g. current FL may remain FL (forest conservation) or it may change to CL, SL etc (deforestation).

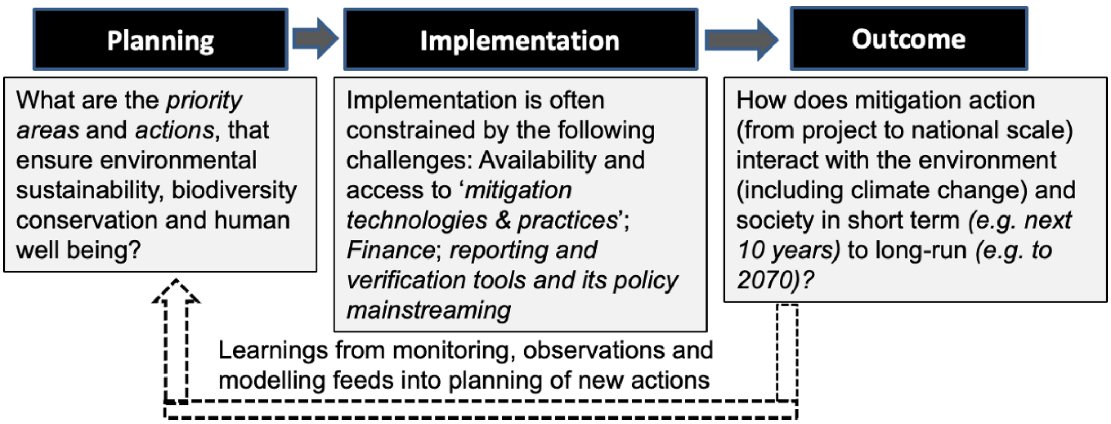

Figure 7. Key challenges for mitigation actions in the LULUCF sector.

demands. Concurrent to these developmental transformations as India plans large scale expansion and restoration of forests and tree cover, it is important to understand the implication of these transformative developmental and mitigation actions on carbon sink capacity as well as on social and economic systems, e.g. employment opportunities, import, export, GDP etc [157]. As India plans large scale expansion and restoration of forests and tree cover, it is important to understand the implication of different scenarios of these transformative mitigation actions on social and economic systems, e.g. employment opportunities, import, export, GDP etc [157]. Further, it is also important to understand how these large scale changes interact with the elements of climate systems and water cycle. Long-term impacts of mitigation actions can be assessed with a combination of systematic observations, and integrated modelling. Historically India has limited number of Long-Term Ecological Observations (LTEOs), covering limited number of ecosystems and LU types. Additionally, there is limited capacity on integrated long-term LU sector modelling in India.

Climate change presents an additional challenge in the form of exposure of forests and tree cover to warmer temperatures and erratic rainfall regimes

[158], increased forest fire risk [80] and other climatic extremes.

Way forward for policy and practice to address challenges

Priority area identification for mitigation action in the LULUCF sector requires access to reliable, scalable and up-to-date land use and land cover (LULC) datasets. Open source (accessible) LULC maps are available for some of the geographies [159, 160]. There is a need to develop open source LULC maps for India with the active participation from the members of the local communities and citizen scientists. Long-term sustainability of carbon sinks are interlinked with biodiversity, its ecosystem services and human well-being [153, 161]. Up-to-date open source LULUC maps with environmental descriptors are also useful for scanning any possible detrimental effect of the project on existing land cover, its ecosystem services and biodiversity. Such maps are also useful in monitoring and verification of mitigation actions [160].

Restoration ecology across the diversity of Indian ecosystems is not very well understood, and there is a dearth of such studies. There is therefore a need to institute studies across different ecosystems to generate knowledge and evidence. More importantly, there is a need to integrate knowledge from existing studies (e.g [162, 163].) into relevant implementation protocols. Further, it is important to ensure that quality seedlings/ saplings are available for restoration and afforestation through provisioning of nurseries, equipment, and training on the ground.

Forest conservation is an area where policy support is particularly helpful. Policy initiatives such as increase in protected areas (PAs), identification and demarcation of ecologically sensitive areas (ESAs) would go a long-way in halting, slowing and reversing losses from deforestation and forest degradation. Redlisting of Indian ecosystems could be an useful policy tool in prioritizing conservation actions [164].

In India LTEO sites are being increased in recent years, however we need to scale up LTEOs by an order of magnitude, covering diversity of LUs, ecosystems and carbon pools. Long-term near-surface remote sensing based observations of natural ecosystems [165] and Farm-scale monitoring initiatives such as Soil Health Card (SHC) scheme needs to be sustained in long-term and strengthened with finance and policy support.

Bridging the capacity deficit on integrated LU sector modelling in India is key to understanding the implications and interactions of the LU sector mitigation actions with society and environment in long-term.

Further, under a warming climate, adaptation actions such as development and deployment of early warning systems (EWS), and integration of other climate change adaptation strategies in forest working plans at local scale should be prioritized to ensure long-term sustainability of forest carbon sinks.

Concluding remarks

Long-term emission pathways (up to 2050) for India suggest that despite best efforts, and most favourable assumptions, still a substantial emission gap would remain. Future development of LULUCF sink would substantially affect this emission gap. Forest conservation, restoration of impaired forests, expansion of forests and trees, and agro-forestry, are proposed as the four key mitigation strategies, to help meet India's NZ goal. Key challenges for each of these mitigation strategies include identification of priority areas, access to mitigation technologies and protocols, verification of mitigation actions, understanding the long-term interaction of mitigation actions with society and environment, and lastly the emerging challenge of climate change. We propose the following science and technological advances to meet these challenges: Participatory open source LULC maps, Restoration ecology studies across different ecosystems, scaling up of LTEOs, near surface remote sensing monitoring of ecosystems, and building national capacity in integrated Long-term modelling. Whereas, the suggested policy advances include: easing out constraints on access to finance, provisioning of nurseries, equipment and training on ground-zero of implementation, Redlisting of ecosystems, expansion of PAs, identification and demarcation of ESAs, and integration of climate change adaptation strategies in forest working plans.

Acknowledgments

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4. Enablers

4.1. Climate institutions

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Advances in the comparative politics literature over a decade suggest that climate ambition and implementation are significantly shaped by domestic political economy variables, including institutional structures established for regulating carbon emissions [166–170]. These climate institutions are shaped by a variety of forces, including national and subnational political institutions, interactions with the international system (such as exigencies arising from climate negotiations), and bureaucratic patterns and practices [169]. In this piece, the term 'climate institutions' refers to rules, norms, routines, and organisational structures that directly and intentionally affect climate outcomes, as well as those that have incidental effects on climate outcomes, and over time are more explicitly considered to be relevant to climate action [171].

Historically, in India, the institutional structure has frequently changed form. Institutions built specifically for climate governance were first established in 2007, beginning with the Prime Minister's Council on Climate Change (PMCCC) to create a National Action Plan on Climate Change (NAPCC) ahead of the 15th Conference of Parties (COP) at Copenhagen in 2009. The NAPCC was detailed through eight sectoral 'missions' (in areas as varied as solar energy and maintaining Himalayan ecosystems), and led to the creation of climate units in several national ministries. It established an incipient implementation coordination structure in the PM's Special Envoy for Climate Change, which was replaced by an Executive Committee on Climate Change (ECCC, a body of senior bureaucrats established 2013) headed by the chief bureaucrat in the Prime Minister's Office (PMO). The coordination of climate policy falls within the jurisdiction of the environment ministry under the country's Allocation of Business Rules [172], but has frequently been assumed by the PMO to solve inter-ministerial coordination problems. Most institutions have, however, not endured; the PM's Special Envoy was discontinued in 2010, the ECCC met a relatively meagre six times between 2013 and 2019, and the PMCCC met only once in that period [171]. Through the 2010s, several Indian states also established their own policy frameworks through State Action Plans on Climate Change (SAPCCs), which are varied in scope and multi-sectoral in nature.

A growing body of comparative literature on climate institutions points to a diversity of institutional forms across countries, with the implication that institutions should suit national context [169, 173, 174]. Further evidence is needed on the conditions under which robust, effective institutions grow, and whether these conditions can be replicated across countries as decarbonization becomes more urgent.

Climate institutions should be capable of addressing governance tasks that are all simultaneously present in addressing the climate crisis: they must be able to define analytically robust national strategic pathways; coordinate across ministries and vertically among subnational governments; and build consensus among stakeholders on these pathways [175].

Current and future challenges

Here, we analyse how India has performed in building climate institutions, and the main challenges associated with them.

Strategy: India's core strategic institution, the PMCCC, has been inactive in recent years, even as climate policies have grown in number and ambition. For example, by 2018, six years after the PMCCC had ceased to meet regularly, 25 of India's 35 listed mitigation actions were being implemented beyond the remit of the national climate plan and the PMCCC [171]. As India commits to more ambitious targets such as net-zero by 2070, and as Indian states craft their own climate actions in diverse areas, the absence of a climate-specific strategic institution could reveal two vulnerabilities: an inability to coordinate multiple divergent policy pathways towards economy-wide goals; and the absence of in-government capacity to weigh and choose between multiple policy pathways and technological choices.

Coordination: The Ministry of Environment, Forest and Climate Change (MoEFCC) is tasked with coordinating climate action, but past evidence suggests it faces challenges in mobilising the bureaucratic authority to shape policies and implementation across government ministries [171]. In the build up to COP 26 at Glasgow, the MoEFCC established the Apex Committee for the Implementation of the Paris Agreement (AIPA), comprised of senior bureaucrats across ministries, to coordinate the delivery of India's NDCs. Further research is needed to establish how effective this body has been.

Consensus building: In the absence of active government-wide climate institutions, consultations with stakeholders occur within sectoral frameworks. Close coordination is reported in areas of high policy activity such as solar energy, electric vehicles, and energy efficiency [171]. Future challenges like consensus-building around the national carbon market might, however, require more institutionalised structures to mediate political fault lines all suggest the need for federal institutional mechanisms to build a stable long-term policy consensus.

Finally, dynamics between national and state governments in climate policy have evolved in recent years. India's top-heavy federal structure—i.e. where fiscal and agenda-setting powers vest more in the national government than more classical forms of federalism [176]—calls for close cooperation between national and state governments. This seems to be emergent with the national government setting policy frameworks (such as the NAPCC), establishing new fiscal instruments, and filling gaps in bureaucratic capacity for the states, while the states use these resources to experiment with new policies and create examples for national emulation. Yet, there are limitations to experimentation due to capacity and finance constraints [176].

Way forward for policy and practice to address challenges

Countries tend to respond differently to various governance tasks [177–179], and change their responses over time based on changes in the underlying political economy. India will therefore have to build a bespoke institutional structure that is responsive to current lacunae but evolves with the context. Like most developing countries starting from a low base of emissions, India's challenge of planning a low-carbon development pathway rather than rapidly decarbonizing places an emphasis on robust decision-making processes to foresee and avoid future emissions. This suggests the need for an institutional model that is different from net-zero regulatory frameworks used in countries that are past their emissions peak. What form should an institutional structure for low-carbon development take?

One plausible approach would combine institutions that: supply credible policy information; create procedural requirements for national and state governments; and establish coordination structures that work together work to facilitate low-carbon policies and technologies. Together, these factors will shape the nature of India's policy lock-ins.

The creation of an independent analytical body within government to recommend strategic pathways, and evaluate policy and technological options for policymakers has precedent in the UK Climate Change Committee and has been adopted elsewhere [179]. Critically, however, this analysis should focus on low-carbon development pathways rather than mitigation alone. If embedded within a transparent operating culture, a similar institution in India could also serve deliberative functions and build consensus among stakeholders, similar to the role played by Brazil's Climate Change Forum [180].

Strategy implementation would require a system of interlocking procedural requirements that establish transparency, and—responding to India's federal structure—alignment between subnational, national and international objectives. This could take the form of mandated reporting requirements from national ministries and state governments to legislatures, and updates to the national legislature from the independent analytical body described above [180, 181].

Implementation would also require revamped coordination mechanisms, such as statutory backing for the ECCC and a mandated meeting schedule, and the continued existence of the AIPA to coordinate international positioning and reporting requirements. Federal coordination might be partially achieved through periodic, mandated updates of the SAPCCs (with due consideration of changing national targets), and new consultation mechanisms [180, 181].

Finally, these institutional innovations might require an anchor in law to promote institutional robustness, which has otherwise been lacking in Indian climate governance. However, again by contrast with past global precedent, any law should be tailored to Indian requirements and foreground mainstreaming climate concerns into adaptation and mitigation [182].

Concluding remarks

The institutional approach laid out here stands apart from compliance-based regulatory systems built around net-zero goals in developed economies. Developing country contexts must contend with the twin challenges of reducing their emissions peak and bringing it forward in time even while meeting development needs, and then creating the institutional conditions for rapid decarbonisation thereafter. This places an emphasis on pathways rather than targets, and procedural requirements that allow the transparent flow of policy information through the system.

Of particular importance is the political sustainability of the institutional framework. Global evidence suggests that institutions fail when they are incongruent with the underlying political economy [177, 183, 184]. Equally, appropriately structured institutions could generate positive political feedback by empowering the winners of current climate policies, thereby creating conditions for more ambitious institutional frameworks in the future [185]. The correct sequencing of institutions could lead to policy stability, stimulate sustained market environment, and allow for dexterity in managing the long-run distributional consequences on the path to net-zero.

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4.2. The climate finance challenge

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Climate change is one of the biggest threats the world faces. Natural calamities have increased in the last few years, raising the demand for countries to act fast to limit global warming. While affected people need protection, investment needs for climate mitigation are also rising.

The International Energy Agency's (IEA) Roadmap to Net Zero Emissions by 2050 [186] requires annual global clean energy investment to more than triple by 2030 to around US$4 trillion. The IEA's latest 2023 report [187] finds that annual clean energy investments in emerging and developing economies need to more than triple from US$770 billion today to as much as US$2.8 trillion by the early 2030s.

A CEEW study [188] estimates India requires a cumulative investment of US$10.1 trillion to achieve net-zero emissions by 2070. BNEF [189] pegged the investment opportunity to fund India's net-zero by 2050 goal at US$12.7 trillion, representing an average of US$438 billion per year. Out of the total investment, an investment of US$2.1 trillion is for grid expansion with increasing adoption of electric vehicles, electrification of industrial processes, electrolyzers for hydrogen production etc. While there is no comparative analysis for the 2070 horizon for the net-zero and fossil fuel driven BAU scenarios, analysis for the 2050 net-zero horizon shows that higher investment would be needed to met the net-zero scenario compared to the BAU scenario: 37% higher in the 2026–30 period [190] and 35% higher in the 2021–30 period [191]. At the same time, higher investment in renewable energy would lead to a decline in savings due to fossil fuel imports, which could significantly offset the higher investment need. Detailed assessments are needed to compare higher investment needs with cost savings across sectors for the Indian economy.

While India is providing a success story by increasing renewable energy adoption, however there is a big gap in terms of capacity installed and investment versus what is needed to achieve 2030 targets. The chart below (figure 8) illustrates investments in India's clean energy technologies since the Paris Agreement. The majority was in renewable energy, while other technologies also witnessed an increasing trend over the last few years.

Emerging economies need investments for deploying new clean technologies and transition financing for fossil fuel phaseouts. While India has set clean development goals, the transition must be just and equitable.

Public finance can play a big role to help India achieve its net zero target. While renewable energy is under the priority sector lending, the limit needs to be increased. A separate limit to fund clean energy projects can increase the money available with public financing institutions. Also, other public sector non-banking financial corporations (NBFCs) can also play a big role in making investment available for renewable energy infrastructure expansion.

India needs access to domestic and international capital from both public and private sectors. It needs to tap a growing ESG (Environment, Social and Governance) capital pool, green bonds, sustainability-linked bonds etc., in addition to conventional sources like banks and financial institutions. For attracting ESG capital, this will entail taking steps such as adopting green bond frameworks, enhancing credit rating of projects, adopting globally recognized ESG frameworks and principles and creating a robust investor outreach program.

Climate mitigation requires both public and private sector investment. The public sector, along with MDBs and philanthropic capital, can de-risk investments by providing guarantees or concessional capital and unlock private capital, especially for new technologies and fossil fuel phaseouts. New innovative business models and financing mechanisms are needed, especially for nascent technologies like battery storage, offshore wind or green hydrogen.

Further, Infrastructure investment trusts (INVITs) will be useful to recycle capital from one set of investors to the next set (usually more long term risk averse investors).

Current and future challenges

Indian companies have been unable to tap a large part of the capital pool in this decade to achieve their net zero targets, increasing their capital costs. This is due to risks [192] like foreign exchange, inflation, regulatory uncertainty and offtaker or payment risks. The pipeline of green projects is slim due to weak demand for products like green steel. Only a few large companies have set net zero goals, resulting in low demand for clean energy solutions.

Access to long-tenure financing remains a significant challenge for developing India's clean energy ecosystem due to the high upfront cost and long lifecycle. Shallow and illiquid domestic capital markets, especially for debt, restrict long-term investment opportunities. India also needs concessional finance and grants to help fossil fuel phaseouts in states. Its

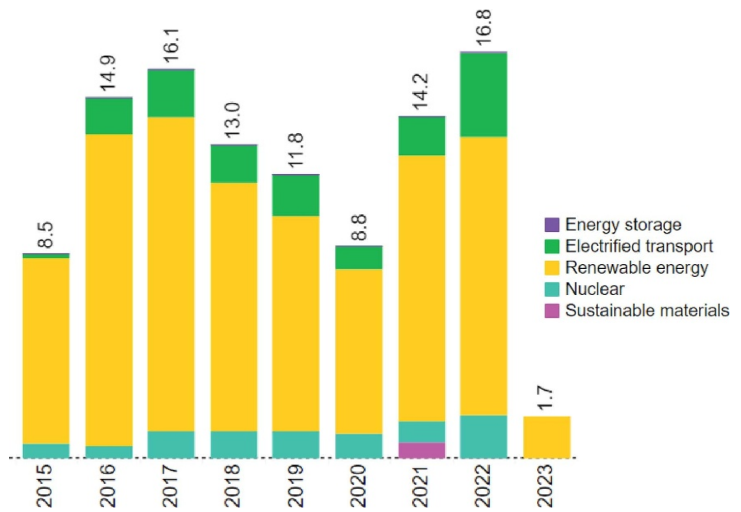

Figure 8. India investment in different energy transition technologies (debt and equity) (US$ billion) *Source*: BNEF. As of May 2023; CCSS since 2018; electrified transport since 2016.

unavailability is delaying the closure of fossil fuel assets.

India can access ESG capital, but the lack of transparent, consistent and comprehensive ESG disclosures [193] and concerns regarding greenwashing restrict long-term debt availability. Further, without a green taxonomy, defining green versus non-green becomes difficult for capital providers.

Asset tagging is not yet mainstream. Without a clear definition, green tagging assets can be misleading. With taxonomies varying in different countries, interoperability is also essential to avoid ambiguity.

There is a shortage of financing for innovative financing ecosystems. While several start-ups are increasingly establishing in India, most will perish in the 'valley of death' without project financing and cash flow assistance.

While large players can raise capital from the market, Micro, Small and Medium Enterprises (MSMEs) need more support to access low-cost capital [194] because of their poor creditworthiness.

Various stakeholders, including banks, financial institutions, regulators, consumers and others, do not fully understand climate risks, climate disclosures, reporting etc., limiting their availability to tap international capital.

Way forward for policy and practice to address challenges

Policy certainty is key to accelerating investment into the renewable energy ecosystem. The government must avoid policy rollbacks that increase project costs or reduce investor returns. It can create demand-side signals through public procurement, demand aggregation and by building a strong pipeline of green projects.

Economic planning in states through budget tagging [195] exercises should be done to mainstream climate finance at the state level. Budgets can provide a self-assessment tool and help identify financing gaps for procuring it from alternative public and private capital sources.

Banks and NBFCs should be required to report on the climate risk on their books through exposure to fossil fuel vs low carbon loans. This will nudge them to diversify their loan books towards low-carbon solutions. Technical assistance in the form of capacity building for appraising climate risks in underwriting and investment practices should be provided.

Given the high risks associated with new technologies, for MSMEs and some sectors like transport and steel, developing blended finance mechanisms that include guarantees, grants, non-interest loan components, concessional loans etc., can unlock private capital. Here government, MDBs, philanthropies, DFIs and commercial capital providers should all come together and provide the risk capital.

For mobilising capital, a few other broader financial sector reforms needed are:

- Clearer definition: By providing a clear, science-based definition, a taxonomy [196] can help classify sustainability in black and white.
- Climate-related disclosures: It is important that banks adopt standard guidelines for measuring and disclosing climate-related risks. Mandating climate-risk disclosure and assessment for its regulated entities can ensure banks within the country diversify their climate risk by providing more financing for low-carbon sectors.
- Widen priority sector lending (PSL) and increase the borrowing limits for clean energy technologies.

Current limit is Rs 30 crores to corporate borrowers. The current PSL bracket for banks for renewable energy should be increased in line with the 2030 target.
- Reserve Bank of India (RBI) should provide prudential regulations by considering renewable energy loan book as statutory liquidity ratio (SLR) compliant, introducing climate capital buyers etc. RBI to designate sustainable bonds from top-rated issuers in the country eligible for SLR [197], which will help channel capital into low-carbon activities. Allow using green debt, like sovereign green bonds, as collateral for borrowing from the central bank.
- Relax external commercial borrowings limits, including for clean energy companies, to raise loans from non-resident entities.
- Allow innovative use of foreign exchange reserves to mobilise foreign investment into clean energy infrastructure. Several central banks have started incorporating climate risk into their foreign exchange reserve management. RBI can use a small portion of the foreign exchange reserve to mobilise foreign investment into clean energy infrastructure, using capital from forex reserves to provide risk mitigation facilities, such as subsidies for currency hedging costs and providing credit guarantees to clean energy borrowers.

Lastly, a robust market for carbon credit trading through a compliance market and framework for trading through the voluntary market can help generate revenues for the projects, improving project viability and increasing capital flow to clean energy projects.

Concluding remarks

India needs to scale up climate finance massively to facilitate its mitigation ambition. At the same time, it must formally present its international finance requirement to the world. Domestic and global financial institutions must increase their capital exposure to clean energy technologies for meeting the requirements of the developing world. MDBs should provide technical assistance and guarantees from blended finance to nascent clean energy technologies. Furthermore, private capital is not yet flowing in the volumes necessary to transition to net-zero emissions at the required speed.

There is an urgent need to phase down fossil fuels and bring big bang reforms in climate finance, as access to low-cost capital will be key in tripling renewable energy deployment, doubling energy efficiency and hydrogen production, as well as facilitate sectoral transitions to achieve India's net zero goal.

4.3. Leveraging carbon markets

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India's transition to net-zero is projected to cost trillions, considering the existing scale of technology development and policy scenario [109]. Carbon markets, implemented as compliance or voluntary market mechanisms, can be a key driver of climate finance. Equally important is the fact that carbon markets reduce the aggregate cost of mitigation by harnessing the lowest cost mitigation opportunities. The emission trading system (ETS) is a compliance mechanism that involves trade of emission allowances (ex-ante units) among obligated entities, and aims at minimizing the cost of achieving climate targets. The offset market involves trade of ex-post emission reduction/removal units generated through voluntary activities, both for compliance (Article 6) and voluntary purposes. The offset market also aims at economic efficiency, that is reducing the economic burden of mitigation. Taking stock of the current carbon market highlights, there is increased traction by policy makers on setting up ETSs, implementing Article 6 of the Paris Agreement and leveraging voluntary carbon market (VCM) mechanisms.

Currently, there are 36 ETSs covering 17.6% of global emissions. By 2022, the ETSs had generated a cumulative revenue of ∼\$65 billion, with emission allowance prices peaking at \$90+/tCO_2e(tons of carbon dioxide equivalent) [198]. India recently announced a 'Carbon Credit Trading Scheme (CCTS)' that establishes the regulatory framework for setting emission intensity targets for obligated entities and the trading of carbon credit certificates.

Several pilots under Article 6.2 (i.e. bi-lateral cooperation between regions/countries) and Article 6.4 (i.e. a centralized crediting mechanism) are underway with more than \$345 million committed to them [199]. A few examples of Article 6.2 pilots are the Canada–Chile cooperation to reduce methane emissions in the waste sector and Switzerland-Ghana agreement to promote climate smart agriculture. India recently announced the list of eligible activities for Article 6.2 participation across three categories: (i) greenhouse gas (GHG) mitigation (such as energy storage, off-shore wind, tidal energy, green hydrogen, compressed biogas, fuel cells for mobility, sustainable aviation fuel etc.), (ii) alternate materials (i.e. green ammonia); and (iii) removal activities (i.e. carbon capture utilization and storage).

The VCM, primarily driven by corporate voluntary offsetting, channelized \$1.5–\$2.0 billion into climate investments in 2022 [200]. India has the highest share of carbon offset generating projects globally, with total issuances and retirements of ∼42 million tCO_2e and ∼37 million tCO_2e in 2022 [201]. Prices vary depending on the project type, ranging from \$2/tCO_2e to \$15+/tCO_2e, with higher prices for projects that yield co-benefits.

Current and future challenges

India's CCTS is envisioned to evolve into a fully-fledged ETS in the long-term. The conceptualization and design of India's CCTS factors in the learnings from other ETS but it needs to overcome several challenges that are inherent in ETSs. These challenges include: (i) policy barriers such as below optimal target setting, ineffective enforcement of penalties, lack of well-defined sectoral emission pathways, and potential adverse distributional implications of carbon pricing mechanisms; (ii) institutional bottlenecks related to the limited technical capacity of policymakers to design and implement ETSs, lack of clearly defined institutional roles and responsibilities, and limited number of accredited verification agencies; and (iii) market infrastructure constraints such as a lack of interoperable registries, and high upfront cost of establishing digital MRV systems. While India also has its own learning from its market-based mechanisms such as the Perform, Achieve and Trade (PAT) scheme, and renewable energy certificates, there is a need to enhance understanding on how ETS works in practice (especially on sectoral coverage, allocation mechanism—free/auction, MRV framework, revenue distribution etc.) [202]. The optimal target setting for different sectors, developing robust market stability measures, and stringent enforcement of rules emerged as key dimensions where these schemes could have done better.

There remains some ambiguity regarding the operationalization of Article 6 in the international carbon market. Some of the key aspects that need clarification before finalizing India's Article 6 engagement strategy include the process of host authorization of internationally transferred mitigation outcomes (ITMOs), rules on corresponding adjustments, accounting of voluntary climate action within nationally determined contributions (NDCs), and market and legal framework necessitated for international interlinkages.

Globally, the offset market witnessed a slight slowdown in 2022, mainly due to concerns over the quality of credits (especially regarding permanence and additionality), price transparency and delays in registration and validation processes by independent standards [203]. In India, there are specific challenges such as the difficulty in identifying reliable methodologies for projects, limited information on the role of voluntary mechanism within the CCTS, ambiguity regarding the use of carbon credits in the country's net-zero strategy, and uncertainty on interplay of the domestic CCTS with the international carbon market. These challenges have increased the perception of risk among investors and buyers in the Indian market regarding the type of projects to finance, potential return on investment, and accrual of estimated carbon offsets.

Way forward for policy and practice to address challenges

India needs to establish robust market infrastructure (including registry, digital MRV, GHG emission inventory system), define science-based methodologies and prepare comprehensive policy frameworks aligned to global best practices.

Emerging digital technologies (such as smart sensors, remote sensing, and blockchain) can improve transparency and cost-efficiency[32]. Developing registries with peer-to-peer linkages to international counterparts can ensure accurate transaction tracking. Blockchain technology is being leveraged to demonstrate interoperability between registries and harmonize market data, a venture led by the World Bank. Digital MRV systems are being piloted to track emissions and reductions for approved sectors and tag the results to the country's NDCs. Countries such as Ghana, Jordan, Chile, and Singapore are actively building end-to-end digital infrastructure.

Countries have limited practical experience in establishing the authorization process for Article 6 [204]. The Climate Action Data Trust is piloting a digital carbon asset development process [205] with a few countries, incorporating a country-level authorization process with corresponding adjustment rules. In terms of policy advancements, few countries have begun outlining their Article 6 strategy, encompassing aspects such as the country's role as a buyer/seller of ITMOs, methodologies for emission accounting, models for Mitigation Outcome Purchase Agreement transactions, and contribution of ITMOs into NDCs.

Global voluntary initiatives, such as the Integrity Council for the Voluntary Carbon Market (ICVCM) and Voluntary Carbon Markets Integrity Initiative (VCMI), are developing frameworks to improve the understanding of carbon offsetting and to establish a uniform governance framework. This includes VCMI's 'claims code of practices' as well as ICVCM's ten core carbon principles to provide threshold standards for carbon credits, including scientific recommendations on emissions impact. Several agencies (such as BeZero Carbon, Sylvera and Calyx Global) have started rating individual projects across multiple criteria, such as the likelihood of additionality and the risk of carbon leakage, by utilizing digital verification methods. Key independent standards organizations are updating methodologies across sectors to incorporate science-based estimations.

The core challenge related to lack of knowledge of ETS market in the Indian ecosystem can only be solved through consistent engagement with stakeholders along with a well-planned roll out that includes the pilot phase and then expansion phase with structured channels for feedback and regular improvements in market design. In addition, analytical research is going to be critical to continuously evaluate the impact of ETS on different sectors and communities, and understand the interaction effects of ETS with other policies co-existing in the system.

Concluding remarks

The carbon market landscape is at an evolving stage in India, with two mechanisms being institutionalized: (i) transitioning the existing PAT scheme to a CCTS; and (ii) establishing key provisions of Article 6.2 and 6.4. This necessitates setting up a robust policy and market infrastructure for the domestic carbon market, with potential linkages to the international market.

Some noteworthy policy developments for India include developing national and sectoral emission reduction pathways as integral components of it is net-zero strategy, defining science-based methodologies (utilizing globally recognized frameworks like Science Based Target Initiative) for emission accounting across eligible sectors (especially hard-to-abate sectors with tax implications under the Carbon Border Adjustment Mechanism), and defining market stability measures (such as price ceiling, market stability reserve etc.) for the CCTS. Moreover, there is a need to formulate comprehensive regulations for Article 6 implementation, particularly addressing corresponding adjustments, the authorization process of ITMOs, and the incorporation of voluntary climate actions within NDCs.

It is recommended to establish an end-to-end digital carbon asset development process for improving transparency and efficiency. This could encompass an emission inventory system, potentially linked with a blockchain-based meta-registry for recording and tracking transactions of all carbon assets, and a digital MRV mechanism.

[32] Note: digital MRV is expected to lead to savings of at least 20%–30% across all stages of a VCM project (i.e. planning and validation, monitoring and verification, issuance and distribution of carbon revenues)

4.4. Can technology co-innovation drive transformative change in India?

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Technology transfer (TT) is the process of disseminating systematic knowledge to enable the creation of products, processes, or services [206]. While proponents argue that TT can expedite innovation and aid developing nations in achieving sustainable socioeconomic goals [207], its transformational potential often remains unrealised. This is partially because the typical focus in TT on generating demand for specific products and services undermines the broader impact of TT. Moreover, the limited absorption capacities and underdeveloped ecosystems in developing economies may further impede its effectiveness. As a result, the transformative promise of TT often appears more as a mirage than a reality.

Like any other country, India too is in need for advanced technologies to address climate crisis and accelerate to net-zero transitions. To achieve these quick and significant changes, bolstering technology collaboration with countries with advanced technologies is imperative [208]. Incremental changes are insufficient; substantial and swift transformations are required to bridge the gap in access to pivotal technologies [209]. The question then arises: how can TT truly drive transformation in India?

A shift from a narrow product-oriented approach to a holistic knowledge-sharing framework is essential. Rather than merely focusing on transferring specific products to India, TT should emphasise the comprehensive dissemination of knowledge ecosystems.

Capacity building also plays a pivotal role. India cannot often fully harness transferred technologies. Effective TT should integrate capacity-building initiatives that enhance local skills, infrastructure, and regulatory frameworks. This can empower the country not only to adopt technologies but to adapt and create contextually relevant solutions and innovate further, leading to sustainable and transformative outcomes. However, this cannot be done alone by the government to government engagement. Other stakeholders including private sectors, research institutions in both supplier (source) countries and India (recipient) must collaboratively facilitate TT, with shared societal and environmental goals at the forefront. This shift from short-term gains to long-term benefits promotes a more inclusive and equitable transformation. By embracing co-innovation—defined as a collaborative and iterative approach involving multiple partners in innovating, manufacturing, and scaling technologies—TT can indeed be transformational, driving impactful changes and paving the way for a more equitable and sustainable future.

Current and future challenges

The pivotal role of TT in addressing climate change has been acknowledged for over three decades, as evidenced by the United Nations Framework Convention on Climate Change (UNFCCC) [210]. However, the actual progress in achieving this goal has been lacklustre. Numerous studies have observed limited success in initial efforts to facilitate TT under the climate regime [211]. The Intergovernmental Panel on Climate Change (IPCC) has highlighted financial, institutional, and technical challenges that hinder various stages of the TT process, and stressed the need for national innovation systems to overcome these obstacles [212]. These have clear implications for India's climate objectives. Current research continues to echo these findings [213], exemplified by China's rapid progress in solar PV technology, attributed to systemic changes within the country and among its partners [214].

As research delves into systemic changes, many of the chief challenges to India in achieving net-zero transitions have become clearer: affordability, adaptability, and scalability.

Affordability is crucial as imported low-carbon technologies often have high initial and operational costs. Adaptability is equally vital. Often, imported technologies are ill-suited to Indian contexts due to a lack of demand or misalignment with development goals [215, 216]. Challenges can arise from a dearth of supporting infrastructure and human resources, hindering contextualisation [217]. Scalability poses a third challenge for India. Treating TT as one-off exchange by source countries limits its transformative potential. To catalyse change within existing systems, innovations must penetrate expanding markets.

Addressing these challenges demands cooperative efforts, adaptable design, and a focus on market expansion in the Indian context. A transformational approach to TT requires not only technological exchange but also systemic changes in governance, policies, and knowledge dissemination. India, along with technology suppliers will need to collectively tackle these challenges to realise the potential advanced technology solutions for net-zero transitions and sustainable development.

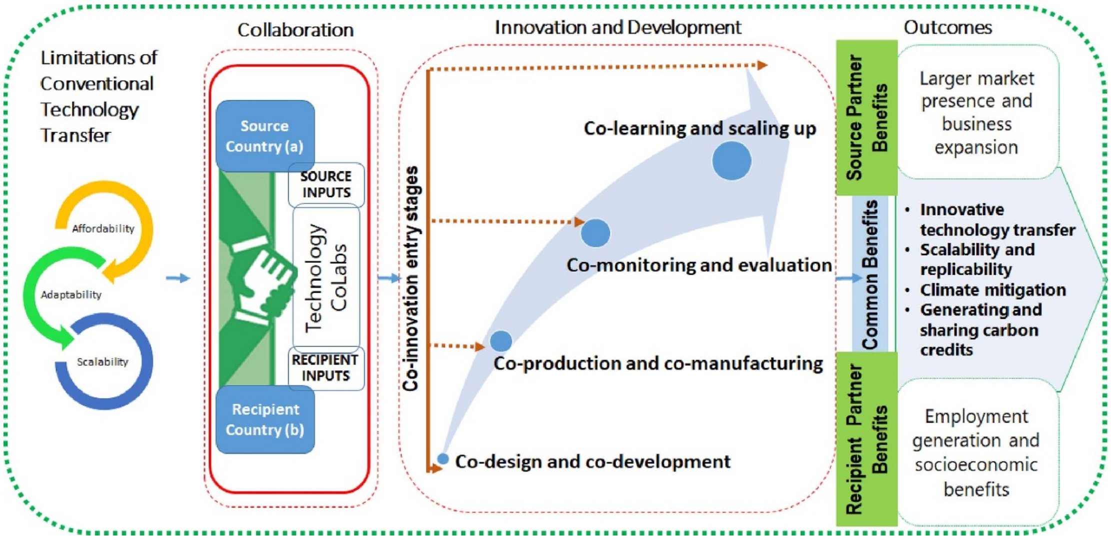

Figure 9. Co-innovation framework.

For India, technology collaboration and building a meaningful engagement with developed countries in capacity development is crucial. Two examples are worth examining. First, India's micro, small and medium enterprises (MSME) sector is a major contributor to the country's GDP and in the fiscal year 2021–22 the share of MSME gross value added (GVA) in all India GDP was 29.15%. However, the sector faces multiple challenges pertaining to energy efficiency and best practices. Collaborating with countries having advanced technologies is of crucial importance to India.

Similarly, as India's renewable energy sector is growing, hydrogen sector is increasingly gaining importance. The significance of overseas stakeholders in India's hydrogen development initiatives is unquestionably substantial. Given that the advancement of green hydrogen necessitates a technology-driven approach, Indian states rich in renewable energy resources must incorporate cutting-edge technologies from these overseas players.

Way forward for policy and practice to address challenges

Co-innovation offers an alternative to traditional TT [218, 219]. Affordability concerns can be alleviated by joint efforts of technology developers, investors, and governments at national and sub-national level in India. Sourcing locally available materials and talent will be crucial in addressing the affordability concerns. Addressing adaptability entails interdisciplinary collaboration to design and test solutions tailored to local requirements and constraints [220]. By incorporating local knowledge, lessons from customer demand and local expertise into design, adaptability of the technology can be improved. The scalability challenge is surmounted through collaborations among technology developers, manufacturers, distributors, and users, establishing resilient supply chains and support networks to facilitate rapid and efficient scaling.

The process of co-innovation, as illustrated in figure 9 based on [221], unfolds across three distinct steps to address the limitations of conventional TT.

As a first step, India will need formalised collaboration which can involve pooling financial and intellectual resources to create context-specific solutions. Preliminary research underpins this step, encompassing technology needs assessments and market studies that provide the necessary groundwork for productive and beneficial collaboration. In the second step, with the technology source country India can engage in diverse collaborations, spanning ideation, co-manufacturing, joint research and development, and scaling. Collaboration can occur at any stage, with the ultimate goal of refining and customising technologies for application to suit domestic contexts [219]. The final step encompasses the delivery and distribution of benefits. Co-innovation offers multifaceted advantages. Source partners expand their market presence, while India can gain economic, environmental, and employment co-benefits. Both parties reap shared benefits through enhanced scalability, reduced emissions for environmental gains, and the mutual sharing of carbon credits.

Co-innovation stands out as a promising process, fostering collaborative technology development and implementation between India and overseas technology partners. It directly addresses barriers to technology adoption, yielding diverse benefits for all stakeholders involved. By adopting a co-innovation approach, source countries and India can jointly drive substantial and sustainable progress, effectively addressing the pressing challenges of TT in the face of global issues like climate change.

Concluding remarks

Achieving net-zero objectives necessitates the profound transformation of unsustainable socioeconomic systems. Within this context, TT holds the promise of playing a pivotal role in developing countries. Nevertheless, conventional TT models have often fallen short of delivering on their transformational potential. This paper has illuminated the co-innovation approach as an alternative strategy capable of fostering iterative learning, while simultaneously reducing initial and operational costs, tailoring technologies to specific contexts, and nurturing the necessary supportive ecosystems for sustainable systemic changes.

Redirecting the emphasis from conventional TT to co-innovation holds the potential not only to advance climate change mitigation and net-zero aspirations but also to bring about profound transformations in India. Policymakers in India will need to prioritise co-innovation in all possible technology collaboration. Such collaborative and innovation-driven approach stands poised to redefine the trajectory of TT, effectively catalysing enduring change in the global endeavour towards a more sustainable and equitable world.

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4.5. Lifestyles for environment (LiFE)

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Status

LiFE: Lifestyles for Environment is an India-led global initiative to shift individual and collective behaviour towards '*mindful and deliberate utilisation, instead of mindless and destructive consumption,*' [222] to combat the triple planetary crises of climate change, biodiversity loss, and pollution [223]. LiFE was introduced to the world by India's Prime Minister Narendra Modi at the UNFCCC COP26 in 2021 [222] to promote pro-environment lifestyles [224] that blend traditional wisdom with scientific methods to:

- Nudge behaviour towards responsible consumption patterns (demand);
- Enable markets towards production of sustainable goods and services (supply); and
- Influence policies to support demand and supply levers [225].

In 2023, inspired by LiFE, the G20 unanimously adopted nine High-Level Principles (HLPs) on Lifestyles for Sustainable Development, encompassing '*all three dimensions of sustainable development—economic, social, and environmental—in a balanced and integrated manner,*' making LiFE a major international effort.

The HLPs suggest leveraging behavioural science approaches to '*promote environmentally friendly individual and community behaviour*' and ramp up '*sustainable value chains, technological transitions, innovations and investments in key areas*' through '*international cooperation, collective action and partnerships.*' The HLPs provide '*strong political impetus*' for high-impact mitigation and adaptation action, especially in developing countries, and lay the foundation for global cooperation in data collection, analytical research, policy formulation, and pragmatic, measurable, and scalable implementation [226]

Associating human development with consumption-led lifestyles is driving a linear 'use-and-throw' economy with a massive ecological footprint [227]. Unsustainable resource consumption [228] has spiked global material use from 43 billion tonnes (BT) in 1990 to ∼92 BT in 2017 [229]. The HLPs support UN Sustainable Development Goal (SDG) 12, which encourages responsible production and consumption and urges governments and citizens to '*work together to improve resource efficiency, reduce waste and pollution, and shape a new circular economy*' [223]. This resonates across goals like SDG 11 to make cities and communities resilient and sustainable, and will help improve the availability of resources like clean water and energy while combating climate change.

In the 2015 Paris Agreement, 194 countries recognised the need for '*sustainable lifestyles and sustainable patterns of consumption and production.*' Leading by example, India has included LiFE in its Paris Agreement commitments and outlined 75 'LiFE actions' to conserve energy and water, reduce waste, promote healthy lifestyles, and adopt sustainable food systems [224].

LiFE's objectives go beyond siloed and sectoral transitions and address complete life systems, i.e. ways of living, of people. They emphasise the need for policy-led, scientifically-sound, commercially viable, financially sustainable, co-developed tools and actions to create a shared pro-environment future.

While LiFE has received political and multilateral support from developed and developing countries, there are major challenges to implementing its ambitions at scale. Especially since in today's connected world, sustainability must be engineered into global value chains of goods and services, extending beyond national jurisdictions. This Chapter delves into some of these challenges.

Current and future challenges

Key challenges to implementing LiFE-centric initiatives at scale include:

No definitions and metrics for sustainable production and consumption, especially in the context of socio-economic growth: Linking socio-economic success to the output-centric economic metric of GDP has constrained public receptiveness, and thus, political will, to research, evaluate, introduce, and scale methods and incentives to move individuals and communities towards more sustainable lifestyle choices, while improving—or without compromising—quality of life. Current GDP metrics do not value sustainability-oriented industrial processes and market mechanisms. Absence of appropriate definitions will impact the on-ground rollout of LiFE.

Need for scientific innovations and technological interventions that engineer sustainability into lifestyles: sectoral transitions such as switching to cleaner fuels only address parts of the sustainable lifestyles challenge. Scientific product and process innovations must combat 'mindless and destructive consumption' while creating transformative systems for 'mindful and deliberate utilisation.'

Integrating efforts across systems and countries: institutional cues, norms, personal desires, and resource availability determine individual and collective behaviours that drive societal consumption patterns [230]. Coordinating efforts across individuals, communities and institutions entails significant transaction and transition costs and effort.

Lack of incentives: In current linear models, ~90% of materials, upstream and downstream, are wasted, lost, or unavailable for use [231]. Beyond profit-linked efficiencies, markets have no incentive to adopt more sustainable systems via complex and costly shifts in design, investment, resource supply, production, packaging, transportation, retail, and end-of-life processes [232]. Markets need a coordinated *pull* via consumer demand and a *push* via policies to move towards more sustainable production and consumption systems.

Inadequate finance for SDG-linked LiFE initiatives: the world needs USD 4.2 trillion annually to achieve the SDGs, including for sustainable production and consumption [233]. Political impetus, policies and frameworks are needed to redirect the 1.1% of global financial assets towards closing the SDG finance gap.

Managing complex trade-offs: government policies to replace unsustainable systems with better options often involve major socio-economic trade-offs—resource security, product specification, cost, market disruption, and public resentment—with few avenues to absorb resultant shocks. Arbitrary efforts to inculcate sustainability in lifestyles often force-fit technocratic fixes that overlook nature, communities, and traditions, overengineer materials and processes, and deepen technology and societal gaps.

Way forward for policy and practice to address challenges

As India has proposed and led this initiative, research and stakeholder engagement work should begin in India to better understand the social, economic, scientific, political, and multilateral constructs of LiFE. Implementing informed decisions will help structure initial processes, establish proofs of concept, and make it easier to build consensus within and outside India. The HLPs should be applied to individual and collective behaviours nationally and multilaterally, in specific and measurable ways replicable across geographies and communities, such that LiFE-centric public and industrial policies can be institutionalised and driven at scale [224].

Today, the capacity to procure and consume resource-rich goods and services is the key indicator of people and countries' wealth and well-being. However, lifestyles are derivatives, and not definers, of global political, social and economic systems. This is a major area for scientific research, public consultation, and policy formulation. Quantified, LiFE actions should help define the degree of sustainability of lifestyle choices and set metrics for a pro-growth, nature-aligned aspirational quality of life.

Applying LiFE needs scientific nudges to reduce the gap between consumers' intentions and actions by redefining their contexts, including by simplifying access to information or altering influencer networks [227]. Nudges can leverage social norms to encourage 'good behaviour', or mandate desired outcomes via policy [234]. Shifting individual and collective consumer choices and actions at scale through behavioural science, assuming that with the right nudges suited for India's context, people can—and likely will—avoid embedding themselves in the high consumption pathways of the developed world, needs research to generate evidence and ease implementation.

Integrating circularity into resource-intensive product and service value chains to improve market capacities needs mapping, tracking, and modifications of intricate, multinational systems of millions of enterprises and consumers. To enable market shifts, governments, industry and academia must collaboratively design policies and products to provide practical and affordable alternatives [226]. For instance, policies to ban single-use plastic must also ensure the availability of affordable recycled and biodegradable materials [225]. Also, if India can champion the bio-economy agenda, it will set a practical example for enhancing circularity across many other countries.

Industrial symbiosis, technology co-development, global standards and protocols, and consumer education will help integrate resource efficiency and circular economy in value chains to reduce, reuse, recycle, and recover material resources [222, 232, 235, 236]. Indigenous knowledge and techniques are rich repositories of locally and culturally viable solutions, and could inspire modern innovation [237].

Low-cost, outcome-linked financing and incentives for LiFE initiatives need to be estimated for India by leveraging data and digital technologies, and included in national budgets, corporate investment plans, and multilateral lending processes. Financial levers like taxes and cesses could disincentivise unsustainable consumption choices, while subsidies, tax breaks, low-cost financing, and production-linked incentives can improve capital availability to scale new products, services, and processes [225].

Concluding remarks

LiFE, inspired by India's millennia-old civilizational wisdom and practices that recognise and inculcate the interconnectedness of human beings with nature, could bring a paradigm shift to sustainable development. It is, therefore, critical to be mindful of the national circumstances and capabilities of each country infusing LiFE into their policies and actions, especially developing countries that must maintain a balance between basic developmental goals, peoples' aspirations, and sustainability.

The HLPs on LiFE have generated political consensus and global dialogue on sustainable lifestyles. The infusion of LiFE into individual and community behaviours using well-researched, structured, measurable, replicable, transparent, and equitable policy and market mechanisms could help reorient human aspirations and consumption patterns towards more sustainable choices. Given the imperatives of net-zero India, it is critical that LiFE is put into practice and adopted by individuals, communities, markets, and policy makers.

4.6. MRV and stocktake

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Status

India has always endorsed transparency in climate actions. It has adhered to the reporting obligations under the United Nations Framework Convention on Climate Change (UNFCCC) and has submitted five communications (two National Communications and three Biennial Update Reports)[1]. In these reports, India also highlighted that there is considerable scope for improvement across all areas of reporting and that it needs additional support to address its capacity constraints [238, 239].

The domestic arrangements that support reporting on climate actions in India are need-based and project-oriented [240]. Multiple ministries, government departments, civil society entities and research institutions provide inputs towards the preparation of these climate reports. The Ministry of Environment, Forest and Climate Change (MoEFCC) acts as a nodal point (implementing and executing entity) towards facilitating this reporting process [238].

In the last few years, it has been observed that India is strengthening its MRV capabilities of its domestic programmes and initiatives. This is visible from various real-time interactive web portals and digital dashboards, which track the effectiveness of national schemes across all states. Further, the nodal ministries, as well as the public department, have developed substantial reporting capabilities and are maintaining centralised data repositories. For important schemes/programmes, a decentralised MRV has been adopted where key actors across different levels of governance track and monitor the effectiveness of the programme [238]. Table 2 below highlights some key MRV arrangement in India:

Parallel to these governmental initiatives, the non-state actors are also strengthening India's climate transparency. Academic institutions are involved in scientific studies to enhance the knowledge of emission factors; several public policy research institutions/ private entities are independently estimating GHG inventories [241]; and some independent agencies are involved in undertaking technical assessments of programmes and policies [238, 239].

Current and future challenges

Support in form finance or capacity building to developing countries to report on climate action has been under discussion for more than a decade. This is evident from UNFCCC's review documents and synthesis reports, where developing countries have stressed on their limited capacities and the need for enhanced support, especially for the newer enhanced transparency framework (ETF) under the Paris Agreement [242, 243].

The newer guidelines of the ETF demand more timely, granular, and accurate data than before [244]. Hence, even the existing arrangement in India, which is project-oriented and need-based in nature, facilitated adhering to the MRV framework established under the Cancun Agreements[2] (decision 1/CP.16), it is not appropriate or suitable for meeting the new reporting requirements under ETF [240].

As per ETF, Parties signatory to Paris Agreement are obligated to submit their first biennial transparency reports (BTR) **from 2024 onwards** [245]. For several mandatory aspects of BTR, India has no experience in reporting. This includes tabular disclosures of detailed sectoral emissions (at three segregation levels), the detailed base year emissions, disclosure of historical emissions as well as projections, articulating NDCs progress indicators—qualitative or quantitative—and reporting progress against them. While the agreed rules do offer flexibilities to developing countries to report them, owing to their capacity constraints, it also urges them to develop improvement plans and gradually build their domestic capacity to report on the elements where flexibilities are availed [245].

To be able to adhere to the newer transparency requirement, India would need to strengthen its existing institutional arrangements and technical capabilities. So far, there is no formal mandate to share climate-reported data (in an easy-to-use format) among departments and ministries [240]. Hence, data sharing among the institutions involves a lot of paperwork and, at times, manual entry, costs and time [246]. Further, institutions lack technical and analytical capabilities, which results in a limited understanding of country-specific data and emission factors for sources and sinks.

Very often, data points are based on assumptions. This is because, sometimes, the data represent only a portion of the required observation or follow a different timeline, which makes it difficult to use data directly for analysis. Also, in some cases, MRV frameworks associated with initiatives (sustainable development policies) are confined to the project-level objectives and track only a few parameters which may not directly showcase climate co-benefits.

Way forward for policy and practice to address challenges

India's domestic MRV system needs to evolve to adhere to the comprehensive reporting obligation of the Paris Agreement. It should consider an integrated arrangement, which would track the state's climate efforts, its GHG inventories and develop standards/guidelines to track the progress of actions by its non-state actors. This is because, moving

Table 2. Examples of MRV arrangement in India.

Dashboard/ Web-based platform	National Power Portal; National UJALA dashboard; Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME India); Farmers Portal; Large Forest Fire Monitoring Programme; India SDG Dashboard; India Climate and Energy Dashboard
Data repository	Central Electricity Authority Database; Energy Statistics, Annual Survey of Industries by Ministry of Statistics and Programme Implementation; Reports and studies by Petroleum Planning and Analysis Cell; National Forest Inventory by Forest Survey of India
Scheme specific MRV	Perform, Achieve and Trade scheme; Standards & Labelling Programme; Renewable Energy Certificates; Twenty Point Programme; Smart Cities Mission

Source: India's Third Biennial Update Report, 2021; NITI Aayog, 2023.

forward, enhanced transparency on assumptions which drive carbon emission and non-carbon statistics (for key sectors) would be necessary. Further, an integrated MRV system would bring a holistic understanding of India's efforts internationally by not just focusing on detailing inventory/mitigation but also highlighting its sustainable development initiatives and associated co-benefits, along with outcomes of adaptation and support measures. To drive the transition towards an integrated MRV system, the following are some proposed recommendations:

- **Institutionalising the reporting process:** a formal legislative directive should be established to institutionalise the reporting process on a continuous basis. This directive should bring together key actors, regulators, databases, and related agencies and ease the data-sharing protocols among them. Also, the legislation should ensure that entities become accountable (retain capacity) and identify the budgetary provisions towards making the reporting process self-sustaining over the long run.
- **Standardise reporting templates, guidelines and procedures:** it is important to first map the gaps across different databases and understand the challenges in the existing reporting formats/templates to support transparent reporting on climate actions. Based on this understanding, the existing reporting templates could be modified or new standardise reporting templates could be formulated towards meeting the new reporting requirements. To ensure adoption of standards and templates, data providers and analysts should not only be trained at the end but should also be involved in its formulation process.
- **Deploying state-of-the-art technology:** technology in the form of a robust data management system and a web-based digital interface is the need of the hour. Such an interface, based on a blockchain framework, can play a role of a facilitator in the flow of information among the entities and automate data collection as well as verification process. It will provide transparent, accurate, consistent, and readily available information for the preparation of BTRs. Further, the inherent design of blockchain promotes standardisation and network security to protect (mask) confidential information and ensure privacy. Additionally, for cases where the bottom-up calculation of GHG emissions remains a distinguishing challenge, satellites, along with ground-based monitoring technologies (sensors), can be utilised to provide information on the atmospheric composition of GHG emissions.

To transition to an integrated MRV system, India should receive timely financial and technical support, so that the reporting obligations do not lead to an undue burden on them.

Concluding remarks

It is evident that India has made noteworthy efforts towards ensuring transparency in its domestic climate action. However, the overall approach to climate reports which is need-based and project-oriented may not be appropriate moving forward because of enhanced reporting obligation of Paris Agreement, necessitating timely and granular information.

Moving forward, domestic climate actions are bound to increase as a result of India's updated NDCs, the net-zero commitment and Mission LiFE. In this context, it is important to highlight that the actors supporting implementation of climate action in India are no longer limited to national governments. The efforts of non-state actors, which include businesses, organisations, cities and regions, should also be monitored.

As India prepares itself to communicate its climate actions in the best possible way, it need not build a new system. However, India needs to leverage upon its excellent domestic capacity and strategically take steps towards formalising the reporting process, formulate standard templates and deploy state-of-the-art technology in the form of data management systems and web-based platforms. This will not only help in tracking the direct impact of mitigation efforts but also quantify the co-benefits associated with various policies and support evaluating the effectiveness of the programmes holistically.

5. Conlcusion

India's Prime Minister's commitment to make India net-zero by 2070 entails multiple simultaneous and overlapping transitions. Irrespective of whether this target relates to carbon dioxide or greenhouse gases which should be clarified in due course, it is critical to view these multiple transitions through the lens of various perspectives to understand the current status of India's net-zero debate, current and evolving challenges, and way forward for policy and practice to address these challenges. This India specific collaborative effort seeks to present a comprehensive view of India's net-zero debate by encompassing various perspectives woven through a common thread within the larger India specific narrative.

We look at three broad dimensions of India's net-zero debate. The first is national and sub-national perspectives which includes issues related to climate equity, macro-economic trade-offs, just transition, and state and city level actions. The second dimension relates to sectoral and technological transition which includes views on sectoral transition (power, transport, industry and buildings), power markets of the future, critical minerals and dematerialisation, CDR, and land use, land use change and forestry emissions. The third dimension discusses key enablers for India's net-zero transition including institutions, finance, carbon markets, co-innovation, the concept of LiFE, and system for measurement, reporting and verification (MRV).

Beyond the current status of the debate and the evolving challenges, the assessment presents ideas related to the way forward for policy and practice. Some of the important suggestions are: (i) a global dialogue on net-zero equity is need of the hour and India needs to build its own body of research on inequity implications of NZ transitions; (ii) tools that can provide inputs on national climate policy based on macroeconomic assessment of mitigation and development pathways need to be developed and strengthened; (iii) economic diversification of fossil-fuel dependent regions in India, repurposing of land and energy infrastructure, reskilling existing workforce and investment in social infrastructure is key for a just transition; (iv) governance approaches that embed climate action within development aspirations and invest in capacity building at the state level are critical; (v) a city level emissions inventory, substantial investment in public transport infrastructure, and climate aligned urban planning guidelines need to be created; (vi) integration of RE capacity with grid scale energy storage, awareness campaigns and regulatory support for climate action, policies for higher energy and resource efficiency in hard-to-abate sectors, and integrated mobility plans need to be devised for energy sector transition; (vii) a power market design to attract investment in essential flexible resources is a strategic choice that needs to be made, and power distribution companies should become financially sound, efficient and dynamic for a net-zero future; (viii) participation in global critical minerals mapping initiatives and investment in overseas mines as well as recycling infrastructure for critical minerals is imperative; (ix) funding provision from the Government of India as well as other funds like Global Environmental Fund (GCF) for effective on-ground assessment of India's geological sink availability is crucial; (x) the capacity deficit on long-term 'integrated' land-use sector modelling that can provide insights related to trade-offs between land-use emissions, energy, food and water sectors to inform the net-zero transition, along with open-source land-use and land-use change maps, is a fundamental gap that needs to be addressed; (xi) an institutional innovation that suits India's own context and focuses on low carbon development pathways rather than mitigation alone, and is anchored in law to promote institutional robustness, is integral for India's net-zero push; (xii) along with policy certainty, a few broad financial sector reforms (including clear definitions, disclosures, priority sector lending, etc.) are needed to attract capital to accelerate India's low carbon efforts; (xiii) a robust market infrastructure (including registry, digital MRV, GHG emission inventory system), emerging digital technologies, robust governance framework, and deep stakeholder engagement process are vital to realize the potential of offset carbon markets and the cap-and-trade system for India; (xiv) a formalised collaboration with other countries which can involve pooling financial and intellectual resources to create context-specific solutions to deliver on the idea of co-innovation needs to be designed and executed; (xv) research and stakeholder engagement work should begin in India to better understand the social, economic, scientific, political, and multilateral constructs of the LiFE initiative and its high-level principles; and (xvi) India's domestic MRV system should consider an integrated arrangement, which would track the state's climate efforts, its GHG inventories and develop standards/guidelines to track the progress of actions by its non-state actors, in order to adhere to the comprehensive reporting obligation of the Paris Agreement.

India is one of the fastest growing economies of the world. Its diplomatic weight in the global climate negotiations and discourse is also increasing given that its greenhouse gas emissions are on an increasing path. The integrated perspectives presented in this India specific collaborative assessment seeks to inform not just India's policy makers and stakeholders, but various researchers, practitioners and governments around the world for them to be better aware of the status of various aspects of India's net-zero debate, understand the high-level issues and challenges related to the transition, and think about way forward for the same. India's net-zero push is bound to be transformative not just for the country, but for communities and ecosystems around the world.

Data availability statement

No new data were created or analysed in this study.

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References

[1] Chaturvedi V 2021 Peaking and net-zero for India's energy sector CO_2 emissions: an analytical exposition *Council on Energy Environment and Water*
[2] MoEFCC 2023 India achieves two targets of nationally determined contribution well ahead of time *Ministry of Environment Forest and Climate Change* (Government of India) (available at: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1987752#:~:text=In%20August%202022%2C%20India%20updated,enhanced%20to%2050%25%20by%202030) (Accessed 18 December 2023)
[3] MoEFCC 2022 India's long-term low-carbon development strategy *Ministry of Environment, Forest and Climate Change* (Government of India) Submitted to UNFCCC
[4] MoP Ministry of Power & Ministry of Environment, Forest and Climate Change to develop carbon credit trading scheme for decarbonisation (Ministry of Power, Government of India) (available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1923458) (Accessed 11 May 2023)
[5] MoEFCC 2023 Third National Communication and Initial Adaptation Communication to the United Nations Framework Convention on Climate Change *Ministry of Environment, Forest and Climate Change* (Government of India)
[6] Durga S, Evans M, Clarke L and Banerjee R 2022 Developing new pathways for energy and environmental decision-making in India: a review *Environ. Res. Lett.* **17** 063004
[7] Chaturvedi V and Malyan A 2022 Implications of a net-zero target for India's sectoral energy transitions and climate policy *Oxford Open Clim. Change* **2** kgac001
[8] Garg A, Patange O, Vishwanathan S S, Nag T, Singh U and Avashia V 2024 Synchronizing energy transitions toward possible Net Zero for India: affordable and clean energy for all *A report prepared for Office of the Principle Scientific Advisor (PSA) to Government of India and Nuclear Power Corporation of India Limited (NPCIL)*
[9] Friedlingstein P *et al* 2022 Global carbon budget 2022 *Earth System Science Data Discussions 2022* pp 1–159
[10] IPCC 2021 Climate change 2021: the physical science basis *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel On* ed V Masson-Delmotte *et al* (Cambridge University Press)
[11] UNFCCC 2015 Paris Agreement to the United Nations framework convention on climate change (available at: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf?gad_source=1&gclid=CjwKCAjwgfm3BhBeEiwAFfxrG2l-4tonq6xLObBDa6tC2AAAPiiBIGX-SSQUAzrXg8aLqU21WFPAzRoCEnUQAvD_BwE)
[12] Van Soest H L, den Elzen M G and van Vuuren D P 2021 Net-zero emission targets for major emitting countries consistent with the Paris Agreement *Nat. Commun.* **12** 2140
[13] Vishwanathan S S, Fragkos P, Fragkiadakis K and Garg A 2023 Assessing enhanced NDC and climate compatible development pathways for India *Energy Strategy Rev.* **49** 10152
[14] Van den Berg N J *et al* 2020 Implications of various effort-sharing approaches for national carbon budgets and emission pathways *Clim. Change* **162** 1805–22
[15] Garg A, Vishwanathan S S, Chaturvedi R, Gupta D, Avashia V and Patange O 2021 Policy lessons on Deep Decarbonization in large emerging economies, India *Deep Decarbonization Pathways (DDP) Initiative-IDDRI* (available at: https://ddpinitiative.org/wp-content/pdf/DDP_BIICS_CountryReport_IND.pdf)
[16] Bloomberg 2023 (available at: www.bloomberg.com/graphics/2023-climate-tech-startups-where-to-invest/) (Accessed 14 June 2023)
[17] Malyan A and Chaturvedi V 2021 The carbon space implications of net negative targets (available at: www.ceew.in/sites/default/files/ceew-study-on-how-negative-emissions-targets-impact-global-carbon-budget-space.pdf) (Accessed 1 September 2023)
[18] Williges K, Meyer L H, Steininger K W and Kirchengast G 2022 Fairness critically conditions the carbon budget allocation across countries *Glob. Environ. Change* **74** 102481
[19] Jabbari M, Shafiepour Motlagh M, Ashrafi K and Abdoli G 2020 Global carbon budget allocation based on rawlsian justice by means of the sustainable development goals index *Environ. Dev. Sustain.* **22** 5465–81
[20] Kanitkar T 2021 Equity in global climate policy and implications for India's energy future *Econ. Political Wkly.* **56** 68–75

[21] MoEFCC 2021 India's Third Biennial update report (BUR3) *Ministry of Environment, Forest and Climate Change* (Government of India)

[22] CSTEP 2018 Greenhouse gas emissions from the informal sector in India (available at: www.ghgplatform-india.org/wp-content/uploads/publications/phase-2/GHGPI-PhaseII-Emissions%20from%20the%20Informal%20Sector%20in%20India-Apr18.pdf) (Accessed 1 September 2023)

[23] MoEFCC 2015 India' Intended Nationally Determined Contribution *Ministry of Environment, Forest and Climate Change* (Government of India)

[24] Merrill R K, Schillebeeckx S J D and Blakstad S 2019 Sustainable digital finance in Asia: creating environmental impact through bank transformation pp 1–58 (available at: https://ink.library.smu.edu.sg/lkcsb_research/7407) (Accessed 1 March 2024)

[25] G20 2023 Mechanisms for mobilisation of timely and adequate resources for climate finance (Input paper for the G20- Presidency of India), with contributions from Indian Institute of Management Ahmedabad, International Finance Corporation, and Council on Energy, Environment and Water (available at: https://g20sfwg.org/wp-content/uploads/2023/04/Mechanisms-for-mobilisation-of-timely-and-adequate-resources-for-climate-finance-G20-Presidency-of-India.pdf)

[26] PIB, New Delhi 2022 Unveiling of the logo, theme and website of India's G20 presidency (available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1874524) (Accessed 5 July 2024)

[27] Ministry of Finance, Economic Survey 2017–18 2018 *Ministry of Finance, Department of Economic Affairs Economic Division, Government of India* (available at: https://www.indiabudget.gov.in/budget2018-2019/economicsurvey2017-2018/index.html)

[28] Kahn M E, Mohaddes K, Ng R N C, Pesaran M H, Raissi M and Yang J-C 2019 Long-term macroeconomic effects of climate change: a cross-country analysis (available at: www.imf.org//media/Files/Publications/WP/2019/wpiea2019215-print-pdf.ashx) (Accessed 28 February 2024)

[29] Kompas T, Pham V H and Che T N 2018 The effects of climate change on GDP by country and the global economic gains from complying with the paris climate accord *Earths Future* **6** 1153–73

[30] Mittal S, Liu J Y, Fujimori S and Shukla P 2018 An assessment of near-to-mid-term economic impacts and energy transitions under "2 °C" and "1.5 °C" scenarios for India *Energies* **11** 2213

[31] Gupta D, Ghersi F, Vishwanathan S S and Garg A 2019 Achieving sustainable development in India along low carbon pathways: macroeconomic assessment *World Dev.* **123** 104623

[32] Chaturvedi V and Malyan A 2022 Implications of a net-zero target for India's sectoral energy transitions and climate policy *Oxford Open Clim. Change* **2** kgac001

[33] IPCC 2014 Climate change 2014 synthesis report, fifth assessment report (available at: www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf)

[34] Agarwal V, Bharadwaj A, Dey S, Kelkar U, Kohli R, Madan N, Mandal K K, Mitra A and Swamy D 2021 Modelling decarbonisation pathways for the Indian Economy *ORF Issue Brief* No. 503 (available at: https://www.orfonline.org/public/uploads/posts/pdf/20230421231250.pdf)

[35] Swamy D and Agarwal V 2023 Macroeconomic impacts of long-term decarbonization in India: implications for a just transition (World Resources Institute) (https://doi.org/10.46830/wrien.22.00155)

[36] Srivastava B and Bhaskar D 2022 Transformation of India towards net zero targets: challenges and Opportunities *Nimit Mai Review.* **5** 1–8

[37] Udetanshu, Khurana S and Nelson D 2020 Developing a roadmap to a flexible, low-carbon Indian electricity system *A Climate Policy Initiative (CPI) Energy Finance Report* (available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2020/08/CPI-India-flexibility-25-August-2020-Executive-summary-1.pdf)

[38] NITI Aayog and Rocky Mountain Institute (RMI) 2020 Towards a clean energy economy: post-COVID-19 opportunities for India's energy and mobility sectors, 2020 (available at: www.niti.gov.in/sites/default/files/202006/India_Green_Stimulus_Report_NITI_VF_June_29.pdf) (Accessed 28 February 2024)

[39] MOEFCC 2022 India's long-term low-carbon emission development strategy *Ministry of Environment, Forest and Climate Change* (Government of India)

[40] CEEW 2023 Addressing Vulnerabilities in the Supply Chain of Critical Minerals *Council on Energy, Environment and Water*

[41] CPI 2022 Landscape of Green Finance in India (available at: www.climatepolicyinitiative.org/wp-content/uploads/2022/08/Landscape-of-Green-Finance-in-India-2022-Full-Report.pdf) (Accessed 29 February 2024)

[42] ASPI 2022 Getting India to net zero (Asia Society Policy Institute) (available at: https://asiasociety.org/sites/default/files/202209/ASPI_Getting%20India%20to%20Net%20Zero_Report.pdf)

[43] Krishnan M, Nauclér T, Pacthod D, Pinner D, Samandari H, Smit S and Tai H 2021 Solving the netzero equation: nine requirements for more orderly transition (McKinsey and Company) (available at: https://www.mckinsey.com/capabilities/sustainability/our-insights/solving-the-net-zero-equation-nine-requirements-for-a-more-orderly-transition)

[44] Gupta D, Ghersi F, Vishwanathan S S and Garg A 2020 Macroeconomic assessment of India's development and mitigation pathways *Clim. Policy* **20** 779–99

[45] Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K and Kriemann B 2014 Climate change 2014: mitigation of climate change *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press)

[46] Bauer N, Edenhofer O and Kypreos S 2008 Linking energy system and macroeconomic growth models *CMS* **5** 95–117

[47] Ministry of Coal, Government of India, Ministry of Coal Organizes Just transition roadmap *Seminar on the side-lines of 3rd ETWG Meeting in Mumbai under G20 Presidency of India* (available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1924239) (Accessed 15 May 2023)

[48] Bhushan C and Banerjee S 2023 Just transition framework for India: policies, plans and institutional mechanisms (International Forum for Environment, Sustainability and Technology (iFOREST)) (available at: https://iforest.global/wp-content/uploads/2023/03/Just-Transition-Framework-For-India.pdf)

[49] Morena E, Krause D and Stevis D (eds) 2019 *Just Transitions: Social Justice in the Shift Towards a Low-Carbon World* (Pluto Press)

[50] Ministry of Power, Government of India G20 energy ministers adopt ambitious and forward-looking outcome document and chair's (available at: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1941796) (Accessed 23 July 2023)

[51] Bhushan C and Banerjee S 2021 Five R's: a cross-sectoral landscape of just transition in India (International Forum for Environment, Sustainability and Technology (iFOREST)) (available at: https://iforest.global/wp-content/uploads/2021/07/Five-Rs-Single.pdf)

[52] Central Electricity Authority 2023 (available at: https://cea.nic.in/wp-content/uploads/pdm/2021/06/list_power_stations_2021.pdf)

[53] Dsouza S and Singhal K 2021 Socio-economic impacts of coal transitions in India: bottom-up analysis of jobs in coal and coal-consuming industries (National Foundation of India)

[54] NITI Aayog, Government of India 2021 Multidimensional poverty index (available at: www.niti.gov.in/sites/default/files/2021-11/National_MPI_India-11242021.pdf)

[55] Prayas (Energy Group) 2021 Energy: taxes and Transition in India *Working Paper* (available at: www.prayaspune.org/peg/publications/item/485-energy-taxes-and-transition-in-india.html)

[56] Tandon S, Mitra A and Robins N, 2021 Towards a just transition finance roadmap for India: laying the foundations for practical action (available at: www.bii.co.uk/en/news-insight/insight/articles/towards-a-just-transition-finance-roadmap-for-india/)

[57] UNFCCC 2023 Katowice committee of experts on impact of implementation of response measures (KCI), implementation of just transition and economic diversification strategies: a compilation of best practices from different countries (available at: https://unfccc.int/documents/624596)

[58] International Labour Organization 2022 Skills development for a just transition (available at: www.ilo.org/global/topics/green-jobs/publications/just-transition-pb/WCMS_860617/lang–en/index.htm)

[59] Central Pollution Control Board 2022 Government of India *CEPI Action Plans* (available at: https://cpcb.nic.in/new-cepi-action-plan/)

[60] European Commission 2020 The EU circular economy action plan (available at: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en)

[61] Aditya Lolla 2022 The good news and bad news of India's race to 175 GW renewables (Ember) (available at: https://ember-climate.org/insights/research/india-race-to-175-gw-renewables-updates/)

[62] Government of Bihar Bihar economic survey 2021–2022 (available at: https://state.bihar.gov.in/finance/cache/12/01-Mar-22/SHOW_DOCS/Press%20Release%20(English).pdf)

[63] Government of India 2023 Economic survey 2022–23, Government of India, ministry of finance department of economic affairs, economic division p 167 (available at: www.indiabudget.gov.in/economicsurvey/doc/echapter.pdf)

[64] Angad A 2022 Jharkhand forms task force to study impact of climate commitments (available at: https://indianexpress.com/article/india/jharkhand-forms-task-force-to-study-impact-of-climate-commitments-8261756/)

[65] Kerala Institute of Local Administration (KILA) 2022 Ecosystem-based disaster risk reduction- a handbook for practitioners (available at: http://dspace.kila.ac.in/bitstream/123456789/630/1/Eco%20DRR%20Handbook.pdf)

[66] Ministry of Urban Development 2011 High powered expert committee (HPEC) for estimating the investment requirements for urban infrastructure services: report on Indian urban infrastructure and services (Government of India) (available at: https://icrier.org/pdf/FinalReport-hpec.pdf)

[67] Department of Finance, Government of Bihar Green Budget 2022–2023 (available at: https://state.bihar.gov.in/cache/12/Budget/Budget/Green%20Budget%20Final%202022-23%20English%2006.12.pdf)

[68] UNFCCC 2023 Outcome of the first global stocktake (available at: https://unfccc.int/sites/default/files/resource/cma5_auv_4_gst.pdf)

[69] IPCC 2022 Summary for policymakers *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) (https://doi.org/10.1017/9781009157926.001)

[70] UN-DESA World urbanization prospects (available at: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf)

[71] Khosla R and Janda K B 2019 India's building stock: towards energy and climate change solutions *Build. Res. Inf.* **47** 1–7

[72] Chaturvedi V, Eom J, Clarke L and Shukla P R 2012 Long term building energy demand for India: disaggregating end use energy services in an integrated assessment modeling framework *EnerPol* **64** 226–42

[73] Dhar S, Pathak M and Shukla P R 2020 Transformation of India's steel and cement industry in a sustainable 1.5 °C world *EnerPol* **137** 111104

[74] Mishra T and Jajal P 2022 Temperature change and mitigation potential of Indian cement industry *Carbon Manage.* **13** 341–51

[75] MoEFCC 2022 India's long-term low-carbon development strategy (available at: https://unfccc.int/sites/default/files/resource/India_LTLEDS.pdf) (Accessed 28 December 2022)

[76] Nagpure A S, Tong K and Ramaswami A 2022 Socially-differentiated urban metabolism methodology informs equity in coupled carbon-air pollution mitigation strategies: insights from three Indian cities *Environ. Res. Lett.* **17** 094025

[77] Dhar S, Pathak M and Shukla P R 2018 Transformation of India's transport sector under global warming of 2 °C and 1.5 °C scenario *J. Clean. Prod.* **172** 417–27

[78] Seth S, Srivastava R, Osho Z and Harper S 2023 From planning to action: rethinking the role of cities in accelerating net-zero transitions *ThinkTwenty (T20) India 2023—Official Engagement Group of G20* (available at: https://t20ind.org/research/from-planning-to-action/)

[79] Das D K and Chadchan J 2023 A proposed framework for an appropriate governance system to develop smart cities in India (Territ. Politic. Gov.) pp 1–22 (available at: https://www.tandfonline.com/doi/full/10.1080/21622671.2023.2229872)

[80] Ministry of Environment, Forest and Climate Change of India 2021 India third biennial update report to the United Nations framework convention on climate change (available at: https://unfccc.int/sites/default/files/resource/INDIA_%20BUR-3_20.02.2021_High.pdf) (Accessed August 2023)

[81] National Power Portal 2023 (available at: https://npp.gov.in/dashBoard/cp-map-dashboard)

[82] Central Electricity Authority 2023 All India Electricity Statistics General Review 2023 (available at: https://cea.nic.in/wp-content/uploads/general/2023/GR_Final.pdf)

[83] US Energy Information Administration Dashboard (available at: https://www.eia.gov/international/data/country/IND) (Accessed February 2023)

[84] Ministry of Statistics and Programme Implementation 2023 National statistical office, GOI, energy statistics India 2023 (available at: www.mospi.gov.in/sites/default/files/publication_reports/Energy_Statistics_2023/EnergyStatisticsIndia2023.pdf) (Accessed 20 June 2023)

[85] Wartlisa and LUT University 2021 A 100% renewable power system across India by 2050 (available at: www.wartsila.com/insights/whitepapers/energy/a-100-renewable-power-system-across-india-by-2050)

[86] Jaiswal S 2022 Rohit Gadre (BloombergNEF) *Financing India's 2030 Renewables Ambition* (available at: https://assets.bbhub.io/professional/sites/24/BNEF-Financing-India%E2%80%99s-2030-Renewables-Ambition_FINAL.pdf) (Accessed August 2023)

[87] Ministry of New and Renewable Energy, Govt. of India National Green Hydrogen Mission (available at: https://mnre.gov.in/notice/the-national-green-hydrogen-mission-13-1-2023-648-kb-pdf/)

[88] Alliance for an Energy Efficient Economy (AEEE), Sustainable Energy for All (SEforAll) 2023 Strategic plan for advancing energy efficiency across demand sectors by 2030 (International Energy Agency (IEA)) (available at: https://www.seforall.org/system/files/2023-10/Energy_Efficiency_G-20_Plan.pdf)

[89] Chattopadhyay D, Chatterjee S K and Soonee S K 2023 Spotlight on the spot market: a review of the Indian wholesale electricity market *Electr. J.* **36** 107239
[90] CEA 2020 Growth of electricity sector in Indian from 2047–2020 (Central Electricity Authority) (available at: https://cea.nic.in/wp-content/uploads/pdm/2020/12/growth_2020.pdf)
[91] CEA 2022 All-India electricity statistics—general review 2022 (Central Electricity Authority) (available at: https://cea.nic.in/wp-content/uploads/general/2022/GR_2022_FINAL.pdf) (Accessed 11 April 2023)
[92] CEA Dashboard (Central Electricity Authority) 2021 (available at: https://cea.nic.in/dashboard/?lang=en) (Accessed 11 April 2023)
[93] CERC 2022 Report on short-term power market in India: 2021–22 (Central Electricity Regulatory Commission) (available at: https://cercind.gov.in/2022/market_monitoring/Annual%20MM%20Report%202021-22.pdf)
[94] Kahrl F, Deorah S M, Alagappan L, Sotkiewicz P M and Abhyankar N 2023 Policy and regulatory recommendations to support a least-cost pathway for India's power sector (Lawrence Berkeley National Laboratory) (available at: https://escholarship.org/uc/item/2dq3589s)
[95] Aggarwal D, Rao H V and Agarwal D 2022 How can discoms optimise power procurement costs? (Council on Energy, Environment and Water (CEEW)) (available at: www.ceew.in/publications/how-can-delhi-discoms-optimise-power-procurement-costs)
[96] Josey A, Mandal M and Dixit S 2017 The Price of Plenty: insights from "surplus" power in Indian States (Prayas (Energy Group)) (available at: https://energy.prayaspune.org/our-work/research-report/the-price-of-plenty-insights-from-surplus-power-in-indian-states) (Accessed 8 April 2023)
[97] Aggarwal P, Ganesan K and Narayanaswamy D 2020 Cost-effectiveness of discom operations in Uttar Pradesh (Council on Energy, Environment and Water (CEEW)) (available at: www.ceew.in/publications/cost-effectiveness-discom-operations-uttar-pradesh)
[98] Hu J, Harmsen R, Crijns-Graus W, Worrell E and van den Broek M 2018 Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: a literature review of market design *Renew. Sustain. Energy Rev.* **81** 2181–95
[99] NITI Ayog RMI, RMI India 2021 Turning around the power distribution sector—a compendium to guide the transformation of electricity distribution in India (NITI Ayog, RMI, and RMI India) (available at: https://rmi-india.org/insight/turning-around-the-power-distribution-sector/) (Accessed 8 April 2023)
[100] Verma M K, Mukherjee V, Kumar Yadav V and Ghosh S 2020 Indian power distribution sector reforms: a critical review *Energy Policy* **144** 111672
[101] Sasidharan C, Bhand I, Rajah V B, Ganti V, Sachar S and Kumar S 2021 White Paper on roadmap for demand flexibility in India (Alliance for an Energy Efficient Economy (AEEE)) (available at: https://aeee.in/our-publications/roadmap-for-demand-flexibility-in-india/) (Accessed 8 April 2023)
[102] CEA 2022 Draft guidelines for resource adequacy planning framework for India (Central Electricity Authority) (available at: https://cea.nic.in/wp-content/uploads/irp/2022/09/Draft_RA_Guidelines___23_09_2022_final.pdf)
[103] POSOCO 2022 SCED pilot—detailed feedback report (Power System Operation Corporation Limited (POSOCO)) (available at: https://posoco.in/wp-content/uploads/2022/04/Detailed-Feedback-on-SCED-Mar-2022.pdf)
[104] Rudnick H and Velasquez C 2018 Taking stock of wholesale power markets in developing Countries: a literature review (World Bank) (available at: http://hdl.handle.net/10986/29992) (Accessed 29 March 2023)
[105] Frei F, Loder A and Bening C R 2018 Liquidity in green power markets—an international review *Renew. Sustain. Energy Rev.* **93** 674–90
[106] Agrawal S, Mani S, Kalra S, Sharma B and Balani K 2023 How can India enable a consumer-centric smart metering transition? (Council on Energy, Environment and Water (CEEW)) (available at: www.ceew.in/publications/enabling-consumer-centric-smart-metering-transition-india)
[107] Glachant J M and Rossetto N (eds) Digest of the handbook on electricity markets International edition *European Union* (Florence School of Regulation) (available at: https://cadmus.eui.eu/handle/1814/75020;jsessionid=40A57B6876344DD911F204E2FB5ABBF0)
[108] IBEF *India Can Achieve Energy Independence by 2047, Says US Energy Department Study* (available at: www.ibef.org/news/india-can-achieve-energy-independence-by-2047-says-us-energy-department-study)
[109] Gupta R, Malik D, Sankhe S, and Unni N 2022 Decarbonising India: charting a pathway for sustainable growth (McKinsey & Company) (available at: https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonising-india-charting-a-pathway-for-sustainable-growth#/)
[110] Wartsila Energy 2021 Front-loading net zero (available at: https://www.wartsila.com/docs/default-source/energy-docs/positioning/front-loading-net-zero.pdf?sfvrsn=6bf97a43_10)
[111] International Renewable Energy Agency 2019 Future of wind: deployment, investment, technology, grid integration and socio-economic aspects *A Global Energy Transformation Paper*
[112] International Renewable Energy Agency 2017 Renewable energy benefits: leveraging local capacity for solar PV
[113] Hallam B, Kim M, Zhang Y, Wang L, Lennon A, Verlinden P, Altermatt P P, and Dias P R 2022 The silver learning curve for photovoltaics and projected silver demand for net-zero emissions by 2050 *Prog. Photovolt.* **31** 598–606
[114] Bhutada G *The Key Minerals in an EV Battery* (available at: https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/)
[115] Hall W, Spencer T, Renjith W and Dayal S 2022 The potential role of hydrogen in India (The Energy and Resources Institute)
[116] acatech and Dechema 2022 Critical Raw Materials for Electrolyser Production: Possible Shortages Due to Russia's Unprovoked Invasion of Ukraine, acatech and DECHEMA (available at: www.wasserstoff-kompass.de/fileadmin/user_upload/img/news-und-media/dokumente/Materials_for_Electrolysers_.pdf)
[117] Government of India (GoI), Critical minerals for India 2023 Ministry of Mines (GoI) (available at: https://mines.gov.in/admin/storage/app/uploads/649d4212cceb01688027666.pdf)
[118] Gupta V, Biswas T and Ganesan K 2016 Critical non-fuel mineral resources for India's manufacturing sector (Council on Energy, Environment and Water (CEEW) and Department of Science and Technology (DST), Government of India) (available at: https://static.investindia.gov.in/s3fs-public/CEEW_0_0.pdf)
[119] Gulley A L, McCullough E A and Shedd K B 2019 China's domestic and foreign influence in the global cobalt supply chain *Resour. Policy* **62** 317
[120] Li H, Zhu T, Chen X, Liu H and He G 2022 Improving China's global lithium resource development capacity *Front. Environ. Sci.* **10** 938534
[121] The Visual Capitalist 2020 Ethical supply: the search for cobalt beyond the Congo (available at: www.visualcapitalist.com/sp/ethical-supplythe-search-for-cobalt-beyond-the-congo/)

[122] Chatterjee B and Chadha R 2020 Non-fuel minerals and mining: enhancing mineral exploration in India *Discussion Note* (Brookings India) (available at: https://csep.org/wp-content/uploads/2022/10/Critical-Minerals-for-India_UPDATED.pdf)
[123] Chadha R and Sivamani G 2021 Minerals for India: assessing their criticality and projecting their needs for green technologies *Working Paper* (Centre for Social and Economic Progress (*CSEP*)) (available at: https://csep.org/wp-content/uploads/2022/10/Critical-Minerals-for-India_UPDATED.pdf)
[124] Neuhoff K *et al* Innovation and use policies required to realize investment and emission reductions in the materials sector (available at: https://repository.ubn.ru.nl/handle/2066/167551)
[125] Kanisetti A, Pareek A and Ramachandran N 2020 A rare earths strategy for India *Discussion Note* (Takshashila Institute)
[126] Singh A and Thirumalai N C 2023 Technology assessment framework 2.0: methodology note *Working Series No. CSTEP-WS-2023-01* (CSTEP)
[127] MoHI 2022 Three companies signed program agreement under (PLI) scheme for advanced chemistry cell (ACC) battery storage (Ministry of Heavy Industries, Government of India) (available at: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1911380#:∼:text=The%20Government%20has%20allocated%20a,Modules%20(Tranche%2DII))
[128] MoP 2023 Government allocates 39600 MW of domestic solar PV module manufacturing capacity under PLI (Tranche-II) (Ministry of Power, Government of India) (available at: https://pib.gov.in/pib.gov.in/Pressreleaseshare.aspx?PRID=1911380)
[129] Clarke L *et al* 2022 Energy systems *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the IPCC Sixth Assessment Report* (Cambridge University Press)
[130] Committee on developing a research agenda for carbon dioxide removal and reliable sequestration 2019 *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (National Academies of Sciences, Engineering, and Medicine) (available at: https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda)
[131] Pozo C, Galán-Martín Á, Reiner D M, Mac Dowell N and Guillén-Gosálbez G 2020 Equity in allocating carbon dioxide removal quotas *Nat. Clim. Change* **10** 640–6
[132] UNFCCC India's long-term low-carbon development strategy (available at: https://unfccc.int/documents/623511) (Accessed 23 January 2023)
[133] MoEFCC 2019 National afforestation programmes to improve the forest cover (Ministry of Environment, Forest and Climate Change, Government of India) (available at: https://pib.gov.in/Pressreleaseshare.aspx?PRID=1596332#:∼:text=The%20overall%20objective%20of%20the,fringe%20communities%2C%20especially%20the%20poor) (Accessed 23 January 2023)
[134] Anand A, Kumar V and Kaushal P 2022 Biochar and its twin benefits: crop residue management and climate change mitigation in India *Renew. Sustain. Energy Rev.* **156** 111959
[135] Patange O S, Garg A and Jayaswal S 2022 An integrated bottom-up optimization to investigate the role of BECCS in transitioning towards a net-zero energy system: a case study from Gujarat, India *Energy* **255** 124508
[136] Vishal V and Singh U 2023 Status and outlook: CCUS in India *Technology Research Brief* (available at: https://climatecollective.typeform.com/CCUSTRB) (Accessed 7 July 2023)
[137] Angom J and Karthiayani V P 2020 Contribution of national rural employment guarantee programme on rejuvenation and restoration of community forests in India' *Front. For. Glob. Change* **3** 91
[138] Anand A, Pathak S, Kumar V and Kaushal P 2022 Biochar production from crop residues, its characterization and utilization for electricity generation in India *J. Clean. Prod.* **368** 133074
[139] Vishal V, Chandra D, Singh U and Verma Y 2021 Understanding initial opportunities and key challenges for CCUS deployment in India at scale *Resour. Conserv. Recycl.* **175** 105829
[140] Vishal V, Singh U, Bakshi T, Chandra D, Verma Y and Tiwari A K 2023 Optimal source-sink matching and prospective hub-cluster configurations for CO_2 capture and storage in India *Geol. Soc.* **528** SP528–2022
[141] Vishal V, Verma Y, Chandra D and Ashok D 2021 A systematic capacity assessment and classification of geologic CO_2 storage systems in India *Int. J. Greenh. Gas Control* **111** 103458
[142] Singh A K, Mendhe V A and Garg A 2006 CO_2 storage potential of geologic formations in India *8th Greenhouse Gas Technology Conference* (*Trondheim, Norway*)
[143] Garg A, Shukla P R, Parihar S, Singh U and Kankal B 2017 Cost-effective architecture of carbon capture and storage (CCS) grid in India *Int. J. Greenh. Gas Control* **66** 129–46
[144] Sharma S K *et al* 2011 Greenhouse gas inventory estimates for India *Curr. Sci.* **101** 405–15
[145] Garg A, Singh U, Jain S K, Maheshwari J, Vishwanathan S S and Singh A K 2023 International study on financing needs for new age critical clean energy technologies: CO_2 capture, utilization, and storage (CCUS) (Ministry of Power, NTPC-NETRA, IIM) (available at: www.iima.ac.in/sites/default/files/2023-03/1_CCUS%20Report%20%2809-03-2023%29.pdf) (Accessed 7 July 2023)
[146] Chiquier S, Patrizio P, Bui M, Sunny N and Mac Dowell N 2022 A comparative analysis of the efficiency, timing, and permanence of CO_2 removal pathways *Energy Environ. Sci.* **15** 4389–403
[147] Singh A K and Hajra P N 2018 *Coalbed Methane in India: Opportunities, Issues and Challenges for Recovery and Utilization* (Springer)
[148] Mitchell A L, Rosenqvist A and Mora B 2017 Current remote sensing approaches to monitoring forest degradation in support of countries measurement, reporting and verification (MRV) systems for REDD+ *Carbon Balance Manage.* **12** 1–22
[149] Ashutosh S, Sharma S, Lakhchaura P, Ghosh S, Tripathi S and Uniyal M 2019 India's nationally determined contribution of creating an additional carbon sink of 2.5–3 billion tonnes of CO_2 eq through additional forest & tree cover: possibilities, scale & costs for formulating strategy (available at: https://fsi.nic.in/uploads/documents/technical-information-series-vol1-no3-16-06-2019a.pdf) (Accessed 1 May 2023)
[150] Chaturvedi R K, Strappason A and Garg A 2022 Forests, trees and agroforestry: their roles in India's sustainable development and climate action *Indian Forester* **148** 539
[151] Gopalakrishna T, Lomax G, Aguirre-Gutiérrez J, Bauman D, Roy P S, Joshi P K and Malhi Y 2022 Existing land uses constrain climate change mitigation potential of forest restoration in India *Conserv. Lett.* **15** e12867
[152] MoEFCC 2022 State of forest report 2021 (Ministry of Environment, Forest and Climate Change, Government of India) (available at: https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/jan/doc20221207001.pdf)
[153] Srivathsa A *et al* 2023 Prioritizing India's landscapes for biodiversity, ecosystem services and human well-being *Nat. Sustain.* **6** 568–77
[154] Fleischman F, Coleman E, Fischer H, Kashwan P, Pfeifer M, Ramprasad V, Rodriguez Solorzano C and Veldman J W 2022 Restoration prioritization must be informed by marginalized people *Nature* **607** E5–E6

[155] Rana P, Fleischman F, Ramprasad V and Lee K 2022 Predicting wasteful spending in tree planting programs in Indian Himalaya *World Dev.* **154** 105864
[156] Pargaien Mohan Chandra 2022 Forest restoration: challenges and opportunities for India *Mongabay Series: Climate Connections, Nature-based Solutions*
[157] Calvin K *et al* 2019 GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems *Geosci. Model Dev.* **12** 677–98
[158] Ashutosh S, Chaturvedi R, Sharma S and Lakhchaura P 2020 Mapping climate change hotspots in Indian forests based on observed climate change and high resolution climate model projections *Dehradun* (available at: http://webline.org.in/technical-information-series-vol2-no5-2020.pdf) (Accessed 1 May 2023)
[159] Lucas R M *et al* 2022 A globally relevant change taxonomy and evidence-based change framework for land monitoring *Glob. Change Biol.* **28** 6293–317
[160] Owers C J, Lucas R M, Clewley D, Planque C, Punalekar S, Tissott B, Chua S M T, Bunting P, Mueller N and Metternicht G 2021 Living Earth: implementing national standardised land cover classification systems for Earth observation in support of sustainable development *Big Earth Data* **5** 368–90
[161] Pörtner H-O *et al* 2023 Overcoming the coupled climate and biodiversity crises and their societal impacts *Science* **380** eabl4881
[162] Osuri A M, Mudappa D, Kasinathan S and Raman T R S 2022 Canopy cover and ecological restoration increase natural regeneration of rainforest trees in the Western Ghats, India *Restor. Ecol.* **30** e13558
[163] Edrisi S A, Tripathi V, Chaturvedi R K, Dubey D K, Patel G and Abhilash P C 2021 Saline soil reclamation index as an efficient tool for assessing restoration progress of saline land *Land Degrad. Dev.* **32** 123–38
[164] Alaniz A J, Pérez-Quezada J F, Galleguillos M, Vásquez A E and Keith D A 2019 Operationalizing the IUCN red list of ecosystems in public policy *Conserv. Lett.* **12** e12665
[165] Chandra S, Singh A, Mathew J R, Singh C P, Pandya M R, Bhattacharya B K, Solanki H, Nautiyal M C and Joshi R 2022 Phenocam observed flowering anomaly of Rhododendron arboreum Sm. in Himalaya: a climate change impact perspective *Environ. Monit. Assess.* **194** 877
[166] Harrison K and Sundstrom L M 2010 Global commons, domestic decisions: the comparative politics of climate change *American and Comparative Environmental Policy* (MIT Press)
[167] Meckling J and Nahm J 2018 The power of process: state capacity and climate policy *Governance* **31** 741–57
[168] Hochstetler K 2020 *Political Economies of Energy Transition: Wind and Solar Power in Brazil and South Africa* 1st edn (Cambridge University Press)
[169] Dubash N K 2021 Varieties of climate governance: the emergence and functioning of climate institutions *Environ. Politics* **30** 1–25
[170] Mildenberger M 2020 *Carbon Captured: How Business and Labor Control Climate Politics* (MIT Press)
[171] Pillai A V and Dubash N K 2021 The limits of opportunism: the uneven emergence of climate institutions in India *Environ. Politics* **30** 93–117
[172] Cabinet Secretariat 1961 *Government of India (Allocation of Business) Rules* (available at: https://cabsec.gov.in/writereaddata/allocationbusinessrule/completeaobrules/english/1_Upload_1187.pdf)
[173] Guy J, Shears E and Meckling J 2023 National models of climate governance among major emitters *Nat. Clim. Change* **13** 189–95
[174] Meckling J, Lipscy P Y, Finnegan J J and Metz F 2022 Why nations lead or lag in energy transitions *Science* **378** 31–33
[175] Dubash N K *et al* 2021 National climate institutions complement targets and policies *Science* **374** 690–3
[176] Pillai A V and Dubash N K 2023 Climate Governance and Federalism in India *Climate Governance and Federalism* 1st edn, ed A Fenna, S Jodoin and J Setzer (Cambridge University Press) pp 177–97
[177] Mildenberger M 2021 The development of climate institutions in the United States *Environ. Politics* **30** 71–92
[178] Tyler E 2010 Aligning South African energy and climate change mitigation policy *Clim. Policy* **10** 575–88
[179] Lockwood M 2021 A hard Act to follow? The evolution and performance of UK climate governance *Environ. Politics* **30** 26–48
[180] Dubash N K, Pillai A V and Bhatia P 2021 Building a climate-ready Indian state: institutions and governance for transformative low-carbon development (Centre for Policy Research) (available at: www.cprindia.org/research/reports/building-climate-ready-indian-state-institutions-and-governance-transformative-low)
[181] Pillai A V, Dubash N K and Bhatia P 2021 Unlocking Climate Action in Indian Federalism *Centre for Policy Research* (Policy Brief)
[182] Sridhar A, Averchenkova A, Rumble O, Dubash N K, Higham C and Gilder A 2022 Climate governance functions: towards context-specific climate laws *Centre for Policy Research, Grantham Research Institute on Climate Change and the Environment* (Climate Legal, Policy Brief) (available at: https://cprindia.org/wp-content/uploads/2022/10/Climate-Governance-Functions_17_Nov_22.pdf)
[183] MacNeil R 2021 Swimming against the current: australian climate institutions and the politics of polarisation *Environ. Politics* **30** 162–83
[184] Hochstetler K 2021 Climate institutions in Brazil: three decades of building and dismantling climate capacity *Environ. Politics* **30** 49–70
[185] Pierson P 2004 *Politics in Time: History, Institutions, and Social Analysis* (Princeton University Press) (available at: https://www.iea.org/reports/net-zero-by-2050)
[186] IEA 2021 Net zero by 2050: a roadmap for the global energy sector (International Energy Agency (IEA)) (available at: www.iea.org/reports/net-zero-by-2050)
[187] IEA 2023 Scaling up private finance for clean energy in emerging and developing economies (International Energy Agency (IEA)) (available at: www.iea.org/reports/scaling-up-private-finance-for-clean-energy-in-emerging-and-developing-economies)
[188] Singh V P and Sidhu G 2021 Investment sizing India's net-zero transition, Council on Energy, Environment and Water (CEEW) Issue Brief (available at: www.ceew.in/cef/solutions-factory/publications/CEEW-CEF-Investment-Sizing-India%E2%80%99s-2070-Net-Zero-Target.pdf)
[189] BNEF 2023 *New Energy Outlook India*
[190] IEA 2024 *World Energy Investment 2024* (IEA) (available at: www.iea.org/reports/world-energy-investment-2024)
[191] IEA 2021 *India Energy Outlook 2021* (IEA) (available at: www.iea.org/reports/india-energy-outlook-2021)
[192] Gandhi H H, Hoex B and Hallam B J 2022 Strategic investment risks threatening India's renewable energyambition *Energy Strategy Rev.* **43** 100921
[193] Venkateshwaran S 2023 ESG reporting in an increasingly volatile world—relevance and evolution (ET Energy World) (available at: https://energy.economictimes.indiatimes.com/news/renewable/esg-reporting-in-an-increasingly-volatile-world-relevance-and-evolution/98803723)
[194] Sen R and Mangla M 2023 From struggling to thriving: How Credit Guarantees can bridge the credit gap faced by MSMEs (The Economic Times) (available at: https://economictimes.indiatimes.com/small-biz/money/from-struggling-to-thriving-how-credit-guarantees-can-bridge-the-credit-gap-faced-by-msmes/articleshow/98204362.cms?from=mdr)
[195] Arora G 2023 Climate budgeting: unlocking the potential of India's fiscal policies for climate action (Observer

Research Foundation (ORF)) (available at: https://www.orfonline.org/expert-speak/climate-budgeting#:~:text=The%20recently%20released%20Union%20Budget,energy%20transition%20and%20sustainable%20development)

[196] Srivastava S and Trivedi S 2023 Indian capital market regulator's updated green debt guidelines: unlocking the potential of sustainable finance (Institute for Energy Economics and Financial Analysis (IEEFA)) (available at: https://ieefa.org/resources/indian-capital-market-regulators-updated-green-debt-guidelines-unlocking-potential)

[197] Srivastava S and Trivedi S 2023 Unlocking sustainable investments: the Reserve Bank of India's crucial role in energy transition (Institute for Energy Economics and Financial Analysis (IEEFA)) (available at: https://ieefa.org/resources/unlocking-sustainable-investments-reserve-bank-indias-crucial-role-energy-transition)

[198] The World Bank 2023 State and trends of carbon pricing (available at: https://openknowledge.worldbank.org/items/58f2a409-9bb7-4ee6-899d-be47835c838f)

[199] Climate Focus and Perspectives 2019 Moving towards next generation carbon markets observations from article 6 pilots (available at: https://climatefocus.com/wp-content/uploads/2022/06/CFI-Moving-towards-next-generation-carbon-markets-1.pdf)

[200] Internal market analysis

[201] Climate Focus Voluntary carbon market dashboard (available at: https://climatefocus.com/initiatives/voluntary-carbon-market-dashboard/) (Accessed May 2023)

[202] Singh N and Chaturvedi V 2023 Understanding carbon markets: prospects for India and stakeholder perspectives (Council on Energy, Environment and Water (CEEW)) (available at: https://ceew.in/sites/default/files/carbon-credit-markets-in-india-prospects-stakeholder-perspectives.pdf)

[203] World Economic Forum (WEF) 2023 The voluntary carbon market: climate finance at an inflection point (available at: https://www3.weforum.org/docs/WEF_The_Voluntary_Carbon_Market_2023.pdf)

[204] Marr M A, Ahonen H M, Figueroa X S and von Unger M 2023 Supporting authorizations under Article 6 of the Paris Agreement: lessons learned and key considerations (available at: https://perspectives.cc/publication/supporting-authorizations-under-article-6-of-the-paris-agreement/)

[205] The World Bank 2023 Authorization for international transfer of emission reduction credits (available at: https://a6partnership.org/wp-content/uploads/2023/03/2-1_World-Bank_Authorization.pdf)

[206] UNCTD 1985 Draft international code of conduct on the transfer of technology (available at: https://digitallibrary.un.org/record/86199/files/TD_CODE_TOT_47-EN.pdf)

[207] Kniivilä M 2004 Industrial development and economic growth: implications for poverty reduction and income inequality *Industrial Development for the 21st Century: Sustainable Development Perspectives* no. 1956 (United Nations, Department of Social and Economic Affairs) pp 295–332 (available at: www.un.org/esa/sustdev/publications/industrial_development/3_1.pdf)

[208] Beard S J, Holt L, Tzachor A, Kemp L, Avin S, Torres P and Belfield H 2021 Assessing climate change's contribution to global catastrophic risk *Futures* **127** 102673

[209] Aslam A, Eugster J, Ho G, Jaumotte F and Piazza R 2018 *Globalization Helps Spread Knowledge and Technology Across Borders* (available at: www.imf.org/en/Blogs/Articles/2018/04/09/globalization-helps-spread-knowledge-and-technology-across-borders) (Accessed 9 April 2023)

[210] UNFCCC 1992 United Nations Framework Convention on Climate Change (United Nations, FCCC/INFORMAL/84 GE. 05-62220 (E) 200705, Secretariat of the United Nations Framework Convention on Climate Change) p 24 (available at: https://unfccc.int/resource/docs/convkp/conveng.pdf)

[211] Tamura K 2006 "*Technology Development and Transfer," in Asian Aspirations for Climate Regime beyond 2012* ed S Ancha (Institute for Global Environmental Strategies) (https://doi.org/10.4337/9781788979191.00019)

[212] IPCC 2000 Methodological and technological issues in technology transfer (available at: www.ipcc.ch/report/methodological-and-technological-issues-in-technology-transfer/) (Accessed 10 April 2023)

[213] Corsi A, Pagani R N, Kovaleski J L and Luiz da Silva V 2020 Technology transfer for sustainable development: social impacts depicted and some other answers to a few questions *J. Clean. Prod.* **245** 118522

[214] Zhang F and Gallagher K S 2016 Innovation and technology transfer through global value chains: evidence from China's PV industry *Energy Policy* **94** 191–203

[215] Deslatte A and Swann W L 2017 Context matters: a Bayesian analysis of how organizational environments shape the strategic management of sustainable development *Public Adm.* **95** 807–24

[216] Bharadwaj B, Malakar Y, Herington M and Ashworth P 2022 Context matters: unpacking decision-making, external influences and spatial factors on clean cooking transitions in Nepal *Energy Res. Soc. Sci.* **85** 102408

[217] Nuru J T, Rhoades J L and Sovacool B K 2022 Virtue or vice? Solar micro-grids and the dualistic nature of low-carbon energy transitions in rural Ghana *Energy Res. Soc. Sci.* **83** 102352

[218] Janardhanan N and Murun T 2023 *Accelerating Net-zero Goals in Asia: The Role of Joint Crediting Mechanism and Co-innovation* (Institute for Global Environmental Strategies) (https://doi.org/10.57405/IGES-12735)

[219] Janardhanan N, Ikeda E, Kalyani S, Murun T and Tamura K 2022 Role of co-innovation in accelerating towards climate neutrality *Asia-Pac. Tech. Monit.* **39** 30–39 (available at: www.iges.or.jp/en/pub/co-innovation-climate-neutrality/en)

[220] Wang K, Li G, Chen J, Long Y, Chen T, Chen L and Xia Q 2020 The adaptability and challenges of autonomous vehicles to pedestrians in urban China *Accid. Anal. Prev.* **145** 105692

[221] Janardhanan N, Pham N-B, Hibino K and Akagi J 2021 Enabling Japan's low emissions technology collaboration with Southeast Asia: the role of co-innovation and co-benefits *Aligning Climate Change and Sustainable Development Policies in Asia* vol 10 (Springer Nature) pp 163–85

[222] PIB 2021 *National Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow* (Press Information Bureau (PIB)) (available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1768712) (Accessed 28 April 2023)

[223] UN 2023 Goal 12: ensure sustainable consumption and production (United Nations (UN)) (available at: www.un.org/sustainabledevelopment/sustainable-consumption-production/#:~:text=Goal%2012%3A%20Ensure%20sustainable%20consumption%20and%20production%20patterns&text=Goal%2012%20is%20about%20ensuring,of%20current%20and%20future%20generations) (Accessed 23 May 2023)

[224] NITI Aayog 2022 *LiFE Lifestyles for Environment* (NITI Aayog, Government of India) (available at: https://www.niti.gov.in/sites/default/files/2022-10/Brochure-10-pages-op-2-print-file-20102022.pdf#:~:text=In%202022-23,%20Mission%20LiFE%20will%20focus%20on%20Phase%20I,%20Change)

[225] Agrawal S and Kalra S 2022 Shifting policy gears to effect global transition towards sustainable lifestyles (Stockholm Environment Institute (SEI) and Council on Energy

Environment and Water (CEEW)) (available at: https://www.ceew.in/sites/default/files/global-policy-effect-transition-sustainable-lifestyles-stockholm50-background-paper.pdf)
[226] G20 Development Ministers 2023 *G20 High Level Principles on Lifestyles for Sustainable Development* (available at: https://www.mea.gov.in/Images/CPV/G20_High_level.pdf)
[227] Global Footprint Network 2023 Socioeconomic relationships *Global Footprint Network* (available at: https://data.footprintnetwork.org/#/SocioEconomics?cn=5001&type=BCtot,EFCtot&misc=hdi) (Accessed 28 April 2023)
[228] World Inequality Lab 2022 Chapter I: global economic inequality: insights (World Inequality Lab) (available at: https://wir2022.wid.world/chapter-1/#:~:text=Global%20wealth%20inequalities%20are%20even,own%2076%25%20of%20all%20wealth) (Accessed 28 April 2023)
[229] UNDESA 2023 Ensure sustainable consumption and production patterns (available at: https://unstats.un.org/sdgs/report/2019/goal-12/) (Accessed 17 April 2023)
[230] Faiers A, Cook M and Neame C 2007 Towards a contemporary approach for understanding consumer behaviour in the context of domestic energy use *Energy Policy* **35** 4381–90
[231] Circle Economy 2023 The circularity gap report (Circle Economy Foundation and Deloitte) (available at: www.circularity-gap.world/2023#download)
[232] Kirchherr J, Reike D and Hekkert M 2017 Conceptualizing the circular economy: an analysis of 114 definitions *Resour. Conserv. Recycl.* **127** 221–32
[233] OECD 2021 Closing the SDG financing gap in the COVID-19 era: scoping note for the G20 development working group (available at: www.oecd.org/dev/OECD-UNDP-Scoping-Note-Closing-SDG-Financing-Gap-COVID-19-era.pdf) (Accessed 18 September 2023)
[234] Brick K, DeMartino S and Visser M 2023 Behavioural nudges for water conservation: experimental evidence from cape town *J. Environ. Econ. Manage.* **121**
[235] Anbumozhi V, Buchoud N J, Charalambous A, Croci E, Jain H, Kochhan M, Mallya H, Raha S, Osuna V R and Sonobe T 2021 Localising the circular economy imperative in a post COVID-19 Era: place, trade and multilateralism *T20 Italy 2021* (available at: https://www.t20italy.org/wp-content/uploads/2021/09/TF2-16.pdf#:~:text=Policy%20brief.%20LOCALISING%20THE%20CIRCULAR%20ECONOMY%20IMPERATIVE%20IN%20A%20POST)
[236] Ghosh A, Harihar N and Jain P 2022 Co-development of technologies of the future (Stockholm Environment Institute) (available at: https://www.sei.org/wp-content/uploads/2022/05/co-development-technologies-stockholm50backgroundpaper.pdf)
[237] IPCC 2022 Chapter 18.7: IPCC WGII sixth assessment report *Intergovernmental Panel on Climate Change* (available at: https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-18/)
[238] GoI 2021 India third biennial update report to the United Nations framework convention on climate change
[239] GoI 2012 Second national communication to UNFCCC (available at: https://unfccc.int/resource/docs/natc/indnc2.pdf)
[240] CEEW 2019 A capacity building assessment matrix for enhanced transparency in climate reporting *A Comprehensive Evaluation of Indian Efforts*
[241] GHG Platform India (available at: www.ghgplatform-india.org/) (Accessed 31 July 2023)
[242] UNFCCC 2016 Third comprehensive review of the implementation of the of the framework for capacity-building in developing countries. Technical paper by the secretariat (available at: https://unfccc.int/sites/default/files/resource/docs/2016/tp/01.pdf)
[243] UNFCCC 2022 Implementation of the framework for capacity-building in developing countries *Synthesis report by the secretariat* (available at: https://unfccc.int/sites/default/files/resource/sbi2022_02E_0.pdf)
[244] CEEW 2022 Communicating climate action effectively: a reporting framework for nations to inform the public (available at: www.ceew.in/sites/default/files/ceew-research-on-climate-change-reporting-framework-for-nations.pdf)
[245] UNFCCC 2018 Decision 18/CMA.1, Modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of Paris Agreement (available at: https://ledslac.org/wp-content/uploads/2020/09/e.-Decision-18-cma.1.pdf)
[246] CBIT 2019 CBIT proposal India—capacity-building for establishing an integrated and enhanced transparency framework for climate actions and support measures (available at: www.thegef.org/sites/default/files/web-documents/10194_CBIT_India_PIF.pdf)