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Accelerating India's Climate Transition: Pathways to the 1.5°C Goal

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Executive Summary

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Executive Summary

Human-induced climate change is unequivocally altering climate impact-drivers across the world, especially heat, precipitation (rain, snow, ice), wind, and sea levels (IPCC, 2021). In India, temperature and precipitation extremes are showing warming patterns and more erratic rainfall respectively (Krishnan et al., 2020). **Over the past few decades, climate trends in the country have worsened compared to 1976-2005,** with mean surface air temperature expected to rise by 1.4°C to 2.7°C by 2050, in addition to the 0.7°C rise since 1901 (IPCC, 2022a).

Local temperatures, influenced by regional effects and Urban Heat Islands, can exceed 2.5°C, with Kolkata already 2.6°C warmer than pre-industrial levels (IPCC, 2021; SUP, 2022). Summer heat waves could occur 3-4 times more often by 2100 compared to 1976-2005 under high-emission scenarios (Krishnan et al., 2020). Rainfall patterns are also becoming more unpredictable, with an increase in the frequency of heavy rain events across most of India.

These climatic changes pose significant risks to regions, ecosystems, and key sectors such as agriculture and food, water resources, labour productivity, health, and infrastructure. Climate-induced risks can impact India's sustainable development targets and economic aspirations, potentially reversing decades of progress. If left unchecked, climate change could lead to annual Gross Domestic Product (GDP) loss of 3 to 10 per cent by 2100 (RBI 2023; Kompas, Pham, and Che, 2018).

As global temperatures rise, climate impacts will worsen, with risks multiplying non-linearly every tenth of a degree increase above 1.5°C, and every half degree increase bringing significant changes (IPCC, 2018; Revi, 2022). For example, at 1.5°C, South Asia, including India, will experience an average of 9.7 months of drought, increasing to 15.4 months at 3°C. The number of people exposed to heatwaves in India will increase by 15 times at 1.5°C and by 92 times at 2°C. A rise from 1.5°C to 2°C is projected to reduce per capita water availability in 90 per cent of regions across India, leaving over 400 million people facing severe water stress. Coastal flooding is expected to affect 5-8 per cent of India's coastal areas at 1.5°C, increasing to 9–13 per cent area at 3°C. At 4°C warming, under high emissions scenario RCP8.5[1], flood risks are projected to increase 20-fold, making India the second most-affected country in terms of population and the fifth in annual economic damages (Alfieri et al., 2017).

Critically, these risks are occurring more frequently and often simultaneously, potentially compounding risks for particular populations and limiting adaptation options. As warming increases, climate impacts could become irreversible, leading to a breakdown of social, economic, and ecological systems. There is however, insufficient evidence to diagnose when and where these limits will emerge, and how they will cascade across systems and sectors. Given growing climate risk and development priorities, it is imperative that India meets the Paris goal of limiting temperature rise to 1.5°C and transitions to a low-carbon, climate-resilient economy.

Currently, India is the fifth largest economy globally, with a nominal GDP of USD 4.1 trillion (IMF, 2024) and aspirations to be an advanced economy by 2047. In the last five decades, India's development has been marked by increasing population and GDP, largely driven by growth in the services sector and to a lesser extent the manufacturing sector. Despite its economic growth, several serious socio-economic challenges, including poverty, inequality, unemployment, and infrastructure deficits persist in the country. For instance, India still has the largest population of poor people in the world (about 229 million) even after 415 million people exited poverty in the last 15 years (UNDP, 2023).

A critical area of concern is slow employment growth, characterised by low productivity, low wages, increasing informalisation, low participation of women in the

[1] The Representative Concentration Pathways (RCPs) describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use. Refer to IPCC AR5 assessment: https://ar5-syr.ipcc.ch/topic_summary.php

workforce, and a lack of adequate skilled workers (Basole, 2022; World Bank, 2024a). India's ongoing urban transition, one of the largest globally, presents both challenges and opportunities for development and climate action. India's urban population is expected to increase to 600 million by 2031 and to 850 million by 2051 (MOEFCC, 2018). To meet the demand of the growing population, adequate infrastructure including environmental services, affordable housing and transport have to be designed and developed from the ground up or upgraded significantly to be climate resilient.

So far, India's growth trajectory has resulted lower emissions per unit of GDP compared to developed countries at similar development levels in the past (MOEFCC, 2015). However, maintaining this trajectory is challenging due rising population, urbanisation, industrialisation, and consumption.

To address these challenges, India needs a new development paradigm that integrates economic and environmental goals, sustainability and growth, and equity and justice. The **Climate Resilient Development (CRD) framework, negotiated by the Intergovernmental Panel on Climate Change (IPCC), across 193 countries, in its Sixth Assessment Report (AR6) does just that by integrating sustainable development, climate and biodiversity goals (IPCC, 2022; IPCC, 2023).** This report adopts the CRD framework to explore climate resilient pathways for India to meet the 1.5°C Paris goal and achieve net-zero emissions.

CRD can be operationalised through simultaneous systems transitions across five key areas: energy; urban and infrastructure; land, freshwater and ocean ecosystems; industry; and societal and behavioural choices (IPCC, 2022). This report assesses adaptation and mitigation actions across key systems to devise a climate strategy that fosters growth, creates jobs, and addresses the climate crisis.

India has established a comprehensive climate policy network, within its federal structure, notably through the National Action Plan on Climate Change (NAPCC) with its eight missions focusing on key sectors (e.g., water, agriculture) and/or regions (e.g., the Himalayas) (MOEFCC, 2018; MoEFCC, 2012). More recently, cities have begun developing climate action plans and rural areas are integrating climate planning into development plans. India's climate policies take a co-benefits approach, aligning adaptation and mitigation goals with broader development objectives.

India's Nationally Determined Contribution (NDC) includes targets such as reducing emission intensity of its GDP by 45 per cent, achieving 50 per cent non-fossil fuels-based power capacity by 2030, promoting sustainable lifestyles, and reaching net-zero emissions by 2070 (GOI, 2023; MoEFCC, 2022). With a strong push for renewables, India is on track to meet its 2030 power capacity target (IEA, 2023). However, deeper emission cuts are necessary by 2030 to stay on 1.5°C pathway (Climate Action Tracker, 2023). To be 1.5°C-compatible, India's coal power generation must decrease significantly and be phased out completely by 2040 (Climate Action Tracker, 2023).

Despite progress in climate-sensitive sectors like agriculture, urban and water, several challenges remain. These include the need for better risk assessments, stronger synergies between adaptation and mitigation actions, and attention to gendered and identity-based vulnerabilities. Risk-proofing social protection and acknowledging rural-urban interconnections, whether through migrant populations or regional infrastructure and resource flows, remain key gaps in current climate action. While India is moving towards renewable energy targets, a clear strategy is needed to scale up energy efficiency, phase out coal power, and ensure job creation, livelihood compensation, and energy security.

India's total GHG emissions increased by 115 per cent from 1994 to 2019 (MOEFCC, 2023), surpassing the global average. Its share in global emissions increased from 1.3 per cent in 1970 to 6.3 per cent in 2015 (Karstensen et al., 2020). **Mitigation efforts will be critical for decarbonising across systems, especially energy, as actions in this sector can impact other areas.** Decarbonisation (from Business as Usual to NDC scenarios) and deep decarbonisation (from NDC to Low-Carbon pathways) of the economy requires focus on several key areas: increasing energy efficiency in supply and demand sectors, enhancing renewable energy deployment, reducing demand through dematerialization, recycling, reuse, and behaviour change, and feasible deployment of CCS. Energy efficiency and renewable energy will play nearly equal roles in CO_2 mitigation under the NDC scenario, while lifestyle changes and new technologies like Carbon Capture and Storage (CCS) (Vishwanathan et al., 2018) and green hydrogen will become more relevant for low-carbon scenarios.

Mitigation pathways can also drive India's economic transition by creating new job opportunities, transforming the dominant services sector (through green jobs), and opening up low-carbon pathways in the manufacturing sector through options like energy efficient buildings, electric vehicles, and clean energy. In urban and infrastructure systems, mitigation offers levers for transformation, including stringent building standards, retrofitting existing infrastructure, and developing climate resilient industrial infrastructure. Demand-side management such as streamlined power storage and distribution, smart mobility, circular economy, and sustainable consumption, further enhances this transition.

There is sufficient evidence on a range of feasible adaptation and mitigation actions including strategies already being implemented across the country. These efforts can be deepened or scaled up to accelerate system-wide transitions in energy, land, oceans and ecosystems, and urban and infrastructure. Systems need to transition through combinations of options that minimise trade-offs and leverage synergies between adaptation, mitigation, and the Sustainable Development Goals (SDGs). For example, in land and ecosystem transitions, options include climate-resilient agriculture production (through changing crop varieties or improved irrigation efficiency), sustainable and climate-proofed food supply chains, and mechanisms to reduce food wastage.

Nature-based solutions in urban systems, such as strengthening green and blue infrastructure, show promise in meeting adaptation, mitigation, and sustainable development goals. These solutions create healthier, more liveable cities, reduce disaster risks, and help develop urban carbon sinks (e.g., in urban forests or parks). In energy system transitions, a mix of supply and demand side mitigation measures exist but institutional and macro/micro-economic feasibility remain key barriers. These include how inter and intra-generational outcomes are managed and delivered. The emerging bottleneck is oriented towards synergising the structural transformation underway (urban and industrial transition) with mitigation options. Significant potential and opportunities exist in certain key sectors like buildings, mobility, in terms of delivering decarbonisation goals and development outcomes (jobs, poverty reduction).

Crucially, these adaptation and mitigation options offer significant synergies to meet multiple sustainable development goals, thereby creating opportunities for triple wins. Various examples across India, in different systems illustrate how these synergies are being leveraged through existing policies and programs. For example, the National Mission on Sustainable Agriculture promotes precision farming and climate smart agriculture, which alleviates hunger and improves nutritional security (SDG 2, 3) and strengthens livelihoods (SDG 8), while maintaining ecosystem functioning (SDG 14). In cities, sustainable water management through smart meter programs and subsidised rainwater harvesting is enabling goals on clean water (SDG 6), sustainable cities (SDG 11), and ensuring health and wellbeing (SDG 3).

The challenge lies in the need for rapid and simultaneous systems transitions across economic sectors. To accelerate climate action, governments, civil society, and the private sector can focus their attention on specific enabling conditions. This report highlights six enabling conditions: enhancing multi-level governance; improving institutional capacities; strengthening policy instruments; expanding and deepening climate finance; enabling technological innovation; and behavioural and lifestyle change. India already demonstrates significant action across enabling conditions especially on policy instruments (e.g., National Solar Mission, Coalition for Disaster Resilient Infrastructure, National Mission on Sustainable Habitat and the Jal Jeevan Mission) and technological innovation (e.g., early warning systems and low-cost electric vehicles). India's Life Mission, first announced at COP 26 in Glasgow, also aims at changing individual and community behaviour by promoting environmentally sustainable lifestyles. However, significant gaps remain around multi-level governance, institutional capacity, and more pressing of all, financial resources to fund these transitions simultaneously.

For instance, an enabling financial environment is crucial starting point for systems transitions, yet the scale of climate finance (USD 44 billion in 2020) in India is grossly insufficient and predominantly concentrated in the power sector. Climate finance is also skewed in favour of mitigation (about 90 per cent) with only about 10 per cent investments for adaptation (CPI, 2022; Srinivasan et al., 2023). Domestic commercial finance and budgetary commitments are the primary sources of climate finance, while private investments are mostly in renewable energy. International finance flows are nominal, for instance MDBs' climate finance to India in 2022 was only around USD 3.7 billion. India's adaptation costs, estimated at INR 29 trillion in 2020 and INR 86 trillion by 2030, far exceed the available green finance of INR 370 billion per annum (DEA, 2020; CPI, 2022). Public budgetary support, the largest adaptation fund source, is constrained by fiscal deficits and budgetary constraints.

India needs to redirect investments from fossil fuels to low-carbon and resilient development, with mitigation investments focusing on energy transition and adaptation investments focussing on building resilient infrastructure, sustainable land use and filling the ecosystem services deficit (Srinivasan et al., 2023). Public and private investments must align with climate action and SDGs. The government should create a facility to de-risk the financial sector from transition risks, and international climate finance should address the mismatch between India's savings, capital flows, and resilient infrastructure needs (Srinivasan et al., 2023).

India's NDC is an ambitious document that forefronts national development goals while aiming to institute mitigation and adaptation actions. While this is a promising start, it's not enough to keep India and the world within the 1.5°C guardrail necessary to avoid devastating climatic risks, **including more extreme events, increased threats to food and water security, human life and health, and extensive biodiversity loss.** India's climate action and commitment to net-zero emissions are critical to the global goal of limiting global temperature rise to 1.5°C. Moreover, given India's climate vulnerability, these risks pose a significant threat to human life and well-being, potentially reversing economic progress and developmental gains made over the past few decades.

The CRD framework, which brings together sustainable development and climate action, can ensure growth and broad based gains via jobs, economic security, and climate protection to vulnerable and underserved population of the country, while also securing societal and ecosystem well-being for all. To operationalise CRD, India needs to enable simultaneous systems transitions across key areas like land, oceans and ecosystems, energy, urban and industrial, to meet adaptation, mitigation, and development goals concurrently.

This report provides actionable and evidence-based insights for governments and policymakers to chart out CRD pathways in the country. It offers a stock take of adaptation and mitigation options across systems in India, highlighting examples of feasibility options and identifying key areas of synergies and trade-offs between adaptation, mitigation and SDGs. By focussing on scaling up win-win strategies in the short term and strengthening key enabling conditions in the short and medium term, India can chart its trajectory towards achieving a net-zero world.

1.

Climate Trends and Projections in India

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Chapter Authors: Teja Malladi, Amir Bazaz and Pooja Rao

1. Climate Trends and Projections in India

- Average temperatures across India have already risen by 0.7°C from 1901 to 2018 and are projected to rise by 4.4°C by 2100, if current trends continue.
- Both daytime and night-time temperatures are increasing. By 2100, the frequency of warm days and warm nights is projected to rise by 65 per cent and 80 per cent, respectively, compared to 1976–2005.
- By 2100, in high-emission scenarios, summer heatwaves over India are estimated to be three to four times more frequent than 1976–2005.
- Rainfall is becoming more erratic and the frequency of heavy rain events across most parts of India is expected to increase. In the near-term, the summer monsoon is expected to increase by 6 per cent (RCP4.5) and 8 per cent (RCP8.5) over Central India; and an increase of 10 per cent (RCP4.5) and 14 per cent (RCP8.5) is expected by 2100.
- As a result, drought and flood frequency is expected to rise. The Brahmaputra river basin will see the highest rise in multi-day flooding events.

1.1 Introduction

India's climate varies widely, encompassing the Himalayas in the north, the arid Thar Desert in the north-west, humid and sub-humid areas in south-west, central and north-eastern regions, along with diverse microclimates spread across the vast subcontinent. These varied climatic zones are characterised by distinct topographic and geographic features. The Indian summer monsoon is a dominant feature of the regional climate, contributing to almost 80 per cent of India's annual rainfall (Rai and Dimri, 2020). The livelihoods of a large share population and the economy of India is still dependant on the quantity and distribution of rainfall during the summer monsoon season (Krishnan and Sanjay, 2017). As of 2022, 55 per cent of net sown area and 61 per cent of farmers in India were dependent on rain-fed agriculture (GOI, 2022).

India's climate is characterised by strong seasonal and spatial temperature variations. The mean temperature ranges from 10°C in the winter (January to February) to around 32°C in the summer (March to May) (Attri and Tyagi, 2010). The mean daily minimum temperature in winter ranges from 22°C in the extreme south to 10°C in the northern plains and 6°C in Punjab. By March, temperatures begin to increase across the country, with interior peninsular India recording mean daily temperatures of 30–35°C by April (Attri and Tyagi, 2010). The Indian subcontinent is also susceptible to a wide spectrum of weather events and climate extremes. This chapter gives a broad overview of the climatic trends in the subcontinent, summarising observed and projected changes in temperature and precipitation, along with climate change impacts on extreme events like heatwaves, floods, droughts and tropical cyclones, and slow onset climatic events like sea level rise.

First, the chapter discusses trends in temperature (section 1.2), followed by trends in precipitation (section 1.3) and climate change impacts on extreme events like heatwaves, floods, droughts, tropical cyclones, and sea level rise (1.4), ending with a brief conclusion (section 1.5).

1.2 Temperature

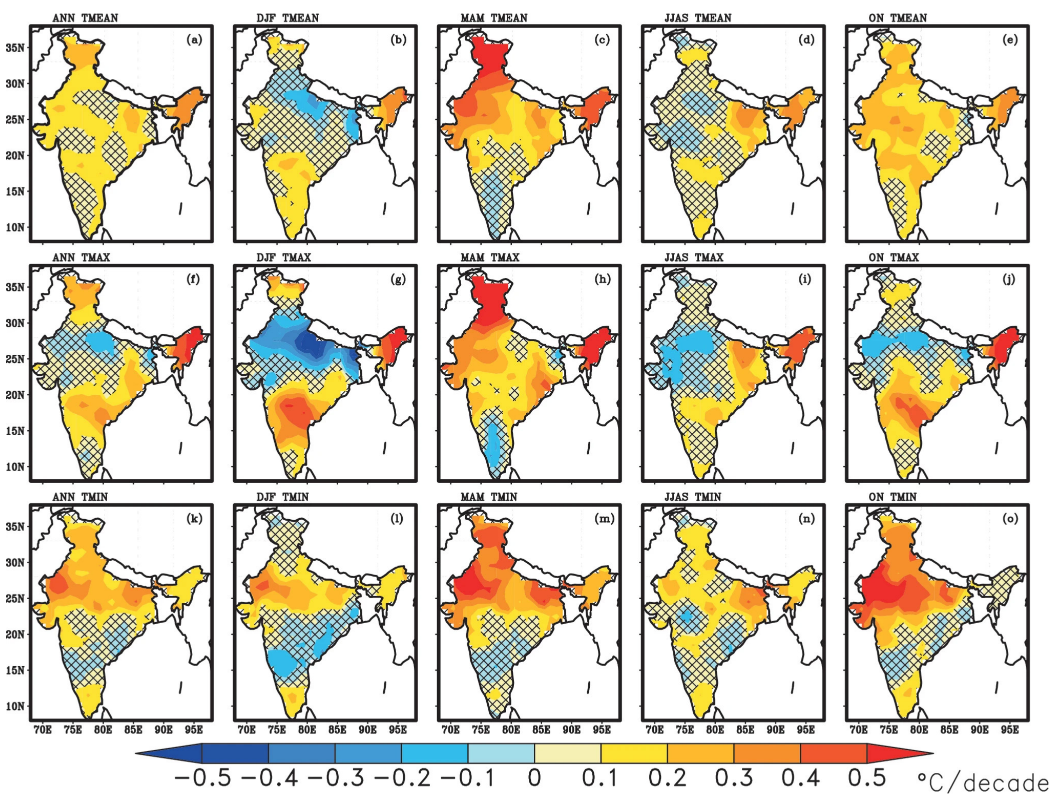
1.2.1 Past temperature trends

The average near surface air temperature in India has risen by around 0.7°C from 1901 to 2018, primarily due to anthropogenic warming, partially offset by the effects of anthropogenic aerosols and land use land cover (LULC) changes (Krishnan et al., 2020).

A significant warming trend has been observed over India (Sanjay et al., 2020), with the annual mean, maximum and minimum temperatures averaged over India during 1986–2015 showing a significant warming trend of 0.15°C, 0.15°C and 0.13°C per decade, respectively. The highest warming trend during 1986–2015 was observed in the pre-monsoon season, followed by the post-monsoon and monsoon seasons. The largest increasing warming trend was observed in parts of north and north-east India, with the annual mean temperature rising by more than 0.2°C per decade. However, warming was comparatively weaker in the southern peninsula, with the mean temperature being lesser than 0.1°C per decade along the west coast.

Warming was non-uniform across seasons over India during 1986–2015. Warming in the winter season was limited over peninsular India, whereas the pre-monsoon season showed predominant warming of more than 0.5°C per decade over north India. The eastern Indo-Gangetic Plain and central India showed warming in the summer monsoon season. The post-monsoon season exhibited a similar warming pattern as that of the pre-monsoon season, but with smaller magnitude and more uniform distribution across the Indian subcontinent as compared to other seasons.

Figure 1.1: Spatial distribution of observed annual and seasonal trends (°C per decade)



Notes: Trends are for mean (top panel), maximum (middle panel) and minimum (bottom panel) temperatures in annual (ANN), winter (December to February, DJF), pre-monsoon (March to May, MAM), monsoon (June to September, JJAS) and post-monsoon (October to November, ON) seasons during the period 1986–2015. Hatched grids represent significant trends with 95% confidence interval.

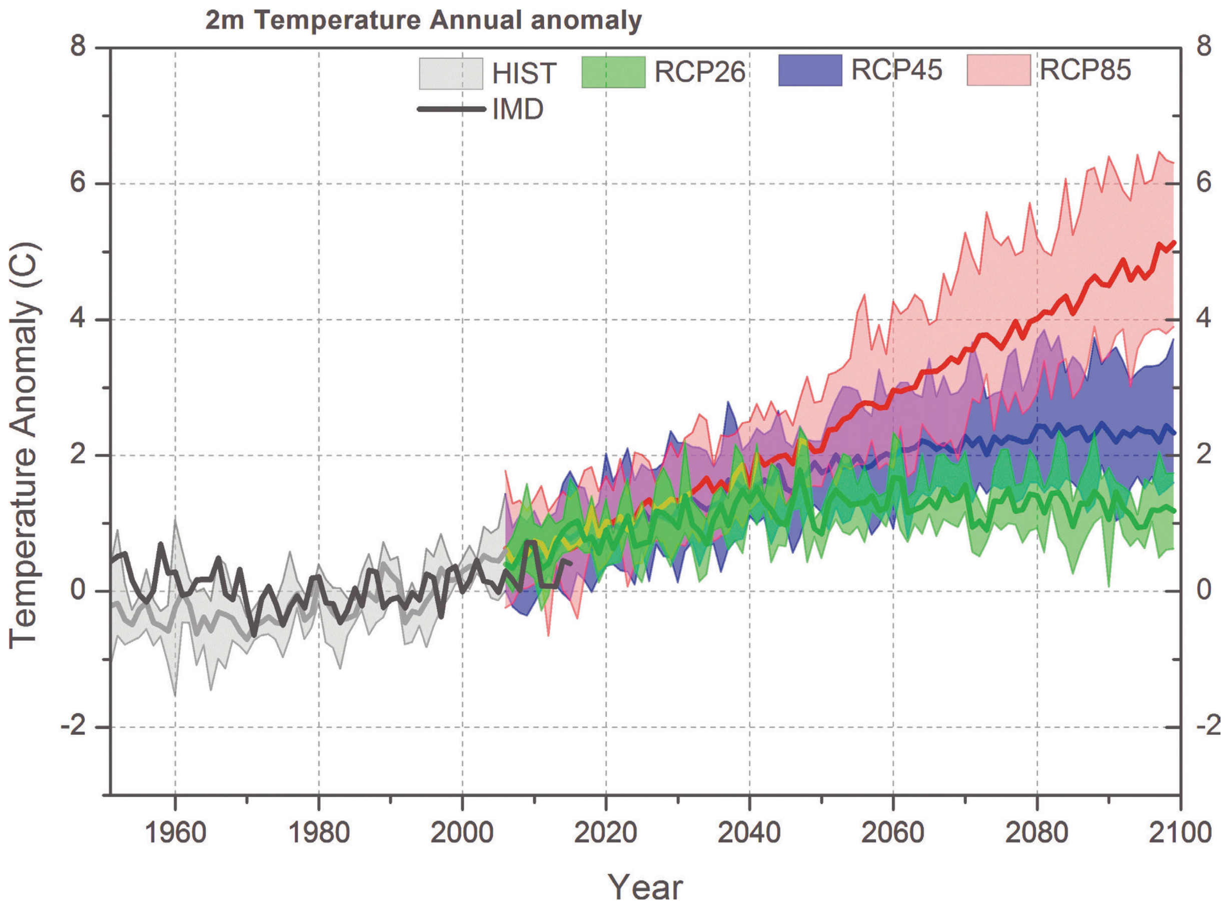
Source: *Sanjay et al., 2020*

1.2.2 Projected temperature

By the end of the 21st century (2070–2099), the average temperature over India is projected to rise by 4.4°C compared to the recent past (1976–2005) under Representative Concentration Pathway (RCP) 8.5 (Figure 1.2) (Sanjay et al., 2020). The projected change in the All-India mean surface air temperature ranges between 1.4°C (under RCP2.6) and 2.7°C (under RCP8.5) by mid-century (2040-2069) relative to 1976-2005, which is larger than natural internal variability (Sanjay et al., 2020).

During the same time (2070-2099), the All-India mean surface air temperature is projected to increase by 1.33 ± 0.24°C under RCP2.6, 2.44 ± 0.41°C under RCP4.5 and 4.44 ± 0.45°C under RCP8.5, respectively, relative to 1976–2005. The semi-arid north-west and north India are expected to warm more rapidly than the All-India mean (Figure 1.3) (Sanjay et al., 2020).

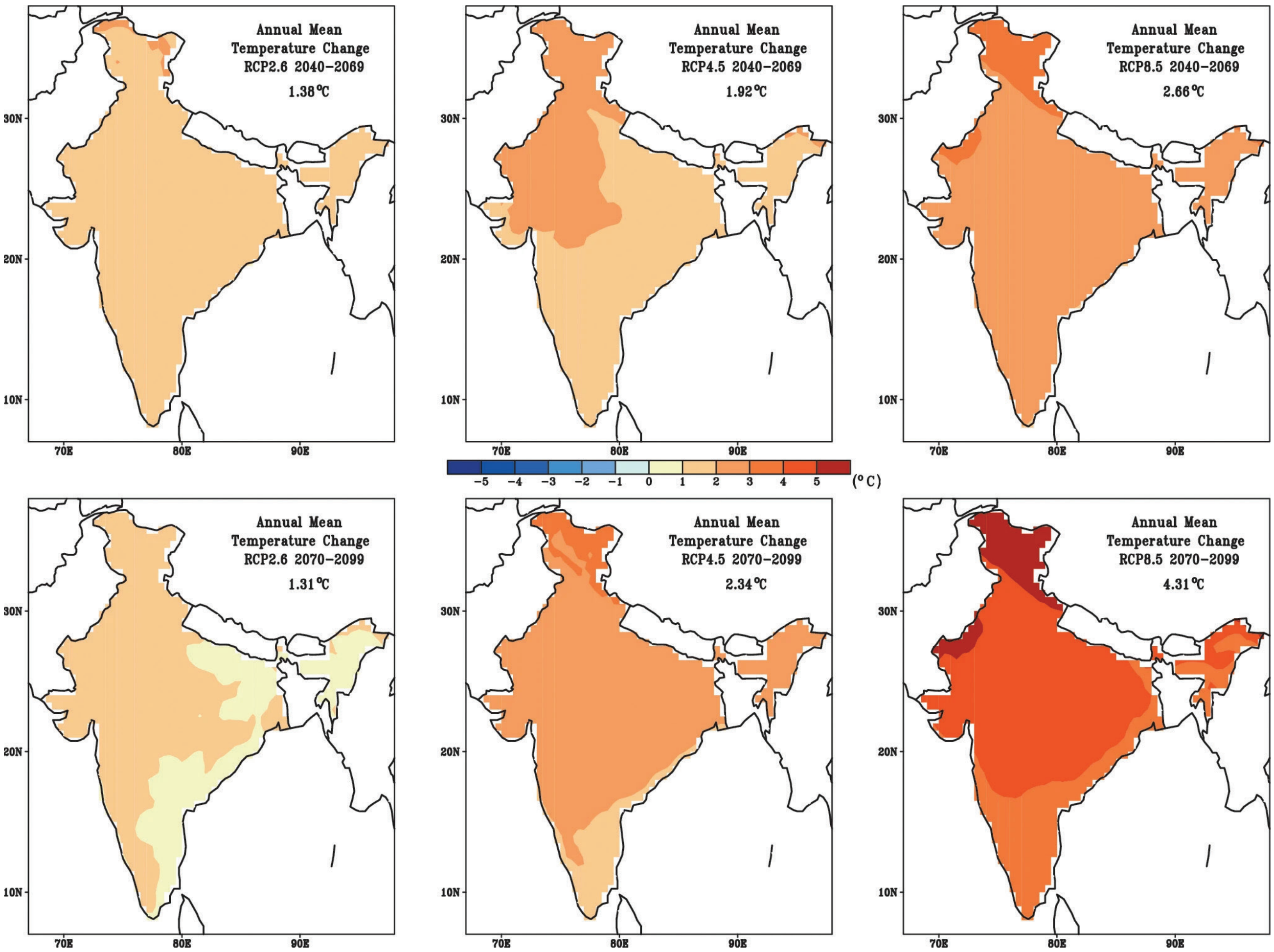
Figure 1.2: Time series of annual mean surface air temperature anomalies relative to 1976–2005



Notes: The data draws from the Coordinated Regional Climate Downscaling Experiment (CORDEX) South Asia concentration-driven experiments. The multi-Regional Climate Models (RCM) ensemble mean (solid lines) and the minimum to maximum range of the individual RCMs (shading) based on the historical simulations during 1951–2005 (grey) and the downscaled future projections during 2006–2099 are shown for RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red) scenarios. The black line shows the observed anomalies during 1951–2015 based on India Meteorological Department (IMD) gridded station data.

Source: *Sanjay et al., 2020*

Figure 1.3: Mean projections of annual average surface air temperature changes (°C)



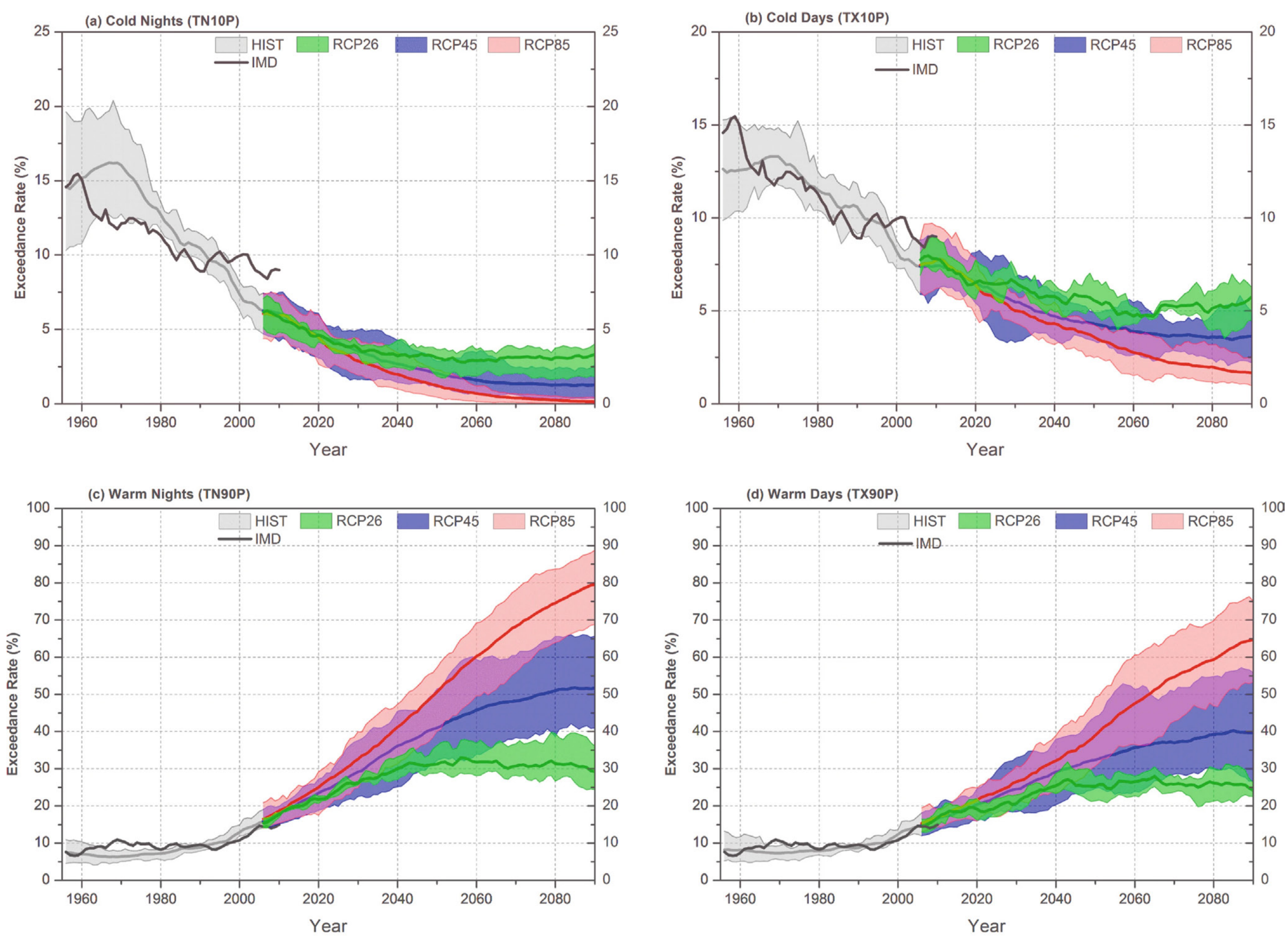
Notes: Data from CORDEX South Asia for mid-term (2040–2069) and long-term (2070–2099) climate, relative to 1976–2005 under RCP2.6, RCP4.5 and RCP8.5 emissions scenario.

Source: *Sanjay et al., 2020*

1.2.3 Temperature extremes

Since 1951, the all-India average frequency of warm days and nights has increased, while the average frequency of cold days and nights has decreased. The temperatures of the warmest day and the coldest night of the year have risen by about 0.63°C and 0.4°C, respectively, in the recent 30-year period (1986–2015) (Krishnan et al., 2020). These temperatures are projected to rise by approximately 4.7°C and 5.5°C, respectively, by the end of the 21st century (2070–2099) under RCP8.5, relative to the corresponding temperatures in the recent past (1976–2005 average) (Krishnan et al., 2020). By the end of the 21st century, the All-India average frequency of warm days and warm nights is projected to increase from 10 per cent to 65 per cent and 80 per cent, respectively under RCP8.5, compared to 1976–2005 (Sanjay et al., 2020).

Figure 1.4: India averages of temperature indices over land



Notes: Data simulated by CORDEX South Asia multi-RCM ensemble for RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red) displayed for annual percentile frequency indices a) cold nights (TN10p), b) cold days (TX10p), c) warm nights (TN90p) and d) warm days (TX90p). Changes for percentile frequency indices are displayed as absolute exceedance rates in per cent. Solid lines show ensemble mean and shading indicates range among individual RCMs. The black line shows the observed indices based on IMD gridded station data. Time series are smoothed with an 11-year running mean filter.

Source: *Sanjay et al., 2020*

1.3 Precipitation

1.3.1 Past trends

Annual rainfall averaged over the Indian landmass does not show any trend over the period 1901–2015. However, in the more recent periods of 1951–2015 and 1986–2015, the annual rainfall series shows a decreasing trend, though this is not statistically significant or evident in all data sets (Kulkarni et al., 2020).

Summer monsoon precipitation (June to September) has declined over India by around 6 per cent during 1951–2015, with a significant decrease over the Indo-Gangetic Plain (IGP) and the Western Ghats. Climate modeling studies indicate that the observed changes are a response to the radiative effects of anthropogenic aerosols in the Northern Hemisphere and regional land use and land cover (LULC), which have countered the precipitation-increasing effect of greenhouse gas warming over the past 60 to 70 years (Krishnan et al., 2020). In the same time, the occurrence of localized heavy precipitation has increased markedly over Central India.

Overall, there has been a shift towards more frequent dry spells (27 per cent higher during 1981–2011 relative to 1951–1980) and more intense wet spells during the Indian summer monsoon (Kulkarni et al., 2020). The frequency of localised heavy rain occurrences over India has also increased during 1951–2015. Urbanisation, land use changes and aerosols are likely contributors to these localised heavy rainfall occurrences (medium confidence) (Krishnan et al., 2020).

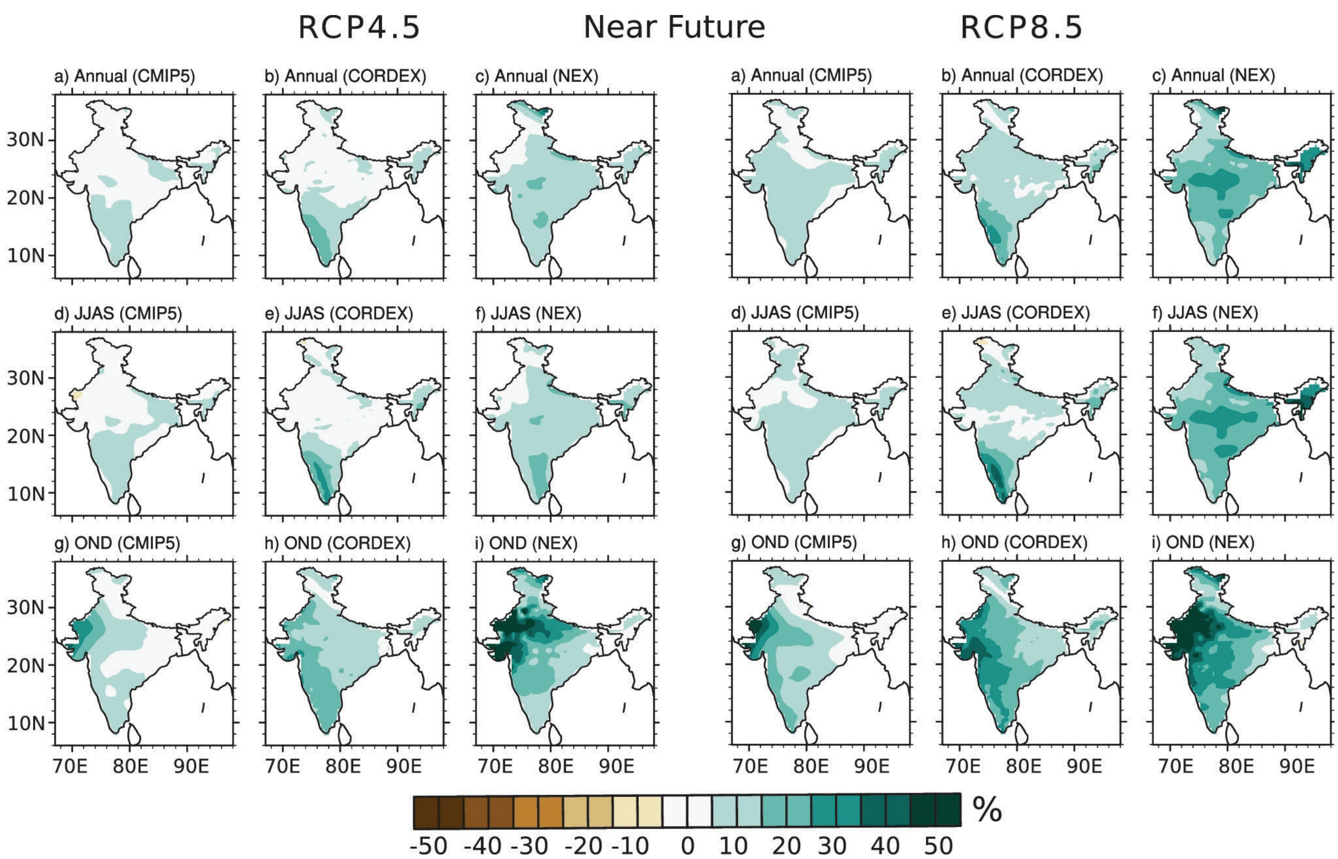
1.3.2 Projected precipitation

Coupled Model Intercomparison Project phase 5 (CMIP5) models suggest wetter conditions in the future. CMIP5 models project a 6 per cent (RCP4.5) and 8 per cent (RCP8.5) increase in the summer monsoon in the near future over the central Indian region, and a 10 per cent (RCP4.5) and 14 per cent (RCP 8.5) increase by 2100. The rise in summer monsoon precipitation projected for the South Asian region by CMIP5 models is primarily driven by an increase in moisture supply resulting from heightened warming (Kulkarni et al., 2020).

Inter-annual variations in the north-east monsoon (October to December) are much larger compared to the south-west monsoon (June to September), with implications of either excess or deficit rainfall for southern Indian peninsula, including states like Tamil Nadu, Karntaka, Andhra Pradesh (see Figure 1.5) (Kulkarni et al., 2020). This is linked to El/nino southern oscillation (ENSO), the Indian Ocean Dipole, and the Equatorial Indian Ocean Monsoon Oscillation (EQUINOO).

Projections from the Coordinated Regional Climate Downscaling Experiment (CORDEX), NASA Earth Exchange (NEX), and CMIP5 show a moderate increase

Figure 1.5: Multi-Model Ensemble (MME) change (%) in annual and seasonal rainfall



Notes: Annual, JJAS and OND rainfall as projected by CMIP5, CORDEX South Asia and NEX-GDDP models for the near future (2040–2069) with respect to 1976–2005 from RCP4.5 and RCP8.5 scenarios.

Source: *Kulkarni et al., 2020*

in annual rainfall over the Indian landmass (Figure 1.5). Annual precipitation enhancement is minimal in the near future (2040–2069) in the RCP4.5 scenario; however, both projections (RCP4.5 and RCP8.5 scenarios) show an increase in precipitation by the end of the 21st century (2070–2099) (Kulkarni et al., 2020). Despite considerable uncertainty in precipitation projections, bias-corrected data shows that precipitation is projected to rise more in river basins located in the semi-arid/arid regions of the Indian subcontinent (Mishra et al., 2020).

1.3.4 Precipitation extremes

The frequency of precipitation extremes is projected to rise more prominently under RCP 8.5 over southern and central India by 2020 and 2100 (Mukherjee et al., 2018). Under RCP 8.5, very wet days and precipitation intensity are projected to rise by 15 per cent and 21 per cent, respectively, by the end of the 21st century. The maximum five-day precipitation is projected to rise by 38 per cent (Kulkarni et al., 2020).

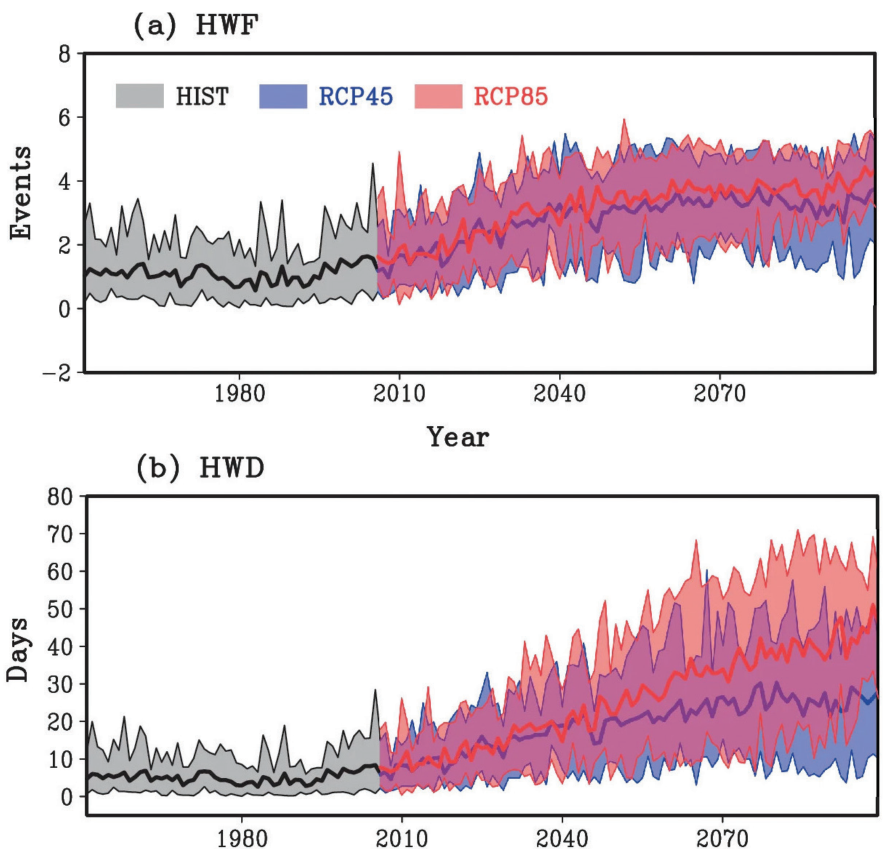
Over central India, the frequency of daily precipitation extremes with rainfall intensities exceeding 150 mm per day increased by about 75 per cent during 1950–2015 (Krishnan et al., 2020).

1.4 Climate Change Impacts on Extreme Events

1.4.1 Heatwaves

The India Meteorological Department (IMD) defines heatwaves as periods when the maximum temperature reaches at least 40°C or more in plains or 30°C or more in hilly regions. Heatwaves are considered severe when the actual temperature exceeds 47°C. Under RCP8.5, the

Figure 1.6: Time series of All-India averaged summer heatwaves



Notes: CORDEX South Asia multi-RCM projections of summer (April to June) heatwave a) frequency (HWF; events per season) and b) total average duration (HWD; days per season) for the CORDEX South Asia RCM ensemble mean (solid line) and the minimum to maximum range of individual RCMs (shading) based on the historical simulations during 1951–2005 (grey), and based on future projections during 2006–2099 under RCP4.5 scenario (blue) and RCP8.5 scenario (red).

Source: *Sanjay et al., 2020*

frequency of summer (April to June) heatwaves over India is estimated to be three to four times higher by 2100 compared to the 1976–2005 baseline period. Moreover, with a substantial spread among various models, the average duration of heatwave events is also expected to double (approximately) (Sanjay et al., 2020).

Heat stress is expected to amplify across India, especially over the Indo-Gangetic and Indus river basins due to the combined rise in surface temperature and humidity (Sanjay et al., 2020).

1.4.2 Meteorological drought

Meteorological drought is deficiency in precipitation and is assessed using the Standardised Precipitation Evapotranspiration Index (SPEI). SPEI uses accumulation of precipitation minus potential evapotranspiration to include the effect of temperature and thereby accounts for changes in the variability of both supply and demand in moisture (Vicente-Serrano et al., 2010).

Over 1951–2015, India witnessed increased susceptibility to droughts, in both frequency and spatial extent, due to the overall decrease of summer monsoon rainfall. Parts of central India and the Indo-Gangetic Plain observed increase in drought severity (Krishnan et al., 2020). During the same period (1951–2015), the area affected by drought increased by 1.3 per cent per decade, with more than two droughts per decade recorded in central India, the southern peninsula, the south-west coast and north-eastern India.

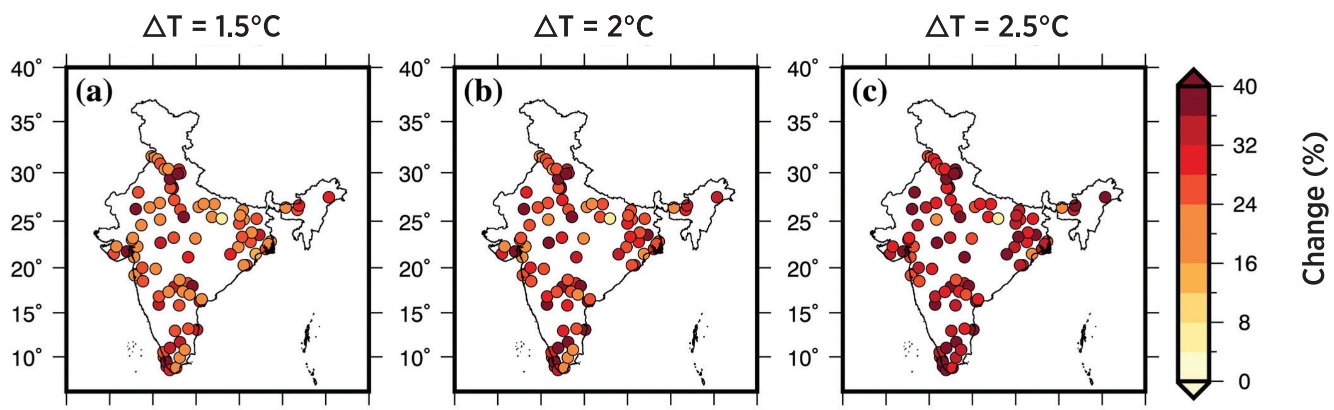
Under RCP8.5, India is expected to see an increase in the frequency (more than two drought events per decade), intensity and area under drought (dry area increasing by 3.81 per cent per decade on an annual timescale) by the end of the 21st century. These projections result from increased variability in monsoon precipitation and increased water evaporation in a warmer atmosphere (Krishnan et al., 2020).

1.4.3 Floods

Floods are classified into different types such as riverine (extreme rainfall for long periods), fluvial (floods in rivers due to extreme rainfall, tropical storm, or snow melt), pluvial (rainfall over a flat surface), flash (heavy rainfall in cities or along steep slopes), urban (largely lack of appropriate drainage) and coastal (storm surge) (Mujumdar et al., 2020). Unless otherwise specified, floods here are generally associated with heavy rainfall events.

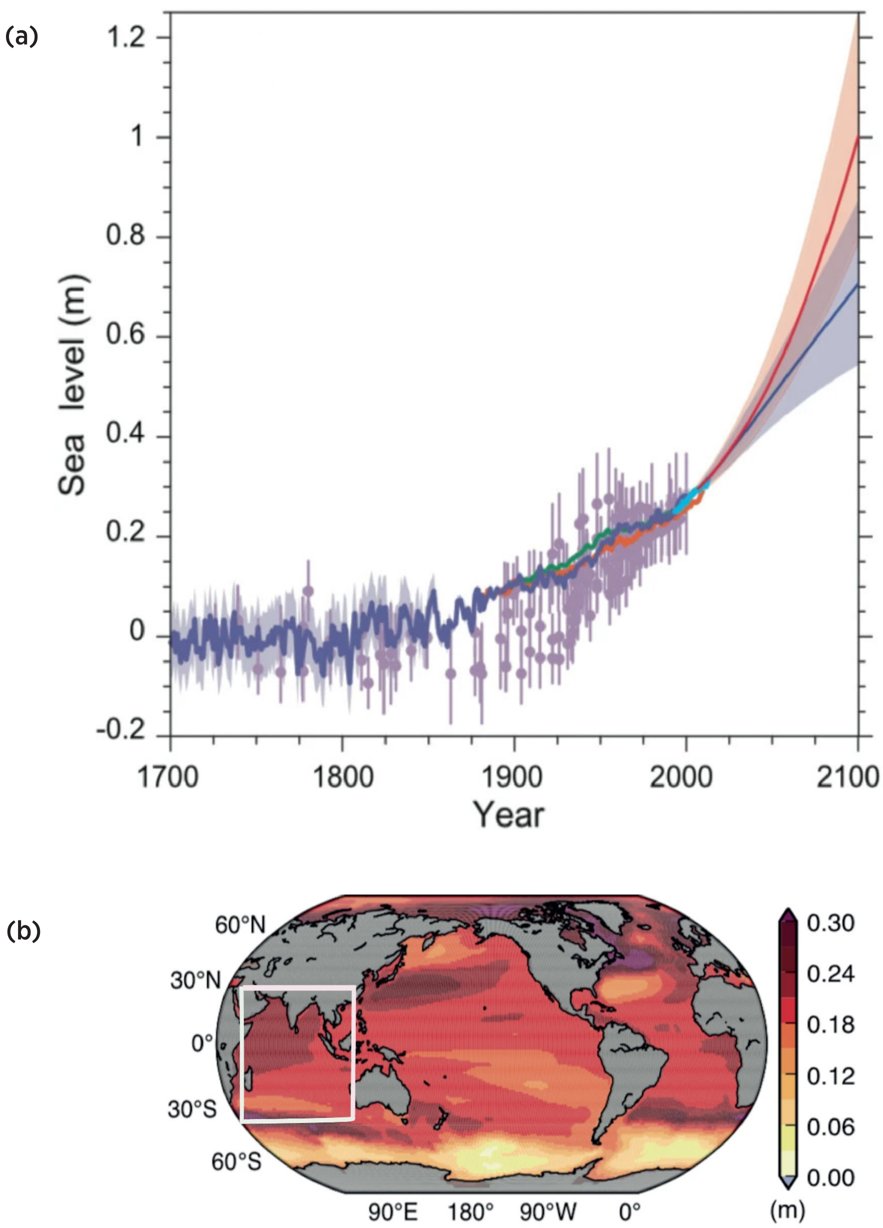
The Indian subcontinent could experience an increase in flood risks due to increasing extreme precipitation events. A 20 per cent (25 per cent) increase in short duration (three-hourly) precipitation maxima at 100-year return intervals is projected for 1.5°C (2°C) global warming levels (Ali and Mishra, 2018). This assessment covered 89 urban areas planned for development as Smart cities, indicating associated flood risks over these urban areas (Figure 1.7).

Figure 1.7: Median change (%) in three-hour 100-year precipitation maxima (design storm) with increase in GMT by 1.5 to 2.5°C



Run-off is projected to increase in the Indus, Ganga and Brahmaputra river basins at least until 2050, mainly due to increase in precipitation and accelerated snow melt (Indus) in warming environment, which is associated with close proximity of river basins to the foothills of the Himalayas (Lutz et al., 2014). Multi-day flood events (of three to five days) are expected to increase across all river basins compared to one-day events under both RCP2.6 and RCP8.5. The Brahmaputra River basin along with river basins in central India are projected to witness the highest increases. The least increase may be observed in the Indus river basin (Ali et al., 2019).

Figure 1.9: Sea level rise in the Indian Ocean



Notes: a) Global mean sea-level evolution derived from the compilation of palaeo sea level data (purple), three different tide gauge reconstructions, altimeter data, and central estimates and likely ranges for future projections of global mean sea level rise for RCP2.6 (very low emissions—blue) and RCP8.5 (very high emissions—red) scenarios, all relative to pre-industrial values. b) Ensemble mean projection of the dynamic and steric sea level changes for the period 2081–2100 relative to the reference period 1986–2005 from 21 CMIP5 models, using the RCP4.5 experiment. Note that these regional sea level projections do not include the effects of terrestrial ice melts. The Indian Ocean is highlighted by a white rectangle.

Source: Swapna et al., 2020

1.4.4 Tropical cyclones

Since the mid-20th century (1951–2018), the North Indian Ocean (NIO) basin has seen a significant reduction in the annual frequency of tropical cyclones. However, during the last two decades (2000–2018), the frequency of very severe cyclonic storms (VSCS) has significantly increased by about one event per decade during the post-monsoon season. Climate models project an increase in the intensity of tropical cyclones in the NIO basin during the 21st century (Vellore et al., 2020).

Observations from 1998–2018 indicate an increase in the frequency of extremely severe cyclonic storms over the Arabian Sea during the post-monsoon season (Vellore et al., 2020). These observations are attributed to increase in human-induced sea-surface temperature warming. However, a clear relationship between anthropogenic warming and an increasing trend of tropical cyclone events has not yet been fully established (Krishnan et al., 2020).

1.4.5 Sea level rise

The rate of sea level rise in the NIO is comparable to the current global mean sea level rise rate, which has been 1.5–1.9 mm/year since 1901. From 1874 to 2004, the sea level in the NIO rose at a rate of 1.06–1.75 mm/year, which accelerated to 3.3 mm/year from 1993 to 2017 (Swapna et al., 2020).

Steric sea level (i.e., variations due to ocean thermal expansion and salinity variations) in the NIO is estimated to rise by around 20–30 cm at the end of the 21st century. The corresponding projection for global mean steric sea level rise is around 18 ± 5 cm (relative to the average over 1986–2005) under RCP4.5, excluding contributions from ice melt (Swapna et al., 2020).

1.5 Conclusion

Climate change trends in India are becoming worse on almost all counts compared to the recent past (1976–2005). The mean surface air temperature is expected to rise by between 1.4°C to 2.7°C by 2050, in addition to the 0.7°C rise since 1901 (Krishnan et al., 2020; Sanjay et al., 2020).

Local temperatures may exceed 2.5°C due to regional climate trends and local phenomena, such as the Urban Heat Island (UHI) effect. For instance, temperatures in Kolkata have already risen by 2.6°C above the pre-industrial average (IPCC, 2021; SUP, 2022). Summer heatwaves are expected to occur three to four times more frequently by 2100, with the frequency of warm days and nights projected to rise by 65 per cent and 80 per cent, respectively (Sanjay et al., 2020). Heat stress is anticipated to increase across India, particularly in the Indo-Gangetic and Indus river basins (Sanjay et al., 2020).

From 1986-2015, mean annual rainfall decreased, notably over the Indo-Gangetic Plain and the Western Ghats. This decline is largely attributed to rising levels of anthropogenic aerosols and urbanisation (Krishnan et al., 2020). However, continued warming along with anticipated reductions in anthropogenic aerosol emissions are expected to lead to a 5 to 8 per cent increase in the summer monsoon, in the near-term.

Under both the RCP 4.5 and RCP 8.5 scenarios, an increase in precipitation is expected by the end of the 21st century (2070-2099). The frequency of extreme precipitation events is set to rise more prominently under RCP 8.5 scenario over central and southern India, with very wet days and precipitation intensity projected to increase by 15 per cent and 21 per cent respectively by 2100 (Mukherjee et al., 2018).

Under the RCP8.5 scenario, India is also predicted to experience more than two drought events per decade, with the intensity and area under drought (dry area increasing by 3.81 per cent per decade on an annual timescale) by the end of the 21st century. The Indian subcontinent is also likely to face heightened flood risks due to more frequent extreme precipitation events. Multi-day flood events (of three to five days) are expected to increase across all river basins compared to one-day events under both RCP2.6 and RCP8.5 scenarios. Additionally, climate models predict an increase in the intensity of tropical cyclones in the NIO basin during the 21st century (Vellore et al., 2020).

The evidence of climate projections and trends and climate change impacts on extreme events indicate severe risks across sectors for India. These risks and impacts threaten India's future growth and development and can seriously undermine well-being of people and the ecosystem, as we discuss in the next chapter.

2.

Climate Change Risks and Impacts in India

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2. Climate Change Risks and Impacts in India

- Climate change is altering impact drivers, especially heat, precipitation, wind and sea level worldwide. In India, climate projections also point to warming patterns, increased precipitation variability, leading to more climate extremes.
- Changes to climate impact drivers pose severe risks to key sectors in India such as agriculture and food, water, terrestrial ecosystems, urban and infrastructure, and health systems. These risks can adversely impact India's economy, well-being of its people and ecosystems.
- Climate impacts and risks are also projected to worsen and multiple as temperatures increase from current levels to 1.5°C and then to 2°C and 3°C and more.
- In comparison to current levels, the maximum population exposed to heatwave days is estimated to rise by 15 times and 92 times at 1.5°C and 2°C, respectively. Heat-related mortality is projected to increase by 71 per cent (RCP 4.5) representing between 2°C to 3°C and by 140 per cent (RCP 8.5) more than 4°C in urban areas with cities like Delhi, Ahmedabad, Bengaluru, Mumbai and Kolkata facing the highest increases.
- At 1.5°C, South Asia will see an average 9.7 months drought and this may increase to 15.4 months at 3°C. Average warming from 1.5°C to 2°C could lead to a reduction in per capita water availability for more than 90 per cent of regions across India, with over 400 million people facing severe water stress.
- At 1.5°C, 0.5–1.5 million people will be flood-affected, which may increase to 2.5–8 million people under 2°C warming and 30–40 million people at 4°C warming. Also, at 1.5°C, the Indian coastline is expected to see an average 0.3 m SLR, which will increase substantially at higher temperatures, impacting 25 coastal cities. Cities like Mumbai, Kochi, Chennai, Visakhapatnam, Mangaluru and Thiruvananthapuram are projected to face severe impacts from rising sea levels by 2050, potentially losing up to 50 per cent of their land area.
- Even without climate change, 30 million Indians would be at risk of hunger by 2050. Under RCP2.6 and a once-per-100-year extreme event, this number is 4.4 million–140 million, which rises to 8.7 million–180 million under RCP8.5.

2.1 Introduction

Anthropogenic climate change is changing impact-drivers across the world, especially heat, precipitation (rain, snow and ice), wind, and sea level (IPCC, 2021). This is true of India where past trends and future projections of temperature and precipitation show warming patterns and more erratic rainfall (Krishnan et al., 2020).

Changes in these climate impact-drivers pose significant risks for key sectors such as agriculture and food, water, terrestrial ecosystems, urban and infrastructure, and health systems. Currently, impacts are visible on crop productivity and food security; type, distribution, productivity and carbon availability in terrestrial ecosystems; damages to infrastructure such as transportation networks, energy and buildings; and increased burden of vector-borne diseases. At higher temperatures, projected risks are expected to intensify and multiply across all key sectors.

This chapter provides an overview of key climate impact-drivers and discusses current impacts (section 2.2) and projected risks for climatic extremes in India under different warming levels. This is followed by an overview of projected climate-induced risks for key sectors in India like agriculture, water, terrestrial systems, urban areas, and health (section 2.3), followed by a conclusion in section 2.4.

2.2 Climate Impact-drivers in India

2.2.1 Temperature

Limiting global temperatures to 1.5°C would halve heat exposure in India by the mid-21st century (Mishra et al., 2017). At 2°C average global warming, there will be a doubling of flows in the Ganges River (Betts et al., 2018), with consistently longer flood events. India is projected to see an increase in the Hunger and Climate Vulnerability Index (HCVI; unprecedented at 1.5°C and 2°C and going into very high category at 4°C) (Betts et al., 2018). At 1.5°C average global warming, the Indus–Ganga–Brahmaputra basin will experience 1.4–2.6°C temperature increase, resulting in more flooding and droughts with implications for regional food security; at 2°C, the basin will see 2–3.4°C temperature increase (Lutz et al., 2019).

2.2.2 Drought

Global warming of 2.5°C will impact almost one-and-a-half times more people across South Asia than 1.5°C warming (Aadhar & Mishra, 2019). Higher warming is expected to increase evapotranspiration, leading to drying trends in South Asia. In South Asia (i.e., Pakistan, Afghanistan, India, Nepal, Bangladesh, Sri Lanka and Bhutan), drought durations are projected to rise at rapidly increasing rates with warming from the baseline mean of 8.3 months at 0.6°C warming compared to preindustrial temperatures, to a mean 9.7 months at 1.5°C and further to a mean 15.4 months at 3°C (Naumann et al., 2018). Droughts are projected to occur 5–10 times more frequently in South Asia even under ambitious mitigation targets. Current 100-year events could occur every two to five years under 3°C of warming (Naumann et al., 2018).

2.2.3 Floods

Under both 1.5°C and 2°C of warming, an increase in extreme precipitation and corresponding flood hazard is projected over the Ganga–Brahmaputra–Meghna (GBM) basin compared to the current climate. There will be an increase in notable monsoon precipitation over the GBM river basin between 1.5°C and 2°C, leading to larger flooded areas (Uhe et al., 2019). At 1.5°C, 0.5–1.5 million people will be flood-affected, which may increase to 2.5–8 million people under 2°C warming and 30–40 million people at 4°C warming. Under RCP8.5, there is a 20-fold increase in flood risk in India at 4°C warming, making it the second most affected country in the world by population and the fifth at risk in terms of economic damages (in euros/year) (Alfieri et al., 2017).

Table 2.1: Projected impacts of drought and aridity under 1.5°C, 2°C and 3°C

Projected Impact at 1.5°C	Projected Impact at 2°C	Projected Impact at 2.5°C
• 790(±336) million people impacted • Increased dryness in 54 (±18)% area of South Asia	• 890 (±485) million people impacted • Moderate *decline* (14% compared to 1.5°C) in areas affected by dryness	• 1,960 (±1033) million people impacted • 59 (±22)% area of South Asia affected by dryness

Source: *Aadhar & Mishra, 2020*

2.2.4 Sea level rise

Almost 136 large coastal cities have projected a median sea level rise (SLR) of at least 0.9 m by 2100, with 95th percentile upper limits close to 2 m for the megacities of Southeast and South Asia (Jevrejeva et al., 2016a). The 7,517 km long coastline of India hosts more than 25 cities with nearly forty million people living in just three big cities: Mumbai, Kolkata and Chennai. Along with these, several other smaller cities like Mangaluru, Kochi, Panaji, Surat, Visakhapatnam, Thoothukudi and Puri host more than 0.1 million population each (MoF, 2021). At 1.5°C, the Indian coastline is expected to see an average 0.3 m SLR, which will increase substantially at higher temperatures. A 2 m, SLR could lead to 1.8 million people being affected in Mumbai alone (Jevrejeva et al., 2016a).

Notably, SLR impacts can continue long after peak emissions as the risk of long-term flooding continues even after temperatures stabilise, posing a threat to deltas worldwide (Brown et al., 2018a). Adapting to the risks of multi-millennium climate-induced SLR can buy time, but effective mitigation is essential for a lasting solution (Brown, Nicholls, Goodwin, et al., 2018).

Table 2.2: Coastal flooding at different warming levels above pre-industrial levels

At 1.5°C	At 2°C	At 3°C
• Without protection 0.16–0.19 m flooding; with protection 0.04–0.06 m flooding • 5–8% area flooded (980–1,470 km^2)	• Without protection 0.17–0.21 m flooding; with protection 0.05–0.07 m flooding • 6–9% area flooded (1,150–1,770 km^2)	• Without protection 0.21–0.27 m flooding; with protection 0.07–0.09 m flooding • 9–13% area flooded (1,620–2,490 km^2)

Source: *Adapted from Brown et al., 2018a*

Table 2.3: Sea level rise in select Indian cities (in metres)

Scenario	Calcutta	Chennai	Cochin	Mumbai	Surat	Vishakapatnam
1.5°C	0.31	0.31	0.34	0.31	0.31	0.30
4°C	1.13	1.14	1.22	1.15	1.15	1.13
5°C	1.77	1.85	1.95	1.79	1.79	1.81

Source: *Jevrejeva et al., 2016a*

Table 2.4: Summary table on observed changes in extremes, their attribution since 1950 (except where stated otherwise) and projected changes at +1.5°C, +2°C and +4°C of global warming

Change in Indicator	Observed (since 1950)	Attributed	Projected			References
			+1.5°C	+2°C	+4°C	
Warm hot extremes: frequency or intensity (One-day and three-day concurrent hot night hot day events)	↑↓ [1]	Main driver[2] ☑	4 fold ↑	6 fold ↑	8 fold ↑	(Mukherjee & Mishra, 2018)
Heavy precipitation: frequency, intensity or amount (three-hourly precipitation in 89 urban areas across India)	↑↓	Anthropogenic warming and urbanisation	> 20% ↑	> 25% ↑	Not assessed	(Ali & Mishra, 2018)
Agricultural and ecological droughts: Intensity and/or frequency	↑ [3]	Main driver ☑	↑ Double no. of dry extremes over 15% of India	↓ Slight decrease over South Asia but increase over Himalayan region	Not assessed	(Kumar & Mishra, 2020) (Aadhar & Mishra, 2020)
Tropical cyclones: Proportion of intense cyclones	↑↓ [4]	Main driver ☑	↑	↑		(Vellore et al., 2020)
Compound events: Co-occurrent heatwaves and droughts	↑	Main driver ☑	Not assessed	Not assessed	Not assessed	(Kumar & Mishra, 2020)
Marine heatwaves: Intensity and frequency	↑ [5]	Main driver ☑	↑	↑	Not assessed	(Koll et al., 2020) (Liu et al., 2021) (Saranya et al., 2022)
Extreme sea levels: Frequency	↑ [6]	Main driver ☑	↑ [7]	↑	↑	

Source: *Jevrejeva et al., 2016a*

High confidence Medium confidence Low confidence

[1] Long-term observations (1951–2018) indicate a significant reduction in annual frequency of tropical cyclones in the North Indian Ocean (NIO) basin [−0.23 per decade over the entire NIO; −0.26 per decade over the Bay of Bengal]. A significant rise [+0.86 per decade] in the frequency of post-monsoon (October to December) season very severe cyclonic storms (VSCS) was observed in the NIO over 2000–2018 (Vellore et al., 2020).

[2] Statistically significant increase in one-day and three-day CHDHN events is observed due to anthropogenic emissions over India (Mukherjee and Mishra, 2018).

[3] Area affected by dry extremes during the monsoon (June to September) and water year (June to May) has significantly increased (-1 per cent per decade) over the last six decades (1951–2015) in India (Kumar & Mishra, 2020).

[4] Long-term observations (1951–2018) indicate a significant reduction in annual frequency of tropical cyclones in the North Indian Ocean (NIO) basin [−0.23 per decade over the entire NIO; −0.26 per decade over the Bay of Bengal]. A significant rise [+0.86 per decade] in the frequency of post-monsoon (October to December) season very severe cyclonic storms (VSCS) was observed in the NIO over 2000–2018 (Vellore et al., 2020).

[5] The Indian Ocean has experienced an average rise of 1.0 °C (0.15 °C/decade) (Roxy et al. 2020). The western Indian Ocean region experienced the largest increase in marine heat waves (MHWs) at a rate of 1.2–1.5 events/decade, followed by the north Bay of Bengal at a rate of 0.4–0.5 events per decade (Saranya et al., 2022).

[6] Sea level rise (SLR) in the Indian Ocean is non-uniform and the rate of north Indian Ocean rise was 1.06–1.75 mm year−1 from 1874 to 2004 and 3.3 mm year−1 in the recent decades (1993–2015), which is comparable to the current rate of global mean sea level (GMSL) rise (Krishnan et al., 2020)

[7] Steric sea level along the Indian coast is likely to rise by 20–30 cm at the end of the 21st century (relative to 1986–2005), under RCP4.5 (for a mid-range emissions scenario, excluding ice melt).

2.3 Sectoral Impacts and Risks

2.3.1 Agriculture and allied sectors

India is the world's largest producer of milk, pulses, and oilseeds, and the second-largest producer of rice, wheat, fruits, and vegetables (FAO, 2024). With about 260 million farmers, agriculture employs over 50 per cent of India's total workforce, and more than 85 per cent of these farmers are small and marginal landholders (MoAFW, 2023). This presents a unique set of challenges for this vulnerable workforce, as the impacts of climate change threaten to undermine their livelihoods in the agricultural sector.

While agricultural productivity has increased since the Green Revolution, concerns have grown over depleting water resources, soil degradation, increasing input costs, and climate change impacts (Aryal et al., 2014; Aryal, Jat, et al., 2018). Climate change is projected to impact agriculture by affecting the quantity and quality of crops through changes in productivity, growth, photosynthesis and transpiration rates, and moisture availability (Mahato, 2014). The impacts of changing temperature and precipitation are multifaceted. An increase in mean seasonal temperature can reduce the optimal growth duration and, in turn, the yield of many crops (Mahato, 2014; Naresh Kumar et al., 2014). However, a projected increase in rainfall could also lead to higher yields for certain crops in some parts of the country (Ahmed & Suphachalasai, 2014; Kelkar et al., 2020). Water scarcity, frequent floods and droughts, and declining soil carbon content are already reducing crop yields and agricultural incomes (Sapkota et al., 2015; Singh et al., 2009).

Crop production in India is expected to fall under higher warming. A global assessment by Hasegawa et al., (2021) identifies India as the country with the largest increase in population at risk of hunger. In the once-per-100-year extreme scenario, crop yield could decrease by 37–68 per cent and 46–62 per cent, while agricultural prices could rise by 90–230 per cent and 115–200 per cent under RCP2.6 and RCP8.5, respectively, compared to the baseline scenario with no climate change in 2050.

Even without climate change, millions of Indians would be at risk of hunger, and under the SSP3 scenario that usually holds true for the low-income countries, as many as 121 million people will be at risk of hunger in India in 2100 (Hasegawa et al., 2015). A multimodel ensemble study in India, projects 16.58 per cent drop in wheat yield at 3°C warming without adaptation due to changes in the availability of soil organic carbon and nitrogen and the shorter effective growing period due to higher temperature's accelerating plant development (Basso et al., 2018).

These broad projections vary by region. For example, in Maharashtra, rice production under RCP4.5 may decrease by 15–25 per cent in the Konkan (except for Ratnagiri) in the 2040s and by 10–40 per cent in the 2080s. In contrast, eastern Vidarbha shows a decrease of 5–10 per cent in the 2040s but an increase of 10 per cent in the 2080s (Kelkar et al., 2020). Table 6 summarises findings on crop yield reduction across five Indian states under different temperature increases based on existing literature.

In terms of wheat, more than half of the Indo-Gangetic Plain could become unsuitable for wheat cultivation by 2050 (Aryal et al., 2015; Aryal, Jat, et al., 2018; Aryal, Rahut, et al., 2018). A 15–17 per cent decrease in wheat and rice yields is projected under 2°C (Department of Agriculture and Cooperation, 2010). Empirical observations suggest that a temperature rise of up to 2.9°C can reduce the biological yield of wheat by ~35 per cent (Pathak et al., 2012).

With current varieties, rainfed maize yield is projected to decrease by an average of 3.3–6.4 per cent under annual mean maximum temperatures increase of 1.4–1.8 °C in 2030 and 5.2–12.2 per cent under 2.1–2.6 °C in 2050, while irrigated maize yield may drop by 3–8 per cent in 2030 and 5–14 per cent in 2050 -(Tesfaye et al., 2017). Even a 2°C rise in temperature can lead to a decrease in maize yield by 10–30 per cent (Aryal et al., 2019). Loss of yield, however, can be partially offset by an increase in rainfall. A maximum yield reduction of up to 55 per cent is estimated in the mid–Indo-Gangetic Plain and up to 35 per cent in the Southern Plateau for a 2.7°C rise in temperature (Byjesh et al., 2010).

Commercial crops will also be affected by climate change. In Maharashtra, an increase in maximum temperature under RCP4.5 may reduce sugarcane production by 40–

Table 2.5: Projected impacts of temperature change on rice yield in India

Region	°C increase	% Yield Reduction	Period	Source
Punjab	1°C	5.4%	-	(Pathak et al., 2012)
	2°C	7.4%	-	
	3°C	25.1%	-	
Bihar	-	31%	2080	(Haris et al., 2010)
West Bengal	1°C–3°C	27.8%	2050	(Banerjee et al., 2014)
Southern India	1°C	~5%	-	(Ahmed & Suphachalasai, 2014)
	2°C	~13%	-	
	3°C	~20%	-	
	4°C	~23%	-	
	5°C	~32%	-	
Tamil Nadu	1°C	4–6%		(Bhuvaneswari et al., 2014)
	2°C	12–15%		
	3°C	22–25%		
	4°C	37–40%		
	5°C	53–56%		

Source: *Authors' compilation*

80 per cent in the 2040s and by 60–90 per cent in the 2080s across almost all districts. An increase in minimum temperature may reduce sugarcane production by 20–40 per cent in the 2040s and by 20–60 per cent in the 2080s. Despite the loss in production in most districts, some regions have shown an overall increase of 20–40 per cent, possibly due to increased seasonal rainfall (Kelkar et al., 2020). Cotton production in Maharashtra may increase by 20–30 per cent in the 2040s but relatively decrease by 20 per cent in the 2080s in most districts under RCP4.5. The increase in minimum temperature may lead to an overall surge in cotton production by 10–20 per cent with the exception of Amravati district, which is likely to see 50–60 per cent loss (Kelkar et al., 2020).

Climate change will also impact livestock productivity due to thermal stress. Increasing air temperatures elevate livestock body temperatures, respiration rates, reduce reproductive efficiency and decrease feed intake (DAC, 2010; Pankaj et al., 2013). A study of Murrah buffaloes in India by Choudhary & Sirohi (2019) determined that the critical threshold level of maximum Temperature-Humidity Index (THI) is 74. They empirically demonstrated that the rate of decline in milk yield surpasses 1 per cent once the maximum THI exceeds 82.

Additionally, Choudhary (2022) forecasted that the annual loss in milk production due to climate change in the Trans and Upper Gangetic Plains of India would amount to approximately INR 11 to 12 billion between 2020–2029, under both business-as-usual and alternate RCP 4.5 scenario, with a projected doubling of this loss in the subsequent decade to INR 21 to 25 billion respectively. Indirect impacts such as reduced grazing land, decline in water and feed, and emergence of new diseases will further compound the impact (DAC, 2010). Fisheries will be impacted by changes in the abundance and distribution of exploited fish species, as well as their habitat quality and quantity.

2.3.2 Water

India receives an annual precipitation of nearly 4,000 billion m³, around 75 per cent of which occurs during the monsoon months from June to September. The country has twelve major river basins with catchment areas exceeding 20,000 km² and 46 medium basins with areas less than 20,000 km² (CWC, 2021a). India possesses an estimated 690 billion m³ of utilisable surface water resources and 437.6 billion m³ of groundwater resources (CGWB, 2022), resulting in an annual per capita water availability of 1,651 m³ (CWC, 2021b).

According to the CGWB (2022), the recorded annual groundwater extraction in 2022 was 299.16 billion m³. This figure, combined with the utilisable water volume of 690 billion m³, falls short of meeting the total water demand of 1093 billion m³ projected for 2025 by CWC (2005). This discrepancy underscores the ongoing issue of undocumented groundwater extraction, which, if left unchecked, could lead to over-extraction beyond the annual extractable limit of 398.08 billion m³. Such over-extraction could deplete groundwater resources, which take hundreds of years to replenish.

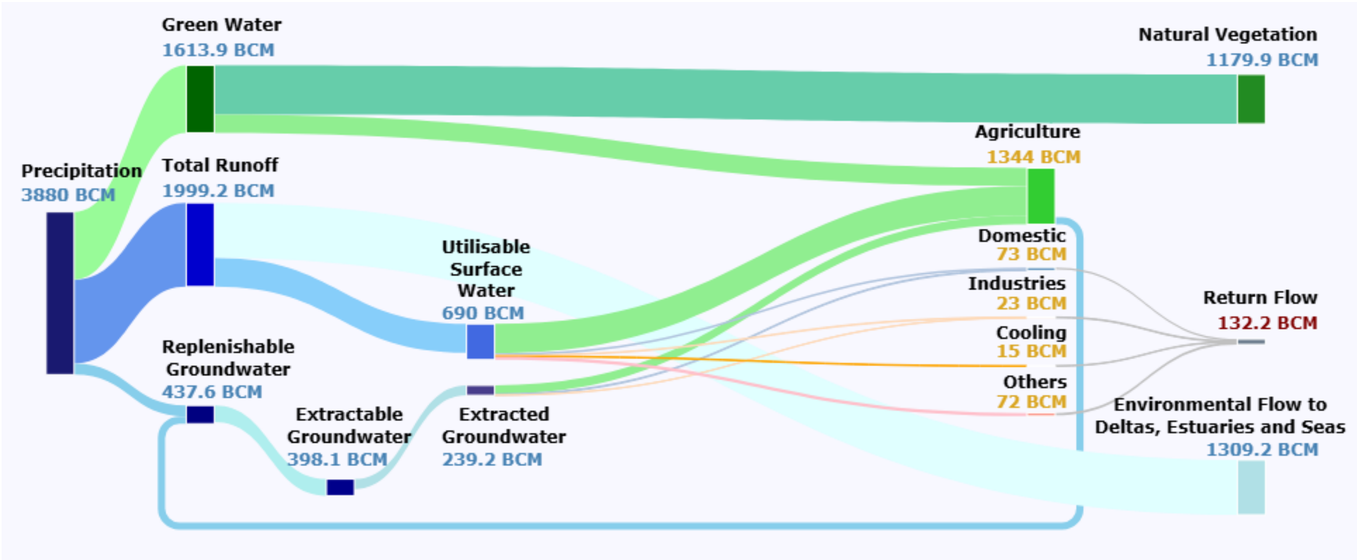
Despite this, India is experiencing substantial water scarcity, with 820 million people living below the official water scarcity threshold of 1,000 m³ as per the Falkenmark Index (NITI Aayog, 2019). India, home to about 17 per cent of the world's population, holds only 4 per cent of the global freshwater resources (IITM, 2014a). Additionally, 82 per cent of rural households lack piped water connections, increasing their vulnerability to water stress, and 163 million people lack access to clean water as an estimated 70 per cent of India's surface water is contaminated (NITI Aayog, 2019).

The average per capita water availability in India is expected to reduce to 1,341 m³ by 2025 and 1,140 m³ by 2050 due to the projected population growth (PIB, 2017). Water scarcity can significantly impact food scarcity as agriculture is directly and heavily reliant on water resources (NITI Aayog, 2019).

This situation necessitates implementing measures to treat and reuse the return flow from various sectors, which is estimated to be approximately 130 billion m³. Currently, most of this return flow is discharged into streams untreated or only partially treated, adversely affecting the water quality in deltas, estuaries, and seas, significantly affecting the biodiversity and livelihood along its stretch.

Climate change will compound water stress in multiple ways. Mallya et al. (2016) show an increase in the duration, intensity and geographical scope of droughts in recent decades, particularly in the Indo-Gangetic Plain, certain

Figure 2.1: Annual Water use in India in billion cubic meters (BCM)



Source: *Authors' compilation from CWC (2021b), CWC(2005), CGWB, 2022), Choudhary et al., (2021), Sushmitha et al., (2019).*

areas of coastal south India, and central Maharashtra. The frequency of droughts in parts of the country is likely to increase with a 1.5°C and 2°C increase in temperature from pre-industrial levels (Mallya et al., 2016). Sahana and Mondal (2023) evaluated drought hazard, vulnerability, and risk across India under future climate scenarios, estimating an overall decrease in drought risk due to increased precipitation. However, western Rajasthan, Haryana, and western Uttar Pradesh are expected to remain at high risk under all future scenarios. Additionally, they projected an expansion of areas falling into the high and very-high vulnerability categories nationwide. Studies project increased precipitation in certain regions and times of the year, likely leading to extreme precipitation events and urban flooding (Ali & Mishra, 2018).

Climate-induced water impacts will extend to agricultural yields, monsoon patterns, glacial melt, desertification, biodiversity loss, and increase risks to industries, energy sector and urban activities, impacting the country's Gross Domestic Product (GDP) (NITI Aayog, 2019). Climate change impacts in India, such as increasing temperatures and shifting monsoon patterns, may result in an economic loss of 2.8 per cent of GDP, adversely affecting the living standards of nearly half the population by 2050 (Mani et al., 2018; RBI, 2023).

Water is not only affected by climate change but also influences it through changes in evaporation and precipitation patterns. The hydrological cycle is projected to intensify, with higher amounts of rainfall as well as increased frequency of droughts (IITM, 2014b). Per capita water availability (PCWA) in India is expected to decrease under 1.5°C, 2°C and 3°C levels of global warming. A rise in temperature from 1.5°C to 2°C could reduce PCWA for more than 90 per cent of regions, with over 400 million people facing severe water stress (R. Singh & Kumar, 2019).

Further, three-hourly precipitation maxima at 100-year return intervals may increase by 20 per cent if the warming increases above 1.5°C from pre-industrial levels (Ali & Mishra, 2018). Observations suggest increased dryness over the Indo-Gangetic Plain from 1951 to 2016, and climate models predict that global warming of 1.5°C, 2°C and 2.5°C could increase dryness over half of South Asia, affecting 790 million, 890 million and 1.96 billion people, respectively (Aadhar & Mishra, 2019).

Despite the projected increase in rainfall in most parts of the country, substantial spatio-temporal variability is likely in the next few decades. For arid regions like Rajasthan, 1°C warming could lead to a rise in water demand by 313 million cubic metre (MCM), while major parts of the country could experience more devastating floods. Cyclone intensity is expected to increase along India's 7,517 km coastline, and salt water intrusion could disrupt groundwater reservoirs in coastal areas (Panwar & Chakrapani, 2013).

During the recent decades of 1981-2019, the spatial variations in the annual maximum rainfall for the 10-, 30-, and 100-year return levels show statistically significant increasing trends across Indian river basins, with the observed decadal changes of rainfall during wet and dry conditions shifting and 15 per cent–58.74 per cent increase in extreme rainfall events over the west-flowing river basins (Chaubey et al., 2022). In the Upper Indus basin, an increase in summer precipitation (RCP8.5: +36.7%) and a decrease in winter precipitation (RCP8.5: -16.9%) have been projected, with an increase in average annual water yield due to glacial melt (Ougahi et al., 2022). The Sutlej basin is projected to receive up to 50 per cent more precipitation by the end of the century compared to 1961–1990 (Nayak et al., 2015). In the Narmada basin, a long-term increase in monsoon season flow is projected in the upper parts, while dry season flows could remain unchanged despite intensified water demand. Using the RCP 4.5 data of climate variability, Mudbhatkal et al. (2017) project a decreasing trend in of total rainfall from 80 to 77 per cent in the Netravathi River catchment.

Among the east-flowing rivers, the Brahmaputra basin will witness extreme precipitation at 2°C, with higher flood frequency (Mohammed et al., 2017). Monsoon precipitation in the Ganges basin is projected to decline, while the Indus basin will see a significant warming (Mishra, 2015). The Teesta River basin may see increased future precipitation, raising the risk of glacial lake outburst floods (GLOFs) (A. Sharma & Goyal, 2020). The Koshi basin could face severe floods and droughts due to an increase in the annual mean temperature by 1°C to 4°C between 2010 and 2050 (Jain & Singh, 2018).

Over Malaprabha catchment, a decrease in monsoon rainfall from 84 to 80 per cent is projected by 2070 under

RCP4.5 scenario, while high flow is estimated to increase (Mudbhatkal et al., 2017). In Odisha's Baitarani River basin, maximum increase in the projected annual average rainfall is observed during the near future scenario 2021–2045 by 427 and 480 mm under RCP 4.5 and 8.5 scenarios respectively (Padhiary et al., 2020). In the Mahanadi River basin, mean monthly streamflow were found to be increasing towards the end of the century, with daily high flows increasing in both magnitude and frequency (Bisht et al., 2020).

2.3.3 Terrestrial ecosystems

India hosts a wide array of terrestrial ecosystems and is home to four out of 36 biodiversity hotspots in the world. The country has over 800,000 km2 total forest and tree cover, accounting for 24 per cent of its total geographical area (Forest Survey of India, 2019). These ecosystems provide services valued at USD 1.8 trillion (in purchasing power parity terms), which is over 30 per cent of India's GDP (Kubiszewski et al., 2016). Climate change significantly impacts the type, distribution, productivity and carbon availability in these terrestrial ecosystems, as discussed below.

Impact on forests: Indian forests face various climatic stresses, including a warming climate, changes in the hydrological cycle, loss of biodiversity and extreme weather events (Sharma et al., 2017). While evidence from the Indian region suggests greening and carbon sequestration in large parts of India in recent decades, it is likely that this is due to tree plantations, horticulture, agro-forestry, invasive species and other land-cover changes, and not due to major contribution from forests (Chen et al., 2019). Prioritizing carbon sequestration through tree plantations in some areas and land-use contexts may have trade-offs especially on hydrologic services (Clark et al., 2021; Sharachchandra & Krishnaswamy, 2021). The influence of forests on regional climate, especially rainfall, further complicates this debate. The ability of forests to continue to sequester CO_2 could be influenced by climate change in multiple ways. For instance, climate change can influence the expansion of the moist broadleaf forests in central India and a shrinking of Himalayan temperate broadleaf and alpine forests; a possible increase in productivity; and a decline in some wildlife species in specific habitats. Recent estimates from in-situ data show a decrease in carbon sequestration rates of intact Indian forests during 2010-2019 compared 1990-99 (Pan et al., 2024). So, additional effort is immediately required to achieve the 2030 target, considering the history of competing demands and ongoing shifts in forest rights and governance (Sharachchandra & Krishnaswamy, 2021).

Evidence from regions such as the Western Ghats suggests that the combination of rapid sub-surface flows systems and non-linear decline in catchment water residence time with rainfall intensity makes even the forested areas and areas under invasive species vulnerable to landslides and flooding under extreme rain events under climate change (Chappell et al., 2017; Nayak et al., 2023). However, forests can also aid in precipitation by modifying the local climate and providing moisture through evapotranspiration (Bonan 2008). For instance, the contributions of Western Ghats to the monsoon rainfall over the East Coast reach nearly a half, during dry periods (Paul et al., 2018). Recently, Williams et al., 2024 showed that, India has relatively very low proportion of land available with potential for natural regeneration in deforested areas. Overall, we need to compare official estimates with independent studies and measurements on the ground, to improve our understanding of forests to help carbon sequestration and to broader functioning of ecosystems.

Studies have shown that the greening-temperature positive relationships in the tropical mountainous regions such as the Himalaya are weakening, which could be due to indirect effects of water stress through enhanced summer heat especially in years with poor post monsoonal and winter rainfall (Zobel et al., 2001; Krishnaswamy et al., 2013; Liang et al., 2014; Sigdel et al., 2018; Sebastain et al., 2018), apart from forest fires. Since different forest regimes are driven by solar radiation, temperature, and monsoon (summer, winter) at different spatiotemporal scales (Sebastian et al., 2019), these interactions between climate-vegetation will remain critical in the future for carbon dynamics. Additionally, human-land use changes such as deforestation and degradation can add more stress on forests to persist as a carbon sink and these sites could potentially become a source of carbon altering the global carbon cycle (Bala et al., 2007).

Modelling studies indicate that at least 30 per cent of the forest cover in the country are vulnerable to climate stress in the short term by 2030. In the long term by 2085, nearly 39 to 88 per cent of forest cover is vulnerable (Chaturvedi et al., 2011; Chaturvedi & Ravindranath, 2017; Gopalakrishnan et al., 2011; Sharma et al., 2017).

Chaturvedi et al., (2020) project that almost all forest cover in India (98 per cent) can be classified as 'very high' to 'extremely high' temperature and rainfall hotspots with a warming of 2.1°C to 5.1°C and rainfall change of 26 to 38 per cent under the RCP 4.5 scenario. Further, under the RCP 8.5 scenario, 16 per cent of the forest cover in the country will be 'critical' with temperature range of 5.1°C to 6.6°C and rainfall change of 38 to 41 per cent, increasing their vulnerabilities.

Changes and shifts in vegetation: Large-scale changes in vegetation are also projected across Indian forests by the end of the 21st century due to changing climatic conditions. Across India, eight out of 19 sub-biomes are projected to increase in area, while the other 11 sub-biomes are projected to lose their area coverage due to projected increase in temperature and precipitation, with maximum loss (more than 50 per cent) in tropical dry forest with increase of 3°C in temperature and 15 per cent in rainfall (Chakraborty et al., 2013). By 2080, endemic flora in the Himalayas, Western Ghats and Indo-Burma biodiversity hotspots may see range reductions of up to 41 per cent and expansions of 24 per cent (Chitale et al., 2014).

Parida et al., (2020) note significant shifts in vegetation trends with large-scale greening trend of up to 80 per cent of area across the northwestern Plain and Central India from 1981 to 2015, mainly due to moisture-induced greening combined with cooling trends of temperature. However, greening trends of vegetation and croplands diminished (i.e., from 84 per cent to 40 per cent of area in kharif season), especially over the southern peninsula, including the west-central area, primarily due to warming trends and declined soil moisture trends. Although in the wet climate regimes as the Western Ghats, Western Himalaya, Eastern Ghats and North-East (NE) India, forests are predicted to be highly resilient against large precipitation alterations and shorter drought periods (Das and Behera, 2019), consistent decline in vegetation (browning trends), especially in north-east India and Western Ghats during the dry season has been observed (Naidu et al., 2019; Murthy & Bagchi, 2019).

In the Western Himalayas, increased temperatures will cause a shift towards higher elevations in all forest types (Joshi et al., 2012; Zomer et al., 2014). A study on vegetation dynamics on alpine summits in Kashmir Himalaya, showed that species richness increased on the lower three summits but decreased on the highest summit (nival zone) and revealed a substantial increase in the cover of dominant shrubs, graminoids, and forbs (Hamid et al., 2020).

Net primary productivity: Net primary productivity (NPP) is the rate at which energy is stored and made available to consumers in an ecosystem, serving as an indicator of ecosystem function and a key component of the global carbon budget. In India, most studies project an increase in NPP under multiple climate change scenarios. Estimates range from 38–100 per cent increase under SRES scenarios (Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; INCCA, 2010; Ravindranath et al., 2006, 2011) to a 10–50 per cent increase under RCP scenarios (Chaitra et al., 2018; Ravindranath & Bala, 2017).

A study on the sensitivity of terrestrial ecosystems across India observed that at least 15 out of 25 river basins were at high risks of drastic reduction in NPP in case of climatic conditions like severe drought, prolonged precipitation deficit and extreme temperature on terrestrial ecosystem (Jha et al., 2019). Decadal changes in NPP are driven by simultaneous changes in temperature and precipitation, and our ability to accurately ensure forests to sustain as a natural climate solution could be restricted under future climate change (Naidu & Bagchi, 2021). For instance, the western ghats and north earth regions showed a decline in NPP over he past two decades. Importantly, a simultaneous change in soil heterotrophic respiration can ultimately limit the carbon sequestration potential of these biodiversity hotspots (Naidu & Bagchi, 2021).

Carbon stock: Forests play a crucial role in the global carbon cycle, storing up to 80 per cent of terrestrial carbon (FAO, 2005). Climate change, by driving land use changes, alters terrestrial carbon fluxes. Most projections suggest an increase in soil organic carbon and an overall rise in the forest carbon pool due to climate change in India. Under the B2 and A2 scenarios, soil organic carbon is projected to increase by 30– 37.5 per cent, respectively, across India, by 2085 (Chaturvedi et al., 2011), while the forest carbon pool is expected to rise by 6–15 per cent under multiple scenarios by 2081–2090, implying heightened carbon dioxide absorption from the atmosphere (Ahmed & Suphachalasai, 2014).

However, long-term carbon sequestration necessitates the storage of carbon into the soil for climate mitigation. Carbon in soil is highly vulnerable to changes in climate at local and regional levels, which can influence multiple climate-feedback (Naidu & Bagchi, 2021). The ability of soils to sequester carbon is also limited by confounding effects such as warming, grazing, nutrient deposition which can alter ecosystem functioning in many ways (Roy, Naidu & Bagchi, 2021).

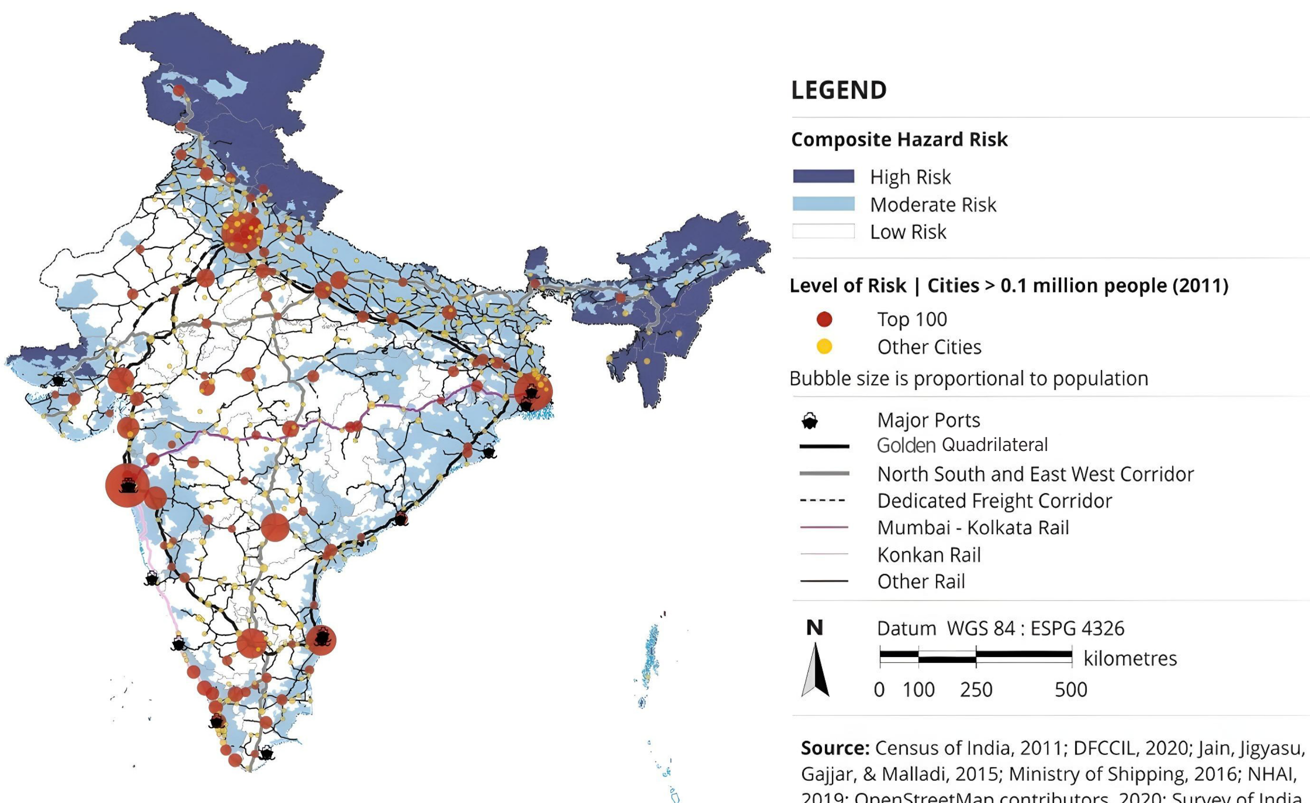
2.3.4 Urban and Infrastructure

India's urban population was 377 million in 2011 (Census of India, 2011) and is projected to reach around 600 million by 2030 (MoF, 2021). India has 53 large cities with populations exceeding 1 million and a total of 7,935 Census towns. Urban poverty is significant, with one-third of India's poor living in urban areas (MoF, 2021). A growing urban population presents complex challenges in providing essential services and infrastructure such as water supply, sanitation, solid waste management, transportation, energy, and hazard risk mitigation services (Ahmad & Choi, 2010; MoF, 2021). Urban expansion has also led to loss of agricultural production, farmland displacement, deforestation, reduced green spaces and disappearing water bodies (Bhat et al., 2017).

The combined effects of urbanisation and climate change exacerbates impacts in urban areas compared to surrounding rural or peri-urban regions (Liu & Niyogi, 2019). Changes in land use such as a loss of vegetation and increase in built-up area can magnify changes in rainfall, humidity, and wind speed, in addition to those caused by climate change (Kuşçu Şimşek & Ödül, 2019; Liu & Niyogi, 2019; Peng et al., 2017; Yang et al., 2017).

This makes urban areas more susceptible to heightened climatic impacts and extreme events such as heatwaves, coastal flooding and higher incidence of diseases. These

Figure 2.2: Composite hazard risk for cities



Source: Census of India, 2011; DFCCIL, 2020; Jain, Jigyasu, Gajjar, & Malladi, 2015; Ministry of Shipping, 2016; NHAI, 2019; OpenStreetMap contributors, 2020; Survey of India, 2019; IIHS Analysis.

Source: *IIHS Geospatial Lab, 2020* risks affect the poor and marginal sections of the society disproportionately, deepening existing social and economic vulnerabilities (Khosla & Bhardwaj, 2019). An analysis shows a decline in overall social vulnerability to climate change in urban India from 2004 to 2012, but vulnerability remains concentrated in central and eastern states like Madhya Pradesh, Chhattisgarh, Odisha, Jharkhand and West Bengal due to higher poverty, inequality, unemployment, lack of housing and poor access to services like drinking water and sanitation (Yenneti et al., 2016).

Risks to coastal cities: India's 7,517 km long coastline hosts over 25 cities with nearly 40 million people in three big cities, Mumbai, Kolkata and Chennai, and smaller cities like Mangaluru, Kochi, Panaji, Surat, Visakhapatnam, Thoothukudi and Puri with population over 0.1 million (MoF, 2021). Coastal cities face challenges like SLR, coastal flooding, and saltwater intrusion (Nair, 2009). India is among the top 10 countries at risk, with low-lying coastal cities increasingly vulnerable to urban flooding due to climate change–induced heavy precipitation (Nithila Devi et al., 2019).

Cities like Mumbai, Kochi, Chennai, Visakhapatnam, Mangaluru and Thiruvananthapuram are projected to face severe impacts from rising sea levels by 2050, potentially losing up to 50 per cent of their land area (Dhiman et al., 2018). Urban areas may also experience land subsidence due to high extraction of groundwater, which can increase vulnerability to SLR (Erkens et al., 2015). Several coastal cities such as Mumbai, Kochi and Thiruvananthapuram experience subsidence rates comparable to or exceeding projected SLR (Jennath & Paul, 2024).

Extreme sea level events (ESL) such as tropical cyclones and storm surges can result in significant loss of life, assets and infrastructure and stall the economy in coastal cities for a long period (Carleton & Hsiang, 2016). A 0.5°C increase in the Indian Ocean sea surface temperature could double ESLs events in coastal areas, making a present-day 100-year ESL event an annual occurrence by the end of the century under all emission scenarios and by the 2050s under a moderate emission scenario (Sreeraj et al., 2022)knowledge about past occurrences of ESL and its progression is limited. Combining multiple tide-gauge and satellite-derived sea-level data, we show that ESL has become more frequent, longer-lasting and intense along the Indian Ocean coastlines. We detect a 2–3-fold increase in ESL occurrence, with higher risk along the Arabian Sea coastline and the Indian Ocean Islands. Our results reveal that rising MSL is the primary contributor to ESL increase (more than 75 per cent. Southern coastal India may see significant changes in the frequency of ESL events by mid-century under a 1.5°C, with northern regions experiencing these changes by 2080–2090. With intermediate warming levels of 2°C and 3°C, these time frames shift earlier for both regions.

In southern India, a 100-fold increase in the frequency of ESL events is likely under the 1.5 °C warming scenario, while northern regions may experience this under 2°C or 3°C scenarios (Tebaldi et al., 2021). Increasing SLR and ESL events will also exacerbate coastal erosion, causing significant damage to sandy beaches (Vousdoukas et al., 2020). Coastal geographies struggle to recover from erosion due to diminishing free foreshores and reduced sediment supply due to settlements and dams in the backshore (Ranasinghe et al., 2019; Small & Nicholls, 2003). However, the variation in SLR and surge-driven coastal erosion has not been adequately quantified for different warming conditions globally and for India.

Extreme rain and floods in urban areas: Urban infrastructure is vulnerable to extreme precipitation. Climate change is projected to affect the seasonality and intensity of rainfall, leading to increased flash floods and storm surges that affect urban infrastructure and water supply and quality. India is a climate change hotspot for flood-related risks at both 1.5°C and 2°C global warming levels (Schleussner et al., 2016). Annual run-off is estimated to increase in many parts of India, raising river-based flood risks (Warren et al., 2022).

The frequency of flooding events is projected to rise significantly in major cities if global warming exceeds 1.5°C, with no significant difference in flood event numbers beyond this threshold (Avashia & Garg, 2020). Projections indicate increased pre-monsoon and monsoon rainfall, especially in north-east India, heightening flood risks in cities downstream of the Brahmaputra River (Yaduvanshi et al., 2019). Rising temperatures will accelerate glacier and snow melt in the Himalayas, compounding flood risks in the densely populated Ganges plains.

Intense precipitation can trigger river discharge and flash floods, leading to flooding in urban areas with inadequate drainage. One-to three-day maximum rainfall is also expected to increase by 2060 compared to the baseline period (1901–2010) (Ali et al., 2014). Extreme rain is projected to rise sharply by the end of 21st century, especially in southern and central India (Mukherjee et al., 2018). In flood-vulnerable cities like Chennai, rising precipitation intensity and reduced permeable land cover driven by urban expansion are projected to increase flood depth by 19 per cent by 2030 and 60 per cent by 2050, compared to 2015 levels (Anuthaman et al., 2023).

Urban drought and water scarcity: Rising temperatures, delayed and weakened monsoons, and socio-economic factors are collectively exacerbating water stress in India. These conditions will impact both water supply and demand, potentially increasing drought frequency by 5 per cent to 20 per cent (Goyal et al., 2023). Climate models and projections of extreme events indicate that urban areas face a heightened risk from these challenges. Currently, India (222 million) followed by China (159 million) have the maximum urban populations facing water scarcity. India is projected to be the most affected in terms of growth in urban population (153-422 million) facing water scarcity by 2050 (He et al., 2021). Goyal et al. (2023) study of urban drought risk for 100 Indian smart cities revealed maximum urban drought risk for Bangalore, Chennai and Surat. The study also showed that NorthWest, West Central, and South Peninsula urban regions in India were at higher risk of urban drought.

Urban heat: Across India, heat waves are already increasing in frequency and severity. Mishra et al. (2017) estimate that the five most severe heatwaves out of the top ten heatwaves in the entire record (1951–2015) have occurred after 1990 and the three most severe heatwaves occurred in 1998, 1995, and 2012, with a magnitude of 17.92, 16.92, and 11.14, respectively. The recent heatwaves of 2022-2024 have crossed these past records. Heatwaves are projected to occur more frequently in all scenarios compared to current conditions, with significantly higher frequencies under higher warming scenarios (Mishra et al., 2017).

At global average warming of 1.5°C above pre-industrial conditions, the frequency of severe heatwaves in India will be 2.7 by end of 21st century; under 2°C global warming, this frequency increases to 8.7 (Mishra et al., 2017). Under the RCP8.5 scenario, heatwave days—already 2.3 days higher in urban areas than rural areas—could increase to 7.1 days by 2045 and 13.8 days by 2100. Urban centers may see heatwave intensity rise from 40°C (1986–2005) to 45°C (2026–2045) and 49°C (2081–2100) (Sharma et al., 2019). Heat-related mortality is projected to increase by 71 per cent (RCP4.5) and 140 per cent (RCP 8.5) in urban areas by the 2080s, with cities like Delhi, Ahmedabad, Bengaluru, Mumbai and Kolkata facing the highest increases (Dholakia et al., 2015).

Critically, heat risk is concentrated in cities, and urban geometry (building density and height, green cover, air flow); water bodies and green cover; and climate change-induced temperature change interact to create urban heat islands (SUP, 2022). It is estimated that in India, ~37.73 per cent of total urban warming is linked to urbanization and this is an ~60 per cent enhancement of warming relative to the surrounding non-urban areas. This relative warming of urban areas to non-urban areas is especially visible in eastern Tier-II cities (Sethi & Vinoj, 2024).

Urban infrastructure: Urban areas, with their valuable properties and economic activity, face significant structural and property damage and economic loss from extreme events (Zope et al., 2017). Housing is crucial for climate resilience, but informal settlements in urban India increase vulnerability to climate hazards due to dense construction without open spaces or green cover (Mahadevia & Pathak, 2020).

Critical urban infrastructure is vulnerable to damage as current design are based on observed extremes rather than projected ones (Olsen, 2015). Extreme weather events like heavy rainfall and high temperatures can cause landslides and track deformation, damaging road and railway infrastructure (Joshi et al., 2024). Frequent extreme events will decrease restoration timelines, reducing quality of services from essential infrastructure like water supply, stormwater systems and energy networks (Vallejo & Mullan, 2017; Varianou Mikellidou et al., 2018). Under the SSP1-2.6 scenario, India could protect nearly all its transportation assets from heat, flood and compound heat-flood damage, whereas under the SSP2-4.5 scenario, exposure could be reduced by up to 50 per cent (Wang et al., 2024).

Kandla port's vulnerability to cyclonic disturbances could increase by 21–25 per cent under RCP6.0 and RCP8.5 by the end of the century. The Konkan Railways' expenditure on geo-safety works could rise from ₹180 million to ₹500 million under RCP4.5, and to ₹1,300 million under RCP8.5 by 2100 (Garg et al., 2015).

Urban road transport networks are also vulnerable to river and coastal flooding and increased cyclones affecting secondary and tertiary roads (Koks et al., 2019). Coastal flooding under various global warming levels is expected to incur significant economic costs for India, with GDP losses of 0.5–0.6 per cent by 2050 under both RCP4.5 and RCP2.6 without further adaptation (Schinko et al., 2020). Adaptation investments could reduce welfare spending by 0.3 per cent (Bosello et al., 2011). Beyond economic loss from physical damage, changes can significantly impact tourism-dependent coastal cities through reduced recreational beaches (Black et al., 2021) and loss of livelihood in the fisheries sector (Senapati & Gupta, 2017).

2.3.5 Health

Climate change is projected to have significant implications for disease burden and labor productivity in India (Lancet, 2023; Parsons et al., 2021). Vector-borne diseases, diarrhea, dengue, Japanese encephalitis, respiratory conditions and malnutrition are expected to increase with higher warming levels.

Heat stress: The frequency of three-day concurrent hot day and hot night (CHDHN) events is projected to increase fourfold, sixfold and eightfold compared to current levels at 1.5°C, 2°C and 3°C warming, respectively. One-day and three-day CHDHN events are estimated to increase fourfold, 5.5-fold and 6.5-fold at 1.5°C, 2°C and 3°C warming, respectively (Mukherjee & Mishra, 2018). The maximum population exposed to heatwave days (MPEHWD) is estimated to rise by 18 times, 15 times and 92 times compared to current levels at 1.5°C and 2°C and under RCP 8.5 by mid-and late 21st century (Mishra et al., 2017).

CMIP5 models project an increase of 1.5–2.5 heatwave events and a 12–18-day increase in duration between 2020 and 2064 (Rohini et al., 2019). PRECIS-based modeling under the A1B scenario projects high maximum temperatures (~45–50°C) for districts in Bihar, Gujarat, Odisha, Rajasthan, Andhra Pradesh, Uttar Pradesh and West Bengal (P. K. Singh & Dhiman, 2012).

Studies have linked heat stress to productivity losses (Lundgren et al., 2014; Venugopal et al., 2015). India is particularly vulnerable to occupational heat stress, with significant productivity losses and health impacts in labor-intensive outdoor occupations (e.g., construction, brick manufacturing and metalworking) compared to indoor ones (Venugopal et al., 2015). While a reduction in winter-time deaths is anticipated, chronic heat stress and increased pollution could severely affect public health (E. Sharma et al., 2009a).

Increasing humidity due to climate change exacerbates the impact of heatwaves, with outdoor workers being at maximum risk (Kovats & Akhtar, 2008). Humid heat impacts could result in the loss of approximately 62 million jobs per year in India, across the working age population, nearly half the jobs lost globally and comparable to the temporary job loss during the global COVID-19 lockdowns (Parsons et al., 2022). A study in Tamil Nadu found that high occupational heat exposure was linked to a higher risk of adverse pregnancy, fetal and birth outcomes, with women exposed to heat facing twice the risk of miscarriage compared to those not exposed (Rekha et al., 2024).

Disease incidence: Deteriorating water quality can lead to an increase in diarrheal diseases, while warmer and wetter conditions can increase the transmission of climate-sensitive infectious diseases such as malaria, schistosomiasis, and dengue (Sharma et al., 2009b; Singh et al., 2011). The risk of cholera, typhoid, rotavirus, hepatitis A, leptospirosis, cryptosporidiosis, and other vector-borne diseases is expected to rise due to increasing monsoon flooding in India (Ahmed et al., 2024). Furthermore, the lack of access to clean water during floods contributes to a spike in dermatological and ophthalmological issues, including scabies and eye infections (Ahmed et al., 2024). Research by Rodriguez-Llanes et al. (2016) established a link between flooding in Eastern India and child malnutrition, showing that the prevalence of wasting was highest in communities affected by flooding.

Malaria, influenced by factors such as agriculture, urbanization, and water availability, could spread to new regions as well as intensify in existing areas.

Projections indicate that the length of the malaria transmission season will extend by 1-2 months in the northeast, central and south central regions, with southern states experiencing year-round transmission under the RCP 8.5 scenario (Chaturvedi and Dwivedi, 2021). Malaria transmission intensity calculated through the historical Entomological Inoculation Rate (EIR or the number of infectious bites) scale of 0 to 1 are also higher by a statistically significant 0.1–0.2 in the under RCP 8.5 scenario in central and southern Indian regions. Some areas may see a decrease in malaria transmission despite these overall trends. For instance, under the same RCP 8.5 scenario, Parihar et al. (2022) predict a 20–40 per cent reduction in malaria transmission during the monsoon season in Odisha, attributed to increased temperatures and rainfall.

Dengue epidemics in India have become increasingly frequent, with cases from 2010 to 2014 more than 2.5 times higher than those reported from 1998 to 2009 (Rao & Nagendra, 2020). A study in central India found that the risk of dengue rises with higher mean temperatures, increased rainfall, and absolute humidity. In Bhopal, the incidence surged from 0.59 cases per 10,000 inhabitants in 2012 to 9.11 cases in 2019 (Sarma et al., 2022). In Kerala, the highest monthly dengue cases (5,251) were recorded in July 2017, coinciding with a slight temperature increase that year (Kakarla et al., 2023).

While dengue primarily affects southern India, its transmission is expected to rise in northern regions with a 2°C increase in temperature (Dhiman et al., 2010). Projections under the RCP4.5 and RCP8.5 scenarios indicate that dengue outbreaks will become more frequent, especially in southern, eastern, and central India (Kakarla et al., 2020a, 2020b). The dengue vector Aedes aegypti shows high prevalence in the urbanised regions of west Uttar Pradesh, Delhi, northern Bihar and north Jalpaiguri division of West Bengal, and could expand to the Thar Desert by 2030, 2050 and 2070 in all RCP scenarios, and to almost all of Rajasthan by the 2070s under RCP 8.5 (Hussain & Dhiman, 2022).

2.4 Conclusion

Climate change is altering climate impact drivers like heat, precipitation (rain, snow and ice), wind, and sea level worldwide. In India, climate projections indicate increased variability in precipitation and an increased frequency and intensity of extreme weather events like droughts and floods. These changes pose significant risks to vital sectors, including agriculture, water resources, ecosystems, urban areas, and public health.

We are already witnessing tangible impacts, such as declining crop yields, reduced per capita water availability, biodiversity loss, and a rise in vector-borne diseases. These impacts translate to risks like food insecurity and hunger, increased water and heat stress, and mortality-linked to climate extremes and diseases. Urban areas face heightened climate risks due to land use changes, vegetation loss, and the urban heat island effect, particularly affecting India's urban residents (estimated to be 600 million in 2030), many of whom belong to poor and marginalized communities.

Scientific evidence underscores that climate-induced impacts and risks will worsen as temperatures continue to rise. For instance, an increase from 1.5°C to 2°C could significantly reduce per capita water availability in over 90 per cent of regions, placing more than 400 million people under severe water stress. Heat-related mortality may surge by 71 per cent (RCP 4.5) and 140 per cent (RCP 8.5) in urban centres, impacting cities like Delhi, Ahmedabad, Bengaluru, Mumbai and Kolkata the worst. Similarly, flood risks could escalate dramatically; at 1.5°C, 0.5–1.5 million people may be affected, rising to 2.5–8 million under 2°C, and potentially 30–40 million at 4°C.

Even in the absence of climate change, projections indicate that 30 million Indians could face hunger by 2050. This number could range from 4.4 million to 140 million people under the once-per-100-year extreme scenario in RCP2.6 and increase to 8.7 million to 180 million under RCP8.5 (Hasegawa et al., 2021).

These risks highlight India's acute vulnerability to climate change and emphasise the urgent need to achieve the 1.5°C climate target to mitigate impacts on our people, economy, and ecosystems.

3.

Navigating India's Development and Climate Goals

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3. Navigating India's Development and Climate Goals

- India faces the dual challenge of achieving the Sustainable Development Goals (SDGs) while simultaneously addressing climate action. It is one of the fastest-growing economies globally but remains a lower middle-income nation with a per capita PPP less than half the world average. It's development in the last five decades has been marked by increasing population and GDP, largely driven by growth in the services sector.

- Despite the increasing GDP, socio-economic challenges including poverty, inequality, unemployment and development deficits persist in the country. India has the largest population of poor people in the world (about 229 million) and the country's Gini Index has been stagnating at about 35 for the last two decades, pointing to continuing inequality in consumption.

- The increase in GDP and the shift to a service sector economy over the long term has not led to a shift to higher value add jobs or created adequate jobs. Employment in India is characterised by low productivity, low wages, increasing informalisation, low participation of women in the labour force and lack of adequate skilled workers.

- India's climate action roadmap is linked to its development agenda and centres on tackling SDGs like ending poverty, ensuring food security, energy security, and reducing unemployment, while reducing emission intensity of its economy.

- The main challenge for India is to meet its aspirations of being an advanced economy by 2047 while maintaining low emissions intensity of GDP in the face of increasing population, urbanisation, industrialisation and growing consumption. This will require a different development trajectory for the country from other developed nations.

- India can adopt Climate Resilient Development (CRD), development framework negotiated by IPCC that brings together agendas of sustainable development, climate adaptation (to limit climate risks), climate mitigation (to reduce emissions) and biodiversity conservation.

- CRD will have to be operationalised within the Indian context to ensure growth and broad-based gains via jobs, climate protection, income security to the bottom half of India's population along with societal well-being for all.

- CRD will require systems changes within four key sectors/ areas: land, oceans and ecosystems (agriculture, forestry and allied sectors), energy, urban and infrastructure, and industrial. Two other cross-cutting sections will also need attention, water and health.

3.1 Introduction

India is the seventh largest country in the world with a geographical area of 329 million hectares, accounting for 2.4 per cent of the world's surface area. As per the 2011 Census, India's population is more than 1.21 billion, approximately 18 per cent of the world's population (MOEFCC, 2015). More recent UN global population estimates pegged the country's population at 1.42 billion in 2023 (UN DESA, 2023). Currently, India is the fifth largest economy in the world with a nominal Gross Domestic Product (GDP) of US$ 4.11 trillion (IMF, 2024), with aspirations to be an advanced economy by 2047.

In the last five decades, India's development has been marked by increasing population and GDP, largely driven by growth in the service sector. The average annual growth rate (AAGR) of the GDP increased from 3.6 per cent in the 1970s to 5.3 per cent in the 1980s and 1990s and 7.3 per cent in the 2000s (Karstensen et al., 2020). Recent data shows that the AAGR of India's GDP was 6.4 per cent per year from 2000 to 2010 and 5.7 per cent per year from 2014 to 2024. The growth rate dipped to 3.9 per cent in 2019 and negative 5.8 per cent in 2020 due to the COVID-19 pandemic (World Bank, 2024b).

Despite the increasing GDP, socio-economic challenges including poverty, inequality, unemployment and development deficits persist in the country. India has the largest population of poor people in the world (about 229 million) even after 415 million people exited poverty in the last 15 years (UNDP, 2023). The country's Gini Index has been stagnating at about 35 for the last two decades, pointing to continuing inequality in consumption (World Bank, 2024b). Employment in India is characterised by low productivity, low wages, increasing informalisation, low participation of women in the labour force and lack of adequate skilled workers (Basole, 2022).

India is also among the top 10 countries most vulnerable to climate change. An estimated annual GDP loss of 3 to 10 per cent by 2100 is likely if the impact of climate change continues unabated (RBI 2023; Kompas, Pham, and Che, 2018). As discussed in Chapter 3, climate change can have wide-ranging adverse impacts across regions and sectors in the country including agriculture, infrastructure, water systems, health and labour productivity. The country's disadvantaged and poorer populations are most vulnerable to these adverse impacts given their lack of access to basic infrastructure and services, inadequate income security, and a weak safety net to protect them from climate vagaries and extreme events.

India's climate action roadmap is inextricably linked to its development agenda and centres on tackling Sustainable Development Goals like ending poverty, ensuring food security, energy security, reducing unemployment, addressing economic inequality, improving health and education access, and addressing infrastructural deficits, while simultaneously reducing the emission intensity of its economy (GOI, 2023).

So far, India's growth trajectory has resulted in a much lower emission intensity of its GDP in PPP terms than the emissions of other more developed countries, which were at a similar level of development in the past (MOEFCC, 2015). Going ahead, this will be a difficult challenge due to pressures from growing population, urbanisation, increasing industrialisation and growing consumption. For instance, India's emissions have increased more than the global average, with its share in global emissions increasing from 1.3 per cent in 1970 to 6.3 per cent in 2015 (Karstensen et al., 2020).

At the same time, India has an opportunity to chart a development trajectory that is unique from that of developed countries by operationalising climate resilient development (CRD). CRD, a development framework negotiated by the Intergovernmental Panel on Climate Change (IPCC), across 193 countries, in its Sixth Assessment Report (AR6) integrates sustainable development, climate and biodiversity goals (IPCC, 2022b; IPCC, 2023). CRD brings together the agendas of sustainable development, climate adaptation (to limit climate risks), climate mitigation (to reduce emissions) and biodiversity conservation, based on complementary development interventions rather than trade-offs between climate action and sustainable development (Stern and Stiglitz, 2023).

Given the national circumstances, India's aspirations to be an advanced economy by 2047 will have to rely on CRD to ensure growth and broad-based gains via jobs, income security, climate protection to the bottom half of its population, along with societal well-being for all. In the next sections, this chapter provides a broad overview of the country's climate vision (3.1.1), its economic structure (3.2), long-term employment trends (3.2.1), national greenhouse inventory (3.2.2), and sectoral focus for climate and development action (3.3), ending with a brief conclusion (3.4).

3.1.1 India's climate vision and long-term low emissions development strategy

India's Nationally Determined Contributions (NDCs) and Long-term Low Emissions Development Strategy (LT-LEDS) affirm India's global commitments to reduce emissions but within the framework of 'common but differentiated responsibilities and respective capabilities' (GOI, 2023). The country's NDCs (updated in 2022) target 45 per cent reduction in the emission intensity of its GDP, 50 per cent installed power capacity from non-fossil fuels by 2030, promoting a sustainable way of living and achieving net-zero emissions by 2070 (GOI, 2023; MoEFCC, 2022).

Overall, India's LT-LEDS envisages a just transition to a green economy with a focus on developing low-carbon electricity, transport and industrial systems along with promoting sustainable urbanisation that incorporates adaptation in its design (MOEFCC, 2022). These climate priorities are being reflected in policy, regulatory measures and through budgetary allocations that support mitigation and adaptation actions (see Chapter 5). For instance, low-carbon urban transportation is being pursued through promotion of metro systems, with Indian Railways targeting to be net-zero by 2030, promoting fuel efficiency standards for vehicles, promoting alternative fuels including the blending of ethanol, and subsidising electric vehicles. Low-carbon energy policy measures include policy and financial support for renewable energy generation, improving energy efficiency, green energy corridors in eight renewable-energy-rich states, and smoother grid integration for renewable energy.

To decarbonise hard-to-abate industrial sectors, the government is looking at setting up a green hydrogen hub. The National Green Hydrogen Mission set up in 2023 aspires to create production capacity of 5 million metric tonnes (MMT) of hydrogen per annum by 2030. Climate adaptation is being pursued within the framework of the National Action Plan on Climate Change (NAPCC), addressing vulnerable sectors and ecosystems, and through flagship schemes like Atal Mission for Rejuvenation and Urban Transformation (AMRUT), Pradhan Mantri Awas Yojana, Jal Jeevan Mission and Swachh Bharat Mission (SBM), which aim to make up infrastructural deficits and provide universal access to housing and environmental services like adequate water supply, sanitation and solid waste management, thereby reducing the climate vulnerability of people.

3.2 Economic Profile and Share of Gross Value Added

Over the last 75 years, India has seen a structural shift from an agrarian to a service-based economy. The GDP share of the agriculture and allied sector has declined from 36 per cent in 1980 to 17 per cent in 2017, amidst an increase in the growth rates of industries and the service sector (Krishna et al., 2022).

The service sector has dominated the country's economic structure post liberalisation with its share in the Gross Value Added (GVA) increasing from 37 per cent in the 1980s to 53 per cent in 2017. The analysis by Krishna et al., (2022) based on KLEMS[1] industry data further shows that in the service sector, the value add of non-market services like public administration, education and health has remained stagnant at about 20 per cent while that of market services like trade, hotels, business and financial services, and transportation has increased from 15 per cent to 32 per cent.

The share of manufacturing has remained largely stagnant since the 1980s, with a marginal increase from 27 per cent

[1] The KLEMS approach considers the roles played by capital, labour, energy, materials and services as inputs to output growth. The KLEMS-India data set provides output, input and productivity trends for 27 industries linked to National Accounts Statistics (NAS). These industries can be categorised and broadly correspond to the main sectors of the economy: agriculture, industries and services.

in 1980 to 29 per cent in 2017. Within manufacturing while the share of chemicals, petroleum, electrical equipment, transport equipment, non-metallic minerals has increased, this increase has not been high enough to offset the decline in other industries like wood and paper products. The share of construction within the industry has however, has increased from 5 per cent in 1980s to about 10 per cent in 2010, followed by a dip to 8 per cent in 2017.

From 2017–18 to 2022–23, the broad trends of GVA contribution have remained similar. In 2022–23, agriculture and allied activities contributed 18 per cent, industry contributed 28 per cent and services accounted for 54 per cent of the GVA (MOSPI, 2024). Table 3.1 shows the share of industries categorised under the three broad sectors contributing to the GVA based on the KLEMS India industry data.

Table 3.1: Industry share (in %) in India's economic Gross Value Added (1980–2017)

Sectors	1980	1994	2003	2008	2017	2022
Agriculture and Allied Activities	**36.3**	**28.8**	**21.4**	**17.9**	**17.2**	**18.2**
Industry	**26.9**	**30.4**	**29.9**	**33.1**	**29.3**	**27.6**
Mining and quarrying	1.9	2.7	2.8	3.2	2.3	2
Manufacturing industries	17.5	18.5	16.9	18.2	16.4	14.3
Utilities	2.1	3.5	2.9	2.1	2.7	2.5
Construction	5.4	5.7	7.3	9.7	7.8	8.8
Services	**36.8**	**40.8**	**48.8**	**48.9**	**53.5**	**54.1**
Market services: Trade, hotel, transport, storage, post and telecom, real estate, financial and business	15.2	20.9	28.5	29.5	32.1	-
Non-market services: Public administration, education, health and others	21.6	19.9	20.3	19.4	21.4	-
Total	**100**	**100**	**100**	**100**	**100**	

Note: The break-up of the service sector into market and non-market services is not compiled separately in the MOSPI data and hence the breakup is not shown for 2022–23

Source: *Krishna et al., 2022 and MOSPI, 2024 (second advanced estimates for 2023-24)*

3.2.1 Employment trends across sectors

India is one of the fastest growing economies in the world today. The country's growth rebounded post the pandemic with a GDP growth rate estimated at 7.6 per cent for 2023–24, on the back of 9.1 per cent growth rate in 2021 and 7.2 per cent in 2022 (World Bank, 2024b; MOSPI, 2024).

However, the increase in GDP and the shift to a service sector economy over the long term has not led to a shift to higher value add jobs or created adequate jobs. The Indian labour market suffers from structural challenges on both demand and supply side, such as low rate of labour force participation of women and lack of adequate skilling, leading to underemployment and high levels of employment informality (Basole, 2022).

A study of the structural change in employment from the 1980s to 2017 shows a shift from the agriculture sector to the service sector. The agricultural workforce reduced from 70 per cent to 42 per cent, while employment in the service sector increased from 17 per cent to 34 per cent in this period (Krishna et al., 2022). Employment in the industrial sector also increased from 13 per cent to 24 per cent in the same period (Krishna et al., 2022). The maximum growth in employment in this period came from the construction sector, which grew by nearly six times, from 2 per cent in the 1980 to 12 per cent in 2017, adding 48 million jobs, and within market services, which grew from 9 per cent

Table 3.2: Distribution of India's employment across sectors

Sectors	1980	1994	2003	2008	2017	2022
Agriculture and Allied Activities	**69.8**	**63.5**	**57.4**	**51.9**	**42.3**	**45.8**
Industry	**13.2**	**15.2**	**17.5**	**20.4**	**24**	**25.2**
Mining and quarrying	0.5	0.7	0.6	0.6	0.4	0.3
Manufacturing industries	10.4	10.4	11.3	11.6	11.5	11.4
Construction	2	3.8	5.3	7.9	11.6	13
Electricity	0.3	0.3	0.3	0.3	0.5	0.5
Services	**16.9**	**21.4**	**25.1**	**27.6**	**33.8**	**28.9**
Market services: Trade, hotel, transport, storage, post and telecom, real estate, financial and business	9.1	12.6	16	17.8	22.2	17.5
Non-market services: Public administration, education, health and others	7.8	8.7	9.1	9.8	11.6	11.4
Total	**100**	**100**	**100**	**100**	**100**	**100**

Source: *Krishna et al., 2022 and PLFS, 2023* in the 1980s to 22 per cent in 2017, adding 77 million jobs. Table 3.2 that shows the distribution of employment across sectors from 1980s onwards.

The rate of growth of employment in the service sector, however, has been only about 3.2 per cent from the 1980s to 2017, with growth slowing down post 2003 (Krishna et al., 2022). Despite a decline, agriculture continues to absorb the highest proportion of labour. Both agriculture and construction have similar composition of labourers with 65–68 per cent unskilled labourers.

These trends have remained broadly similar from 2017 to 2022. In 2022–23, agricultural workforce increased to 46 per cent, while the workforce in service sector decreased to 29 per cent and in industries it increased marginally to 25 per cent (PLFS, 2023). Agriculture and the construction sector still made up for 59 per cent of workforce in 2022.

Overall, the employment ratio in India is well below other emerging markets and developing economies (EMDEs), with employment weakness registered in non-agriculture sectors (World Bank, 2024a). From 2000 to 2023, employment growth in India was well below the average working age population growth and the employment ratio declined. The country's annual Periodic Labour Force Survey for 2022–23 shows that about 10 per cent of the population in the age group of 15–29 are unemployed (PLFS, 2023).

Basole (2022) argues that low labour productivity and the nature of employment in India that is largely non-skilled, informal and low paying, leading to weak generation of demand from the majority of households and stimulating only a limited set of economic activities. The bulk of demand comes from a small population of elites and middle classes with relatively high income, which creates demand for capital-intensive products and services, in turn increasing the capital intensity of production and slow growth of employment (Basole, 2022). Most households living in India's large subsistence economy are not able to meet their consumption needs and are forced to look for multiple sources of livelihoods, which are available only as informal employment (Basole, 2022).

This indicates that India's economic policy needs to focus not only on growth but also on structural transformation in employment to reduce inequality and improve conditions for the majority of the country's population (Basole, 2022; World Bank, 2024a).

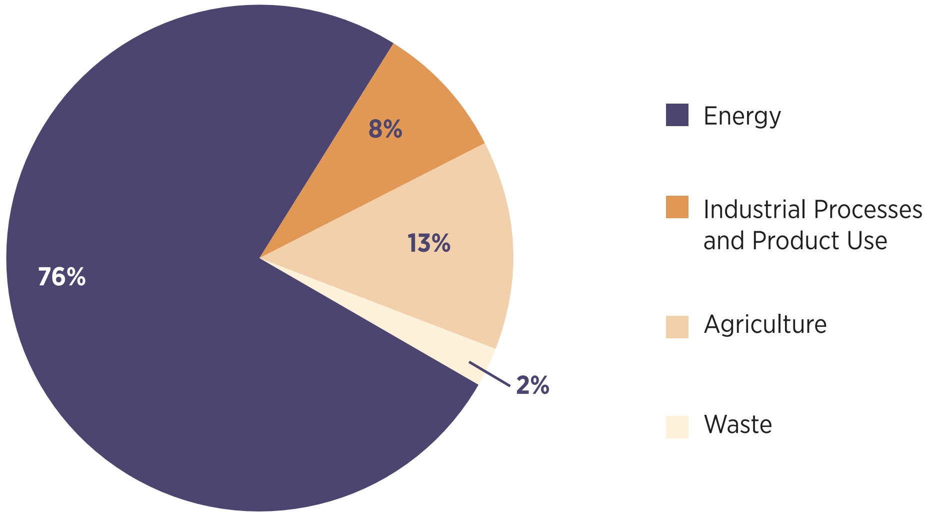
India's transition to a domestic market–driven 'green economy' is imperative to address climate change. A green transition can lead to a 'new growth story' as investments, technology transfers and more efficient use of resources can increase productivity in developing countries, if the enabling conditions are conducive (Stern and Stiglitz 2023, p. 287). This will also require a wide range of policy initiatives and investment in people to ensure that those dislocated during the transition and those already existing within the subsistence economy get new and better opportunities.

In India, the climate transition costs in terms of job losses from the coal economy are significant. A just transition requires climate action strategies to include policies that can incentivise private investments, entrepreneurship and jobs in the service sector (as it is less emission intensive; see section below), along with newer, cleaner labour-intensive industries. Policies need to address the issue of low participation of women in paid work (e.g., through incentives and better childcare policies), provide re-skilling and training for new jobs and offer social security (e.g., through programmes like an urban employment guarantee scheme) to raise the base floor of decent work and reduce economic vulnerability. CRD in India should simultaneously and consciously respond to the climate crisis and adopt mitigation and adaptation pathways that can create new jobs and continue economic growth.

3.2.2 India's national greenhouse inventory

Globally, India is the third largest emitter of greenhouse gas (GHG), after China and the US, even though its per capita emissions are below the global average of 4.7 tonnes. India's total emissions in 2019 were 3.13 billion tonnes of carbon dioxide equivalent, as per the country's third national communication submitted under the Kyoto Protocol (MoEFCC, 2023). The net emissions were 2.64 billion tonnes after accounting for CO_2 emissions absorbed by the forestry sector, which was less than half of the United States and less than a fourth of China (MoEFCC, 2023; Sinha, 2023).

Figure 3.1: Distribution of greenhouse gas emissions (GgCO²e) by sectors in 2019



Source: *India's Third National Communication, 2023*

The national inventory of GHG emissions in 2019 shows that the energy sector (76 per cent) contributed the most to overall emissions, followed by the agriculture sector (14 per cent), the industrial processes and product use (IPPU) sector (8 per cent) and the waste sector (2 per cent) (MoEFCC, 2023).

The total emissions from the energy sector (including consumption of fossil fuels for various activities and their fugitive emissions) increased by 11 per cent from 2016. The energy sector includes subcategories of manufacturing, construction, transport, energy industries, residential and commercial buildings, and fugitive emissions from solid fuels, oil and natural gas.

The IPPU sector contributed 8 per cent to GHG emissions in 2019; an increase of 16 per cent from 2016 due to increase in the production of cement, aluminium and lime (MoEFCC, 2023). The sector represents GHG emissions produced by industrial activities that transform raw materials by chemical or physical means, including the metal, chemical and mineral industries.

The agriculture sector accounted for 13 per cent of GHG emissions in 2019; a decrease of one per cent from 2016 (MoEFCC, 2023). The main source of these emissions in the agriculture sector are in the form of methane from livestock and rice cultivation, and nitrous oxide from manure management and soil under agriculture.

These sectoral subcategories are based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and not strictly aligned with GVA sectors and sub-sectors, but broadly point to industry and agriculture as high-emission sectors. Globally, the service sector has not been seen as emission intensive and in India, service-led growth post the 1980s has been linked to a lower emission intensity trajectory (RBI, 2023; Karstensen et al., 2020). However, India's service sector includes transport, a high-emission sector, followed by real estate (residential and commercial buildings). Within the industrial sector, electricity production, cement, steel and iron, manufacturing industries, and construction are high-emission sectors.

The GVA sectoral data, along with the emissions data, is useful to identify high emitting categories to design climate mitigation strategies and policies. This data also shows the extent to which sectors like electricity production, agriculture, buildings, transport, steel and cement industries that contribute significantly to the country's GVA are exposed to climate transition risks or social and economic costs associated with a low-carbon transition.

An RBI report (2023) bringing together two data sources (National Sample Survey and climate data from the International Monetary Fund) calculates the country's sectoral contribution to GVA and its emission intensity (see Table 3.3). This data makes it evident that sectors like electricity production, manufacturing and transport that contribute significantly to the country's GVA are carbon intensive. The priority must be to decouple these sectors from fossil fuel–led growth but also creating more job opportunities at the same time. The transition of these sectors to low carbon is necessary, but it has to take into account India's employment prerogative, including by absorbing people who will lose livelihoods in this transition.

3.3 Sectoral Focus for Climate Action and Systems Transitions

Effective climate action to reduce emissions across these sectors and subcategories requires systems change/ transition, rather than siloed sectoral approaches. As discussed in the introduction, India needs to pursue inclusive growth-led CRD pathways. CRD can be operationalised through simultaneous systems transitions in five key areas: energy, urban and infrastructure, land, freshwater and ocean ecosystems, industry, and societal choices around behaviour (IPCC, 2022b). Using the IPCC framework, this section examines the current state of play across four key sectors of the Indian economy: agriculture and forestry, urban infrastructure, industry, and energy that are also climate sensitive and require systemic change. The section also briefly discusses two other critical cross-cutting areas for climate action, water and health.

3.3.1 Agriculture

Agriculture plays a crucial role in India's economy. While its contribution to GVA is declining, it continues to be a significant contributor to the country's output. Nearly 46 per cent of the country's workforce is dependent on agriculture for a living. This includes nearly 70 per cent of households in rural India. A majority of India's cultivators are small and marginal farmers (82 per cent), who own less than 2 hectares of land. The average size of landholdings (1.08 ha in 2015) is decreasing even as the number of marginal landholdings (less than 2 hectares in 2015) is increasing (MoEFCC, 2023). The percentage of female operational holders is also increasing (14 per cent in 2015) pointing to feminisation in agriculture.

Table 3.3: Sector-wise share in GVA and CO_2 emission intensity (2018–19) in India

Sector	Share in GVA	CO_2 Emission Intensity (Metric Tonnes of CO_2 emissions per US $ 1 million of output)
Agriculture, forestry and fishing	14.8	8.8
Mining	2.6	567.3
Manufacturing	18.3	2913.3
Electricity, gas and water supply	2.3	7374.2
Construction	8.1	115.9
Transport	3.9	3176.9
Financial, real estate and professional services	22.5	220

Source: *RBI, 2023*

Around 43 per cent of India's total geographic area is under cultivation. Fourteen states including Andhra Pradesh, Tamil Nadu, Kerala, Telangana, Karnataka, Maharashtra, Gujarat, Chhattisgarh, Madhya Pradesh, Rajasthan, Uttar Pradesh, Bihar, Odisha and West Bengal account for 91 per cent of landholdings in the country. India is the world's largest producer of milk, pulses and jute, and the second largest producer of wheat, rice, sugarcane, groundnut, cotton, and fruits and vegetables (FAO, 2024).

Agriculture in India is predominantly rainfed (52 per cent) (MoEFCC, 2018). Water availability, which is imperative for productive agriculture, is hampered by climatic impacts such as decreased rainfall, drought, flooding and glacial retreat, which impact perennial river flows and groundwater, posing a serious threat to food security.

Agriculture is one of the most vulnerable sectors to climate change in India given its livelihood dependence, low value-added share in GVA, and the impact of food and nutrition security and price volatility on poverty and inequality. Climate change through increased frequency of extreme events, climate change variability and long-term climate change is expected to have a significantly adverse impact on farm incomes, livelihoods and food production (RBI, 2023). For small farmers, climate change is exacerbating existing economic distress of increasing cost of inputs, high indebtedness, and lack of assured and adequate prices. About 115 districts in India are highly vulnerable to climate change based on their exposure as well as socio-economic indicators (MoEFCC, 2023).

This makes climate adaptation for the sector crucial. Climate adaptation strategies for the agriculture sector include missions like the National Mission for Sustainable Agriculture (NMSA), National Livestock Mission (NLM), National Horticulture Mission (NHM) and National Food Security Mission (NFSM), and policy support measures like the Pradhan Mantri Fasal Bima Yojana (PMFBY) and Pradhan Mantri Krishi Sinchai Yojana (PMKSY), among others.

While the agriculture sector has less CO_2 emission intensity than the industrial and service sector, it emits methane and nitrous oxide, contributing 13 per cent of GHG emissions. Agriculture also accounts for 17 per cent of electricity consumption, besides 0.6 million tonnes a year of diesel used to energise agriculture pumps (RBI, 2023). Decarbonising agriculture will require better livestock feeding and management, diversifying away from rice cultivation to other less water-intensive crops like maize and millets, reducing post-harvest and food waste, promoting and subsidising soluble fertilisers, promoting agro-ecological practices, and expanding renewable energy use on farms (Gulati and Thangaraj, 2021; Padhee and Whitbread, 2022).

3.3.2 Forestry

India is among the few countries in the world where total forest and tree cover has been increasing despite development activities. Forests and tree cover made up 25 per cent of India's total land area (81 million hectares.) in 2021 (MoEFCC 2023). India has a diverse forest cover, ranging from tropical wet forests in the southern Western Ghats and Northeast states to dry deciduous forests across large parts of the country and alpine forests in the Himalayan region.

There was a net increase in India's forest cover by 26,666 km^2 from 2011 to 2021. This increase is attributed to increase in very dense forests (with tree canopy cover of more than 70 per cent), which increased by 20 per cent in this same period. The top five states in terms of having dense forests include Andhra Pradesh (21per cent), Maharashtra (9 per cent), Odisha (7 per cent), Chhattisgarh (7 per cent) and Madhya Pradesh (7 per cent).

Forests promote climate change adaptation and mitigation by storing more carbon than other terrestrial ecosystems, and providing ecosystem and livelihood benefits. The carbon stock in India's forests is estimated at 7 gigatonnes (GT) in 2019, which is 30 billion tonnes of CO_2 equivalent carbon sequestered.

India's forests are also vulnerable to climate change due to livelihood dependence of tribal communities and commercial activities like timber harvesting, mining and expanding eco-tourism. Around 45 per cent of the national forested grids in India are projected to change due to climate impacts, with vulnerable grids (due to climate change risk, low tree density, low biodiversity status and high levels of fragmentation) in the Upper

Himalayas, parts of central India and northern western and eastern Ghats (Gopalakrishnan et al., 2011). Government schemes to conserve forests and natural ecosystems include Green India Mission (GIM), Compensatory Afforestation Fund Management and Planning Authority (CAMPA), National Afforestation Programme (NAP), Green Highways Policy 2015, Policy for Enhancement of Urban Greens, National Agro-forestry Policy, and the Sub-Mission on Agroforestry (SMAF).

3.3.3 Urban Infrastructure

India's ongoing urban transition, one of the largest in the world, is a critical area of challenge for both development and climate action. India's urban population is expected to increase to 600 million by 2031 and to 850 million by 2051 (MOEFCC 2018). To meet the demands of the growing population in cities and towns, adequate infrastructure including environmental services of sanitation, water, solid waste management, affordable housing and transport have to be designed and built from scratch or upgraded significantly in such a way that the infrastructure is low-carbon and climate resilient.

Public investments in these areas are critical for disadvantaged groups that cannot afford to spend on them and hence also face climate risks and impacts disproportionately. An estimated 1.1 per cent of India's annualised GDP (in 2020) of ₹2.3 lakh crores will be required from 2021 to 2031 to meet the needs of urban expansion and upgradation of existing infrastructure and services in urban areas (Revi et al., 2020). Current expenditure on urban infrastructure has been only 0.6 per cent of the GDP from 2011–2018.

Urban areas also concentrate climate risks due to their large population, density, and differential exposure to climate change. Climate change impacts through droughts, increased rainfall, floods, coastal flooding and sea level rise (SLR) in urban areas are severe and growing. These events co-exist with developmental deficits, increasing the vulnerability of the urban poor and marginalised communities (Revi, 2008). At the same time, given the scale and pace of urbanisation in India and its consequent rise in consumption and production, urban emissions are expected to increase from transport, buildings, waste and industry.

This makes climate adaptation essential in cities to prepare for risks and increasing coping capacities of urban residents. Recognising this need, adaptation actions are being explored in Indian cities but much of the adaptation underway is 'reactive, sectoral, and risk-focussed' (Singh et al., 2021, p. 17). The Indian government's flagship schemes like AMRUT-U and SBM-U, focus on universal provision of water supply, sanitation and solid waste management services in urban areas, address urban development deficits, and also help in adaptation.

Transport: Road transport (9 per cent) and residential and commercial buildings (4 per cent) contribute significantly to the country's GHG emissions and are key areas for climate mitigation in urban areas. There were 324 million registered vehicles in India as of March 2021, with a six-fold increase in vehicles over the last two decades (MoRTH, 2023). India is also one of the largest automobile markets in the world, with total industry sales estimated at 2.1 million automobiles in 2020. The transport sector overall accounts for 10 per cent of total energy consumption in India. Besides GHG emissions and high energy consumption, transport also has air pollution and health-related implications (Aggarwal, 2017).

Developing low-carbon transportation is one of India's NDC objectives to meet its climate goal of maintaining temperature elevation well below 2°C. Government strategies to reduce emissions in this sector include: stricter fuel efficiency norms (BS-VI emissions), scrapping of old vehicles, promoting alternate fuels like LPG, CNG and ethanol, and adopting the National Policy on Biofuels to achieve 20 per cent ethanol blending in petrol (MoEFCC 2023). The government is also promoting the development of mass transit projects in cities and providing incentives for the manufacture and adoption of electric vehicles (EV), including public buses, three-wheelers and private cars. The uptake of EVs is increasing in India, with sales growing from 0.4 per cent in 2021 to 1.5 per cent from in 2022 (Jaeger, 2023). However, India's market share is only 1.5 per cent when compared to 80 per cent in Norway and 22 per cent in China.

Buildings: India's urbanisation is leading to an increase in residential and commercial buildings. Emissions from buildings include those during construction (energy embedded in construction materials) and use (energy use during lifecycle of the buildings). Residential and commercial buildings account for 33 per cent of total electricity demand in the country (MOEF, 2023). Energy sector demand is slated to increase by five times in residential buildings and three times in commercial buildings by 2032. India is looking to reduce emissions from this sector through better energy efficiency protocols and regulatory policies like the Energy Conservation Building Code (ECBC), Building Energy Efficiency Programme (BEEP) for retrofitting energy efficiency measures in existing buildings, Eco Niwas Samhita for residential buildings and building rating programmes. These policies are aimed at making the design and construction of buildings more energy efficient and reducing its energy consumption.

3.3.4 Industry

The industrial sector plays a pivotal role in the Indian economy, contributing around 31 per cent to the GDP on average between 2012 and 2021 and providing employment to over 121 million people (GOI, 2023). There has been consistent growth in key industries such as coal, fertilisers, cement, steel, electricity, refinery products, crude oil and natural gas over the last three years, indicating a broad momentum in industrial activities. India ranks second globally in steel and cement production and is among the top five producers of ammonia (RBI, 2023).

The industrial sector is highly energy intensive and its low-carbon transition is challenging, given high fixed investments and long shelf life of assets. Decarbonisation in this sector requires significant alterations in production processes, costly retrofitting, deployment of new technologies, and changes in business practices and policies. The Indian manufacturing sector relies on 45 per cent of coal for its energy requirements and 23 per cent on electricity. Energy consumption by the sector has been reduced in recent decades because of improvement in energy efficiency and shift in industries towards less energy-intensive industries like electronics (RBI, 2023).

Regulatory mechanisms like the Perform, Achieve and Trade (PAT) scheme, which has set energy-saving targets for various industries and activities and enables the trading of energy efficiency certificates, has also helped to improve energy efficiency. Yet, there is an urgent need to diversify into low-carbon technologies for certain hard-to-abate sectors like steel, cement and ammonia, which are poised to grow in the coming years.

The government is looking at setting up green hydrogen to aid low-carbon transition in the industrial sector. The National Green Hydrogen Mission was set up in 2023 with a proposed outlay of ₹19,744 crore from 2023–24 to 2029–30 to make India a green hydrogen hub with a capacity of 5 MMT per annum. There are several challenges in achieving a hydrogen economy including high production costs, technical difficulties in transport and storage, and lack of supportive policies and regulation (NITI Aayog, 2022). The RBI (2023) also suggests two long-term options to reduce emissions from hard-to-abate industries, including incorporating carbon pricing and making use of carbon capture utilisation and storage (CCUS) technology. The Energy Conservation Act, 2023 envisaged the setting up of a carbon market or Emissions Trading System to make the shift in policy from energy efficiency to emissions reduction.

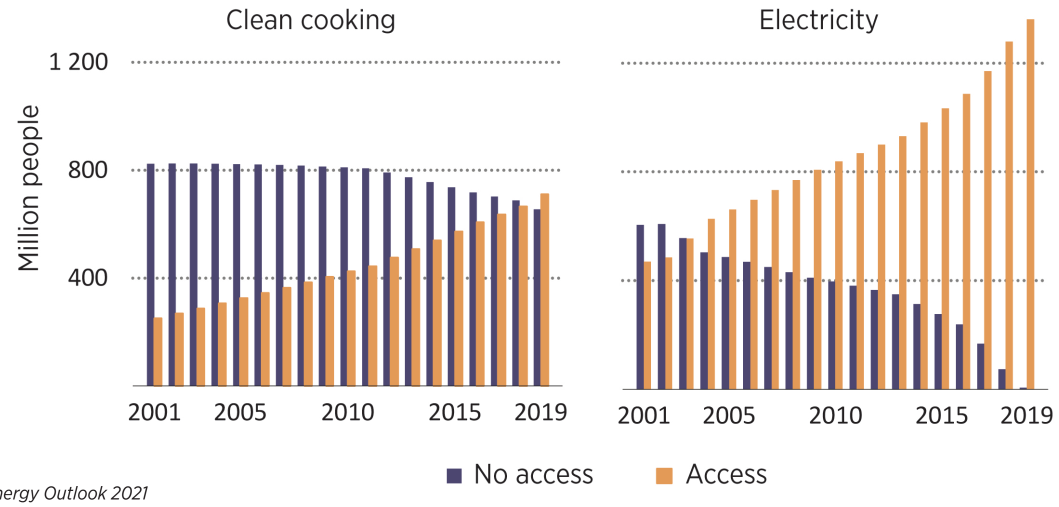
3.3.5 Energy

In terms of energy resources, India has about 0.6 per cent of the world's total gas, 0.4 per cent of the world's oil reserve and 9 per cent of the world's coal reserves. More than 80 per cent of the country's oil and natural gas requirement is met through imports (MoEFCC, 2023).

India is the world's third largest energy consuming country and is projected to see the largest increase in energy demand over the next three decades, thanks to its expanding economy, increasing urbanisation, population and rising incomes (IEA, 2023). Energy use in the country has doubled since 2000, with 80 per cent of the demand still being met by fossil fuels (coal, oil and solid biomass) (IEA, 2021). Yet, on a per capita basis, India's energy use is still less than half the global average.

India has taken rapid strides in the power sector since the 2000, providing electricity to 810 million people, and clean cooking fuel access to 655 million people (IEA, 2023). However, 450 million people still live in households dependent on traditional biomass for fuel. Despite near-universal electricity access at the household level, issues

Figure 3.2: Access to electricity and clean cooking in India



Source: *India Energy Outlook 2021*

of affordability and reliability of power supply continue to be concerns for a majority of Indian consumers.

As discussed in the earlier section, the energy sector accounts for 76 per cent of the total GHG emissions and electricity production contributes to 39 per cent of GHG emissions. Hence, the energy transition is crucial for climate action and to meet India's 2070 net-zero emissions target. India's energy transition has taken off with an emphasis on domestic manufacture of clean energy, especially solar PV, energy efficiency and policies to scale up clean energy supply.

Currently, fossil fuels make up for 56 per cent of the installed power generation capacity, with coal accounting for 49 per cent of the capacity (Ministry of Power, 2024). Total non–fossil fuel capacity including hydro, wind, solar and nuclear accounts for 44 per cent (183 GW) of the installed capacity as of February 2024. Of the non–fossil fuels, solar power capacity is the largest at 17 per cent, followed by hydro at 10 per cent. Nuclear power accounts for 1.7 per cent of the total installed generation capacity. Over the last decade, the growth in renewables has been significant, with installed capacity increasing from 13 GW in 2008–09 to 125 GW in 2022–23 (CERC, 2023). Given the country's push for renewables, India's NDC target of achieving 50 per cent non–fossil fuel power generation capacity is projected to be met by 2030 (IEA, 2023).

India's electricity mix is dominated by coal with a share of 74 per cent in electricity generation in 2022–23. The share of electricity generated from renewables was 12 per cent in 2022–23, a modest increase from 3.7 per cent in 2008–09. It is estimated (based on current policies and commitments) that electricity generated from renewables and coal could converge at 30 per cent by 2040 (IEA, 2021). However, in the coming decades, demand for electricity is set to increase significantly primarily due to rising demand for air conditioning, vehicles and buildings.

Despite the investment in clean energy and the likelihood of renewables capturing the market significantly in the coming decade, there are several challenges to achieve India's distant net-zero target. For starters, India will require greater investment in clean energy, nearly three times the current investments by the end of 2030 to achieve this target. The other challenges include achieving flexibility in power supply systems, improving the financial viability of power distribution companies, deploying new technologies, ensuring energy security amidst rising fuel imports, sustaining the momentum on renewable energy growth and ensuring a just transition.

Additionally, India will have to rehabilitate people, communities and areas dependent on the coal economy via training, jobs and investments. While the country has stated that coal will continue to be a source for power generation in the foreseeable future given its affordability, reliability and the country's development goals, India has to prepare for just transition as the share of coal in the energy mix will reduce and eventually be phased out in the long term.

India's future energy situation will depend largely on how policies in this sector are conceived and implemented to ensure a sustainable future. India has put in place several policy initiatives to achieve its net-zero target. Important policy initiatives include production linked incentives to subsidise the domestic manufacture of solar PV modules and batteries, setting up the National Green Hydrogen Mission, setting the stage for a domestic carbon market, implementing the Green Energy Corridor Project to increase the transmission capacity of variable renewables and meet the target of 500 GW of renewable energy capacity by 2050 (IEA, 2021). The impetus to clean energy also offers significant opportunities for employment by creating new jobs to absorb those who will be impacted by the low carbon transition.

3.3.6 Water

Water is necessary for all life on earth. It is vital for the economy, societal well-being and sustainability of ecosystems. India has about 4 per cent of the total global freshwater resources and its total catchment area is about 253 million hectares, which covers more than 75 per cent of its total land area. Groundwater is a major source, but is being depleted alarmingly. India also has a long coastline running across 7,500 km.

Water links all 17 Sustainable Development Goals (SDGs) and is closely interlinked with biodiversity and climate. It is central for 'socio economic and ecological prosperity' (Grafton et al., 2023, 4). Like elsewhere with the global water cycle, decades of mismanagement of water resources have led to a severe crisis of too little, too much and too dirty water in the country. This systemic crisis is worsened by climate change. India faces challenges of a depleted groundwater table, variable precipitation leading to cycles of droughts and floods, increasing demand and inefficient water usage, which further threatens to deepen existing inequity in access to water and sanitation, and food security.

It has been projected that at 1.5°C average global temperature, there will be dryness in more than half of South Asia, affecting more than 790 million people (Aadhar and Mishra 2019). Drought intensity and severity has increased substantially between 1972 and 2004, and droughts are projected to transition towards coastal areas of southern India, central Maharashtra and the Indo-Gangetic Plain in the future (Mallya et al., 2016). Further, frequencies of both droughts and wet events are projected to rise because of climate change across India for a 48-year period (2050–2099) (Ojha et al., 2013) Hydrological modelling suggests that by 2050, run-off will reduce substantially, and drought severity and flood intensity is projected to rise (Ministry of Environment and Forests, 2008). These projections indicate the far-reaching effects of climate variability on water resources. Some of these impacts are already lived experiences in a majority of Indian cities.

Modelling projections of heat stress and blue water stress on food production and hunger further reveal that food supply in India could reduce by 6.5 per cent and 16 per cent by 2050 under the RCP4.5 and RCP8.5 scenarios, respectively (Grafton et al., 2023). This highlights the need for significant investments in grey, blue and green water infrastructure (i.e., the natural infrastructure of wetlands, lakes and floodplains) along with regulatory measures (for better water distribution and recovery of costs) to enhance water availability, improve its use efficiency and improve its quality.

The Government of India along with state governments have been implementing several projects to address some of these challenges in the water sector in recent years. These include the National Water Mission, Namami Gange Programme, Jal Jeevan Mission, Jal Shakti Abhiyan, Atal Bhujal Yojana (Atal Jal), PMKSY, SBM, Dam Rehabilitation and Improvement Programme (DRIP) and Flood Management (MOEF, 2023).

3.3.7 Health

Around 60 million people are forced into poverty as a result of India's low public investment in healthcare, which is only 1.3 per cent of the GDP, and high out-of-pocket expenditure (85.6 per cent, among the highest in the world) (Narain 2016a; Balarajan et al., 2011).

The burdens and costs associated with healthcare are disproportionately high for marginalised communities, with caste, gender, class, educational attainment and geographic location playing a predominant role in access to healthcare (Reddy et al., 2011). For example, Scheduled

Tribes (ST) have a higher mortality rate and higher incidence of under-nutrition, anaemia, tuberculosis, visual impairment resulting from preventable causes and leprosy as a result of inadequate access to healthcare and social determinants of health (Shrivastava and Shrivastava, 2013). Further, rural areas face physical impediments in terms of access to preventive and curative healthcare services. The risk of disease, malnourishment and premature death is markedly high for people residing in rural and peri-urban areas, where there is staff shortage as India has the lowest density of healthcare workforce (Narain, 2016a) and physical infrastructure is inadequate (Reddy et al., 2011; Kasthuri 2018a; Balarajan et al., 2011). Maternal care is another area of concern as women are additionally burdened due to inadequate access to affordable health services, with women from backward castes and resource-poor groups being especially vulnerable due to low access and the economic costs associated with this (Sanneving et al., 2013).

Overall, healthcare in India suffers from deficits in equitability, accountability and affordability (Reddy et al., 2011). Climate change is expected to exacerbate health risks, especially from weather-induced disasters, increasing the frequency of heat and cold waves, and vector-borne diseases such as malaria and dengue. Diarrhoeal and psychological disorders will also witness an increase in incidence due to changing climate (Moors et al., 2013; Pailler and Tsaneva, 2018).

In terms of heatwaves, vulnerable groups—like people working in the open and other resource-poor groups living in low-resource settings that lack access to shelter and cooling technologies—are the most impacted (Knowlton et al., 2014). Climate change can impede India's efforts in terms of containing vector-borne diseases like malaria, dengue and chikungunya as the distribution, commonality of spread and extent of outbreak in a region is influenced by climatic conditions (Dhiman et al., 2010). Jammu and Kashmir, Uttarakhand and Arunachal Pradesh will witness open transmission windows in new districts and north-eastern India will see an increase in the intensity of malaria transmission (Dhiman et al., 2011). Another serious health and environmental challenge for India is increasing air pollution. There were nearly 1.2 million premature deaths from air pollution in India in 2019 (IEA, 2021).

3.4 Conclusion

India faces the dual challenge of achieving the SDGs along with climate action. While it is among the fastest growing economies in the world and the third largest behind China and the United States in terms of purchasing power parity (PPP), it is still a lower middle-income economy with PPP per capita less than half of the world average (IEA, 2021). India has to prioritise its responses to address socio-economic challenges such as unemployment, poverty, inequality, a burgeoning urban population, and to address significant development deficits including that of adequate infrastructure. A critical area of concern is its slow employment growth that threatens to squander the demographic dividend (World Bank, 2024a). At the same time, projected climate risks and impacts on the country's economy and key economic sectors make the transition to a low-carbon economy imperative.

India has a climate vision and long-term strategy to achieve net-zero emissions by 2070 (MoEFCC, 2023). This includes mitigation and adaptation actions across different climate sensitive sectors. Some headway has also been made in the energy sector with a massive increase in renewable energy capacity led by solar PV generation capacity. However, given the pace and intensity of climate change, a lot more needs to done. Effective climate action that also has synergies with the SDGs will require systemic changes in key areas or sectors of the Indian economy including agriculture, urban infrastructure, energy and industry.

Despite conventional thinking that climate action can undermine growth, scholarship increasingly tells us that the two are complementary and 'innovation, investment and systemic change' brought about by strong climate action can create 'a sustainable growth story' (Stern and Stiglitz 2023, pp. 278–279) In the coming decades, India can chart a new growth story, including generating jobs through climate resilient development to integrate climate action with sustainable development and biodiversity conservation. In the next chapters of this report, we will see how this can be operationalised.

4.

Adaptation and Mitigation in India

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4. India's Adaptation and Mitigation Responses

- India is at a crucial crossroads in its development trajectory, focusing on development goals such as poverty reduction, improved delivery of public services, and increased employment opportunities, while simultaneously transitioning towards low-carbon development and climate-resilience.

- The country's climate polices hence adopt a co-benefits approach, intertwining adaptation and mitigation goals with broader development imperatives.

- Climate change policy in India is framed within the context of three simultaneous ongoing transitions: a rural-to-urban demographic shift centered focused on value addition in metros and the growth of secondary cities; an energy transition from biomass to fossil fuels to renewables, and greater energy efficiency; and an environmental transition addressing brown (water, sanitation, and environmental health), grey (air and water pollution), and green (biodiversity and climate change) issues.

- India has established a comprehensive climate policy framework, within a federal governance structure, notably through the National Action Plan on Climate Change with its eight National missions and State Action Plans on Climate Change. More recently, cities are developing climate action plans and rural areas are beginning to mainstream climate planning into development plans.

- Despite progress, challenges remain, including the need for better risk assessment, stronger synergies between mitigation and adaptation, and attention to gendered and exclusion-based vulnerabilities. While India is moving forward to achieve its renewable energy targets, a clear road map to implement energy efficiency at scale and phase out coal power while ensuring job creation and energy security is needed.

- Significant funding, estimated at INR 57 trillion until 2030, is required to meet India's adaptation needs, with current funding channels proving grossly inadequate.

4.1 Introduction

India is characterised by the largest national population in the world, high poverty and expanding inequality, only one-third of the population in urban areas, and significant economic dependence on climate-sensitive sectors. The country's development trajectory has focused on meeting development imperatives such as building infrastructure (e.g., roads, schools, sanitation systems and power lines), providing basic services (e.g., water, sanitation, health, and education) and addressing chronic issues (e.g., poverty, food insecurity, and malnutrition).

However, human-centric development has not adequately addressed rising differential exposure to weather and climate-related risks (Krishnan et al., 2020; Joshi et al., 2020; Mishra et al., 2017), environmental degradation, notably of forests, air and water (Shrivastava and Kothari, 2013), and the precarity of nature-based livelihoods (Angelsen and Dokken, 2018; Singh et al., 2018c; Oldekop et al., 2020; Guntukula, 2020; Praveen and Sharma, 2020). As mentioned in the earlier chapter, Climate Resilient Development (CRD) negotiated by the IPCC AR6 cycle provides a framework to address these interlinked challenges as it acknowledges the tight coupling between social and economic systems, technology, the climate system and ecosystems (Revi and Ghoge, 2024). CRD brings together agendas of sustainable development, climate action, biodiversity conservation on the basis of complementary actions instead of trade-offs.

While India is yet adopt CRD, the pressing need to adapt to changing climate risks, while also meeting development needs and GHG mitigation opportunities is also acknowledged and operationalised in India's Long-Term Low-Carbon Development Strategy (MoEFCC, 2022).

In recent decades, a growing global impetus on climate action and increasing domestic acknowledgment of exposure to climatic and non-climatic risks has led to national and sub-national actions on climate change, undertaken through mitigation and adaptation measures (Khosla and Bhardwaj, 2019; Jogesh and Dubash, 2014; Dubash et al., 2016). These actions are enshrined in national policy through the National Action Plan on Climate Change (NAPCC), which is divided into eight missions focusing on key sectors (such as water and agriculture) and/or regions (such as the Himalayas) (MOEFCC, 2018; MoEFCC, 2012).

Within the country, various stakeholders also plan for and implement risk-based or sectoral climate adaptation and mitigation projects in agriculture (Mittal and Ray, 2015; Birthal and Hazrana, 2019; Singh et al., 2019c), specific cities (Singh et al., 2021a; Bhardwaj and Khosla, 2020) and particular industries (e.g., cement and energy sectors). In addition to domestic climate action, India is also an active player in global climate policy and continues to be a leader in fields such as solar energy and disaster management (Box 4.1).

Climate change in India should ideally be seen in the context of three simultaneous ongoing transitions: a rural-to-urban demographic transition centred around the growth of secondary cities; an energy transition from biomass to fossil fuels to renewables, and greater energy efficiency; and a three-part environmental transition—brown (water, sanitation and environmental health), grey (air and water pollution) and green (biodiversity and climate change) (Sami, 2016). Policymaking related to climate change and resilience building rests with the national and state governments, with local bodies limited to acting as implementing agencies.

India's approach to climate change action involves mainstreaming climate change mitigation and adaptation policies into existing sectoral development programmes (Chaturvedi, Rajiv K, Kattumuri, Ruth and Ravindranath, 2014; Sethi & Puppim de Oliveira, 2018; Sharma & Tomar, 2010; N. P. Singh et al., 2019). It also prioritises actions that offer co-benefits, such as clean cook stoves that reduce emissions and improve health, or afforestation that meets ecosystem conservation goals and sequesters carbon dioxide.

This chapter outlines the architecture of climate action in India at national and sub-national scales (section 4.2), focusing on sectoral adaptation and mitigation policies and programmes. It showcases how India is already seeing significant implementation across sectors to mitigate emissions (section 4.2.1), especially in energy, transport, agriculture and allied sectors and improve adaptation (4.2.2) in vulnerable sectors such as resilient infrastructure, disaster management, forestry, water, and agriculture.

Box 4.1: India's global leadership on climate change: International Solar Alliance and Coalition for Disaster Resilient Infrastructure

Globally, India has anchored multiple initiatives in mitigation and adaptation, positioning itself as a leader in climate action. Two notable initiatives driven by the national government are the International Solar Alliance (ISA) and the Coalition for Disaster Resilient Infrastructure (CDRI).

In 2015, India conceived the ISA, a coalition of 122 solar-rich countries located between the Tropics of Cancer and Capricorn, to address their unique energy needs. The ISA aims to create a dedicated platform where governments, organisations, and other stakeholders can collaborate to harness solar energy sustainably and equitably. It seeks to overcome common challenges, mobilise investments exceeding US$ 1 trillion by 2030, and foster solar technology and research in member countries, positioning India as a global leader in climate change mitigation and solar energy.

In September 2019, during the UN Climate Action Summit, the Prime Minister launched the CDRI. This coalition, comprising national governments, UN agencies, multilateral banks, the private sector and knowledge systems, promotes resilient infrastructure systems that can withstand climate and disaster risks. The government allocated ₹480 crore for CDRI's technical assistance and research projects over five years from 2019 (PIB, 2019b). CDRI aims to (a) serve as a knowledge platform for disaster and climate resilience of infrastructure; (b) assist countries in upgrading their infrastructure development practices; and (c) focus on risk assessment, regulatory standards, finance roles and disaster recovery mechanisms. CDRI complements ISA's efforts, in addressing both adaptation and disaster resilience (PIB, 2019b).

Partnerships like ISA and CDRI enable India to emerge as a global leader in climate action, disaster resilience and renewable energy, while also creating opportunities for expanding India's infrastructure and technology services abroad.

4.2 Climate Action Architecture in India

Climate change policies in India are firmly anchored within a co-benefits framework, focusing on leveraging synergies between development and climate action (Jogesh and Dubash, 2014; MoEFCC, 2018; Sami et al., 2016; Sreenivas et al., 2013). The NAPCC, set up in 2008, is organised around eight missions, which outline long-term, integrated strategies towards national climate change goals. These missions address areas ranging from solar power development to agriculture and water, including a specific mission on Himalayan ecosystems, which are particularly vulnerable to climatic risks (Byravan and Rajan, 2013; MOEFCC, 2018). The NAPCC missions include the National Mission for Enhanced Energy Efficiency (NMEEE), National Water Mission (NWM) and National Mission for a Green India (GIM), National Mission on Sustainable Habitat (NMSH), National Mission on Sustainable Agriculture (NMSA). Several of these like NMSH, NMEEE offer urban-specific engagement opportunities, while others like National Mission for Sustaining Himalayan Eco-system (NMSHE) are targeted specifically at climate sensitive ecosystems. Table 4.1 summarises the eight national missions.

Table 4.1: National missions in India with key aims and budgetary allocations

Mission	Objectives	Implementing Agency	Initial Budget (in crores)
Jawaharlal Nehru National Solar Mission (JNNSM)	To increase the share of solar energy in the total energy mix.	Ministry of New and Renewable Energy	₹5,00,000 crore (total initial estimate in 2010 for 100GW solar power).
National Mission for Enhanced Energy Efficiency (NMEEE)	To strengthen the market for energy efficiency by creating a conducive regulatory and policy regime. It envisages fostering innovative and sustainable business models.	Ministry of Power, through Bureau of Energy Efficiency and Energy Efficiency Services Limited (EESL)	Outlay of ₹235 crore (2011–12); Total outlay of ₹775 crore for continuation of NMEEE (proposed in 2014)
National Mission for a Green India (GIM)	To enhance ecosystem services and carbon sinks through afforestation on degraded forest lands	Ministry of Environment, Forests and Climate Change	₹13,000 crore (2012–2018)
National Mission on Sustainable Habitat (NMSH)	To promote energy efficiency in buildings, management of solid waste, and modal shift to public transport.	Ministry of Housing and Urban Affairs	₹54,200 crore (in 2010 when it was set up) At present, NMSH is implemented through flagship centrally sponsored schemes like AMRUT, PMAY, SBM, SCM.
National Water Mission (NWM)	To ensure integrated water resource management, conserve water, minimise wastage and ensure equitable distribution of water among states.	Ministry of Jal Shakti	₹3,576 crore for central sector and ₹65,818 crore for state sector schemes
National Mission on Sustainable Agriculture	To transform agriculture into an ecologically sustainable, climate-resilient production system.	Ministry of Agriculture and Farmers Welfare	Rs 13,650 crore between 2012 to 2017 (CBGA, 2019; Srinivasan et al., 2023).
National Mission for Sustaining the Himalayan Ecosystem (NMSHE)	To assess scientifically the vulnerability of the Himalayan region to climate change in physical, biological and sociocultural context.	Department of Science and Technology and six task force institutions	INR 550 Crore (2012-2018).
National Mission on Strategic Knowledge for Climate Change (NMSKCC)	To identify challenges and responses to climate change through research and technology development and ensure funding of high quality and focused research.	Department of Science and Technology	INR 2,500 Crore (proposed in 2010)

Source: *Authors' compilation.*

While these missions were announced in 2008, it took until 2014 to approve these missions and set them up. Many of these missions face challenges, including that of inadequate budgetary support and lack of monitoring mechanisms (Down to Earth, 2018; Rattani, 2018). While solar, energy and forestry missions had mitigation components, those focussed on sustainable water, agriculture, and Himalayas were adaptive in nature and difficult to quantify. NSM and NMEEE were successful in drawing investments and had quantifiable targets but other missions including NMSA, NMSHE, NMSH were inherently multi-sectoral and involve collaboration across various departments (Rattani, 2018). Their progress has been slow. Several centrally sponsored schemes are in principle aligned with these missions but their integration with the mission needs to be leveraged. More recently, ministries have laid out clearer visions for these missions. For instance, MoHUA has laid out a clearer outline for NMSH 2.0 from 2021-2030, linking mission objectives with SDGs as well as ongoing schemes (MoHUA, 2021).

Following the NAPCC, the States formulated policies and plans aligning with their missions and state-specific development priorities (Jogesh and Dubash 2015). This resulted in State Action Plans on Climate Change (SAPCCs), and by October 2016, 32 States and Union Territories in India had SAPCCs endorsed by the National Steering Committee on Climate Change (MOEFCC, 2018). The SAPCCs primarily focused on sustainable development practices rather than climate-specific strategies, with an emphasis on adaptation over mitigation (Sami, 2016). Important sectors addressed include forest and biodiversity, agriculture, water resources, energy, urban development, and transportation. Additionally, sectors like disaster management, health, industries, tourism and coastal development have also been identified. Many of the states are currently revising, and/or have already updated their SAPCCs to align with the Paris Agreement, India's Nationally Determined Contributions (NDC), and evolving risk and solution spaces.

The implementation of state actions and plans has progressed slowly, with room for improvement through more fine-scaled risk assessments, synergising mitigation and adaptation efforts, and addressing gendered and intersectional vulnerabilities (Pahuja et al., 2020; Singh et al., 2021; Kapoor, 2012; Jogesh and Dubash, 2014, 2015). SAPCCs are mandated to develop baseline vulnerability assessments and greenhouse gas (GHG) inventories to prepare adaptation and mitigation targets that align with state development goals (Department of Science and Technology, 2019). However, a key gap in this approach is the lack of a common framework for vulnerability assessments (Dhanapal and Panda, 2014), a static and gender-blind approach to assessing vulnerability in many SAPCCs (Singh et al., 2021), and inadequate discussion on the synergies and trade-offs between different adaptation and mitigation actions proposed in the plans. The next sub-section will discuss India's climate action in detail, focusing on key mitigation and adaptation measures.

4.2.1 Mitigation

Over the years, the national government as well as different state governments have undertaken proactive policies and measures to mitigate GHG emissions directly or indirectly, spanning across sectors and scales. Efforts have focused on increasing the share of clean, renewable energy sources such as solar, wind, nuclear and waste to fuels and biofuels in its energy mix. As of February 2024, total non–fossil fuel capacity including hydro, wind, solar and nuclear accounted for 44 per cent (183 GW) of the installed capacity in the country (Ministry of Power, 2024).

The country's updated NDC (2022) targets 45 per cent reduction in the emission intensity of its GDP, 50 per cent installed power capacity from non–fossil fuels by 2030, promoting a sustainable way of living and achieving net-zero emissions by 2070 (GOI, 2023; MoEFCC, 2023).

A key aspect of India's mitigation targets is GHG sequestration through creating additional carbon sinks of 2.5–3 billion tonnes of carbon dioxide equivalent. This target has remained unchanged in the original NDC in 2015 and the updated one in 2022.

Given the country's push for renewables, India's NDC target of achieving 50 per cent non–fossil fuel power generation capacity is projected to be met by 2030 (IEA, 2023). Climate Action Tracker's (2023) analysis of India's updated NDC also indicates that the country will overachieve its promised pledges with its current level of climate renewables deployment, but cautions that the targets will not drive further emission reductions. This implies that deeper emission cuts will be required by 2030 to put India on a 1.5°C pathway. This analysis estimates that by 2030, India will achieve 49–53 per cent reduction in emission intensity below 2005 levels and a non-fossil capacity target of more than 60 per cent. However, Climate Action Tracker points out that to be 1.5°C compatible, India's coal power generation would need to reduce significantly and be phased out completely by 2040. There is no clarity on the trajectory of coal phase-out in the country so far.

- **Energy:** The energy sector accounts for 76 per cent of total GHG emissions and electricity production contributes to 39 per cent of GHG emissions (MOEFCC, 2023). Ensuring energy security, improving access and affordability of modern energy resources for all Indians, diversifying energy resources, enhancing resource use efficiency, reducing technical and commercial losses in power transmission, and enhancing renewable energy are pillars of Indian energy policy (MOEFCC, 2018). Some recent policy initiatives and new laws covering the energy sector such as the National Green Hydrogen Mission, National Electricity Plan (NEP 2023) and the recently amended Energy Conservation Act, 2022 will play a crucial role in shaping the country's energy sector landscape going ahead (Climate Action Tracker, 2023). India's energy efficiency measures including PAT for industries, star labelling programme for appliances, the Ujala program for LEDs, the Energy Conservation Building Code (ECBC) and Eco Niwas Samhita for buildings have resulted in the reduction of CO_2 emissions by 280 million tonnes per annum (MoEFCC. 2023)

  The Energy Conservation Act amendment is aimed at meeting the country's NDCs, to enable faster decarbonisation of the economy. The amendment envisages setting up of a carbon market through a carbon credit trading system and allows the government to prescribe a minimum share of non-fossil sources as energy or feedstock by designated industry, besides setting up a new energy conservation code for buildings, and fuel consumption and emission standards for vehicles (PRS, 2022). The National Electricity Plan envisages increasing the contribution of non-fossil power capacity to 68 per cent by 2031–32 (Aggarwal & Kannappan, 2003). It also states that no new coal capacity would be added in the country in the next five years, except for plants already under planning.

- **Transport:** Developing low-carbon transportation is one of India's NDC mechanisms to meet its stated climate goal of maintaining temperature well below 2°C. As discussed in Chapter 4, government strategies to reduce transport-led emissions include promoting public transport in cities via mass transit systems, incentivising manufacture and adoption of electric vehicles, stricter fuel efficiency norms (BS-VI emissions), scrapping of old vehicles, and promoting alternate fuels like liquefied petroleum gas (LPG), compressed natural gas (CNG), and ethanol through the National Policy on Biofuels to achieve 20 per cent ethanol blending in petrol (MoEFCC, 2023). India has set a sales target of 6–7 million electric vehicles (EVs) year-on-year from 2020 in its National Electric Mobility Mission Plan, which is around 2–4 per cent of the total vehicle stock. This target is to be met.

  In civil aviation, Adoption of Carbon Accounting and Management System (CAMS) for reducing GHG emissions of airports and for quantification and reporting of emissions and removals, adoption of the Environment Management System, Energy Management System and Greenhouse Gas Reporting mechanism are some of the measures taken (MOEFCC, 2018). In shipping, technical and operational energy efficiency measures were adopted to reduce the amount of CO_2 emissions from international shipping. These mandatory measures e.g. the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships entered was applied to ships of over 400 gross tonnage and above (MOEFCC, 2018).

- **Agriculture and forestry:** Agriculture is responsible for 14 per cent of India's total GHG emissions and plays a vital role in India's economy, with 46 per cent of the workforce dependent on the sector and its allied activities (MOEFCC, 2018). Some government initiatives aimed at addressing the sector's vulnerability to climate change include the National Mission for Sustainable Agriculture (NMSA), National

Innovations in Climate Resilient Agriculture (NICRA) and National Horticulture Mission (NHM), among others. NMSA aims at transforming agriculture into an ecologically sustainable climate-resilient production system. NICRA aims to enhance the 'resilience of Indian agriculture to climate change and climate variability through strategic research and technology demonstration' (MoEFCC, 2018). NHM promoting holistic agriculture growth by enhancing production, strengthening nutritional security, and providing technological support for high value fruits and vegetables, has sequestered 137.72 metric tonnes of carbon dioxide equivalent ($MtCO_2$) of carbon from 2010–2016 (MOEFCC, 2018).

Scheme like the Kisan Urja Suraksha Evam Utthaan Mahabhiyan (KUSUM) launched in 2019 aim to improve irrigation access to farmers through solar-powered irrigation. The scheme envisages setting up 1.75 million solar pumps in locations where the grid has not reached and 1 million solar pumps where the grid is available (Vibhuti Garg, 2018). The scheme can help to decarbonise energy use in agriculture, but its implementation needs improvement.

Approximately 80 per cent of the country's terrestrial biodiversity exists in forests, with over 300 million people dependent on them for their livelihood (MoEFCC, 2016). Mitigation and adaptation measures in this sector are implemented through plantation/afforestation/reforestation programmes to conserve and enhance carbon sinks. Key initiatives include the National Afforestation Programme, which contributes to 15–20 per cent of afforestation efforts in India and aims to improve the quality and productivity of the existing forest cover. Between 2017 and 2020, afforestation of 13,000 hectares took place under this programme (MOEFCC, 2023). The Green India Mission aims to increase forest and tree cover by 5 million hectares, and to increase the quality of existing forest and tree cover in another 5 million hectares of forest/non-forest lands in 10 years (MOEFCC, 2018). The carbon stock in the forests in 2021 was estimated at 7,204 million tonnes, signifying an increase of 79.4 million tonnes compared to the assessment in 2019 (MOEFCC, 2023).

- **Waste:** The waste sector contributes 2 per cent to India's GHG emissions, mainly from solid waste disposal (23 per cent) and wastewater treatment and discharge (77 per cent) (MOEFCC, 2023). Solid waste management (SWM) programmes, such as the Swachh Bharat Mission aim to eliminate open defecation and achieve 100 per cent scientific management of municipal solid waste. In urban areas, the mission intends to construct 6.6 million household toilets, 0.3 million community toilets and 0.3 million public toilets, along with 100 per cent door-to-door collection and scientific management of solid waste (MOEFCC, 2018). Modernising sanitation facilities must be prioritised to mitigate emissions (MOEFCC 2018). Various waste-to-energy initiatives are also in place in the country, with 33 operational plants generating over 275MW.

- **Buildings:** Buildings consume over 30 per cent of India's electrical energy, with energy sector demand rising by 8 per cent annually and slated to increase further across both residential and commercial buildings. Initiatives for sustainable growth include setting standards for buildings and reducing electricity consumption through sustainable and green technology (MOEFCC, 2018). Major actions include the National Building Code (NBC) and the Energy Conservation Building Code (ECBC). The NBC regulates and sets standards for construction activities across the country. The ECBC sets minimum requirements for energy-efficient design and construction of commercial buildings with a connected load of 100 kW or greater, or a contract demand of 120 kVA or greater. Similarly, the Building Energy Efficiency Programme (BEEP) is aimed at retrofitting energy efficiency measures in existing buildings and Eco Niwas Samhita to set minimum energy efficient norms. As of 2019, 11 states and only a few cities like Gwalior, Ludhiana and Hyderabad had included ECBC in their building by-laws (Behal, 2023).

4.2.2 Adaptation

India is ranked fifth in the Global Climate Risk Index (Eckstein et al., 2019), highlighting the high vulnerability of a large section of its population to climatic risks. Dependence on climate-sensitive sectors such as agriculture and increasing risk accumulation in urban settlements (e.g., through flooding, water scarcity and sea level rise) necessitate adaptation actions. Out of the eight missions under the NAPCC, five missions focus on adaptation in sectors like agriculture, water, Himalayan ecosystems, forestry, capacity building and knowledge management. There is also significant focus on climate adaptation at the sub-national level; for example, climate smart villages in rural areas (Aryal, Rahut et al., 2020; Aryal, Sapkota, et al., 2020) and heatwave action plans to tackle the heat season in cities like Ahmedabad and Hyderabad (C. Singh et al., 2021).

According to India's third national communication to the UN Climate Change, adaptation expenditure reached about 5.6 per cent of GDP (INR 13.35 trillion) in 2021-22, up from 3.7 per cent in 2015 (MOEFCC, 2023). Business-as-usual scenarios estimate a need for INR 57 lakh crore by 2030, which could rise to INR 72 lakh crore due to climate-induced damages. The current funding for adaptation in India is grossly inadequate even though there has been an increased focused on improving adaptive capacity in vulnerable sectors.

The sectors with outlined adaptation policies are water, agriculture, health, coastal regions and islands, disaster management, biodiversity and ecosystems, and rural livelihoods (Table 4.2). Other initiatives include social safety net schemes such as the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), which aims at providing a source of livelihood to rural people and drought-proofing villages. The adaptation priorities for the country stem from three sources – one, from an understanding of potentially high consequences and highly likely climate risks facing the country; two, from the socio-economic context and the development needs of the country; and three, from addressing the constraints to adaptation.

The three broad categories of adaptation priorities for the country as indicated through existing policies include –

1. priorities related to knowledge systems on climate change risks and adaptation.

2. priorities related to a reduction of exposure to climate risk, and

3. priorities related to building resilience and adaptive capacity.

Table 4.2: Key sectoral risks and illustrative policy instruments to address them

Sector	Risks	Key Missions/Policies
Agriculture	• Predominantly rainfed with high dependence on monsoonal rainfall • Unsustainable groundwater extraction • Highly exposed to erratic rainfall, drought and hailstorms	• National Mission for Sustainable Agriculture; National Food Security Mission • Paramparagat Krishi Vikas Yojana to promote organic farming practices • Pradhan Mantri Krishi Sinchai Yojana to promote efficient irrigation practices
Water	• Erratic rainfall and increasing temperatures; higher evaporation • Higher water demand (especially for urban areas and industry) and unsustainable abstraction	• Enhancing efficient use of water and ensuring equitable water access • National Water Mission (NWM) to conserve water, minimise wastage and ensure more equitable distribution both across and within states
Health	• High incidence and spread of vector-borne diseases • High air pollution • Longer and more intense heatwaves leading to increased mortality and morbidity	• National Health Mission (NHM), along with the National Rural Health Mission (NRHM) and National Urban Health Mission (NUHM) include components like reproductive and maternal health, neonatal, child and adolescent health, and communicable and non-communicable diseases • Integrated Disease Surveillance Programme under the National Centre for Disease Control to study the climate change impacts on diseases • National Vector Borne Disease Control Programme • Heat Actions Plans in some cities and states
Coastal areas	• Sea level rise, coastal flooding and land subsidence • Tropical storms and cyclones • Soil salinisation • Ocean acidification	• Coastal Regulation Zone (CRZ) to demarcate vulnerable coastal areas and restrict the setting up and expansion of industries, operations and processes in these areas • Integrated Coastal Zone Management (ICZM) to build national capacity on comprehensive coastal management through ecological management, conservation and protection of critical habitats
Cryosphere	• Shifts in snowfall, rainfall and temperature extremes • Changes in river flow and landslides	• National Mission for Sustaining the Himalayan Ecosystem (NMSHE) • National Mission on Himalayan Studies to build a body of scientific and traditional knowledge
Disaster management	• 85% of India's area is vulnerable to one or multiple hazards	• Disaster Management Act, 2005 • National Disaster Management Policy 2019 (NDMP) provides direction to government agencies for all phases of the disaster management cycle. • National Cyclone Risk Mitigation Project (NCRMP) aims at minimising vulnerability to cyclones • Disaster relief funds at all levels and launching of the National Disaster Relief Fund

Source: *Authors' compilation*

4.3 Conclusion

India is taking significant steps towards addressing climate change through a combination of national and state-level policies and programs. While progress has been made in key sectors such as energy, infrastructure, transport, forestry, agriculture, waste, and water, challenges remain in ensuring effective implementation, particularly at the sub-national level, and securing adequate financing for adaptation. The country's commitment to a low-carbon development pathway is evident, but further action is needed to accelerate the transition and ensure a climate-resilient future

India's climate policies are underpinned by the need to balance its development needs (providing secure livelihoods while delivering basic services) and addressing climate change risks, environmental degradation, and structural vulnerabilities. Recognising this, India prioritises climate actions that offer co-benefits for development, such as clean cookstoves, climate-resilient infrastructure, and afforestation. More recent policy priorities have attempted to balance mitigating GHG emissions and adapting to climate change impacts.

Overall, India's development trajectory has focused on infrastructure, essential services, and poverty reduction, but hasn't sufficiently addressed rising climate risks and environmental degradation. Key constraints remain around financing climate action, institutional capacities to implement existing plans and policies, and leveraging cross-sectoral synergies.

5.

Mitigation Pathways

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5. Mitigation Pathways

- India's emissions are growing. The country's greenhouse gas (GHG) emissions in 2019 increased by 4.6 per cent compared to the total national emissions in 2016 and by about 115 per cent since 1994.
- Modelling studies project a wide range of CO_2 emissions projections for India by 2030, with the lowest projections indicating 9 per cent increase from 2012 levels and the highest projections a 169 per cent increase.
- The energy sector contributes about 76 per cent of the total GHG emissions and 93 per cent of the total CO_2 emissions in 2019.
- Decarbonisation (a transition from business-as-usual to NDC scenarios) and deep decarbonisation (a transition from NDC to low-carbon pathways) require attention to increased energy efficiency in supply and demand, enhanced deployment of renewables, demand reduction in end-use sectors through dematerialisation, and recycling, reuse and changed user behaviour.
- Critically, energy efficiency and renewable energy will play almost equal roles in CO_2 mitigation under various mitigation scenarios, with demand reduction linked to significant changes in a service-oriented urban economy. The role of end-of-pipe solutions like CCS are still being examined, studies indicate an important role for such technologies to stay within the 1.5°C guardrail.

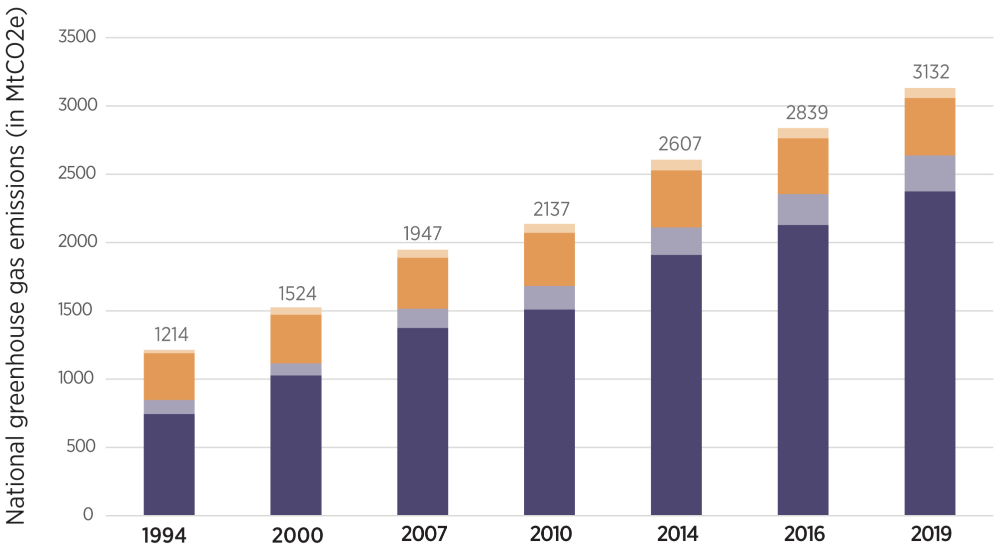
5.1 Past Mitigation Trends

India's total national emissions in 2019, including Land Use, Land-Use Change and Forestry (LULUCF), increased by 4.6 per cent compared to the total national emissions of 2016 and by 115 per cent since 1994 (MOEFCC, 2023). The main contributors to total greenhouse gas (GHG) emissions are CO_2 emissions from burning fossil fuels, methane emissions from livestock, and increasing aluminium and cement production. The LULUCF sector remained a net sink during the national greenhouse gas inventory period of 2019, accounting for the removal of 485.47 gigatonnes of carbon dioxide equivalent (GTC) emissions.

The energy sector contributed the most to the overall emissions, with 76 per cent, followed by the agriculture sector at 13 per cent, the Industrial Processes and Product Use (IPPU) sector at 9 per cent and the waste sector at 2 per cent (MOEFCC, 2023). The energy sector saw the highest growth at 219 per cent from 1994 to 2019 due to continuous increase in fossil fuel combustion. The waste sector experienced the second highest growth at 215 per cent over the same period due to the increase in population and industrial activities (see Figure 5.1). However, its contribution to overall emissions has remained around 2 per cent as its absolute contribution is very low. During this period, the IPPU sector grew by 157 per cent, while the agriculture sector grew by 22 per cent. Between 2000 and 2019, the LULUCF sector reported a growth in GHG removals of 118 per cent.

The energy sector was responsible for 93 per cent of the total national CO_2 emissions in 2019. This was primarily caused by

Figure 5.1: Sector-wise national green house gas emissions (in $MtCO^2e$) for 1994 to 2019



Note: Land Use, Land use change and forestry is not included in this figure. For total emissions with LULUCF please check table in Annexure 1.

Source: *MoEFCC, 2023*

fossil fuel combustion activities, which included the energy industries as well as manufacturing, transportation and other industries. Energy-related fuel combustion activities accounted for 98 per cent of all emissions.

Within the energy sector, electricity production accounted for 39 per cent of total emissions, followed by road transport (9 per cent), residential (5 per cent), iron and steel industries (5 per cent), cement production (4 per cent), and other non-specific industries (5 per cent), among others. It is evident that decarbonising the energy sector is essential as it impacts other sectors. Efforts to reduce GHG emissions through energy use are a pivotal component of India's low-carbon development strategy because the sector is the largest source of GHG emissions. This is tightly coupled with the delivery of the country's overall development priorities of eliminating poverty, improving per capita income and increasing the gross domestic product (GDP) growth rate.

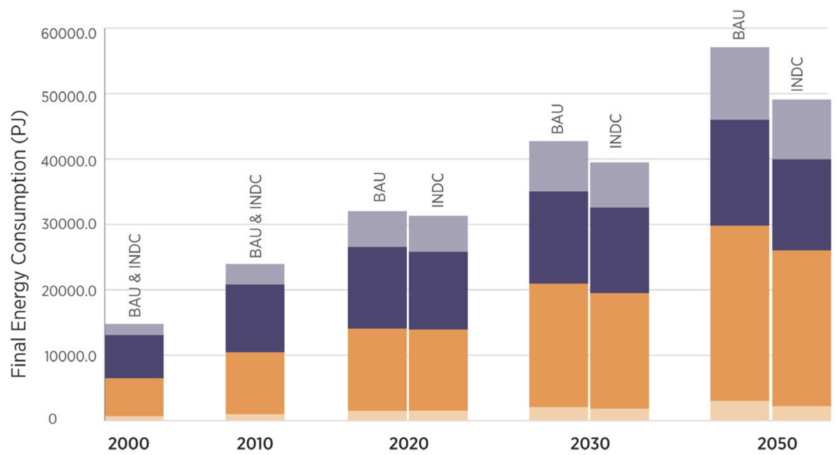
Next, this chapter examines projected emissions across key systems including agriculture, energy, and urban (buildings and transport) (section 5.2), followed by mitigation option on both demand and supply sides (section 5.3), ending with a conclusion in section 5.4.

5.2 Projected Emissions and Mitigation

India's modelling studies project a broad range of CO_2 emissions scenarios for 2030. The lowest projections estimate a 9 per cent increase from 2012 levels, while the highest projections estimate a 169 per cent increase (Dubash et al., 2018). Dhar et al., (2018) indicate that CO_2 emissions will rise rapidly under the Nationally Determined Contributions (NDC) scenario. However, in the 2°C and sustainable 2°C scenarios (SE4ALL plus 2°C scenario), emissions are projected to peak by 2040 due to stronger decoupling. Specifically, in the sustainable 2°C scenario, emissions are expected to flatten out after 2020.

Vishwanathan et al., (2018) estimate India's cumulative CO_2 budget for low-carbon scenarios from 2011 to 2050 to be approximately 115 billion tonnes of CO_2, compared to 165 billion tonnes of CO_2 for the reference scenario. Total CO_2 emissions are projected to decline by about 20 per cent, 46 per cent and 62 per cent in the NDC, 2°C and 1.5°C scenarios, respectively, by 2050 relative to the business-as-usual (BAU) scenario. Additionally, the carbon intensity of energy is expected to decrease at an annual average rate of 0.15 per cent, 1.3 per cent, and 1.9 per cent for the NDC, 2°C, and 1.5°C scenarios, respectively.

Figure 5.2: Sector-wise final energy consumption in BAU and INDC scenarios (in petajoules)



Notes: BAU = Business as usual. INDC = India's Intended Nationally Distributed Contributions

Source: *Vishwanathan et al., 2017*

The power sector contributes more than 40 per cent of total carbon emissions, decreasing to about 36 per cent in the NDC scenario and 30–33 per cent in low-carbon scenarios. While retrofitting old, inefficient coal plants offers attractive returns and negative carbon prices, its feasibility remains doubtful. Carbon Capture and Storage (CCS) has the potential to play an important role in the 2°C and 1.5°C scenarios. In terms of policy framework, Niti Ayog has proposed a CCUS policy that aims to reach a CCUS capacity of 750 million metric tons per year by 2050 (Niti Ayog, 2022). Some initial steps have been taken in this direction like NTPC setting up carbon capture plant at its 500 MW coal-fired plant in Vidhyachal in Madhya Pradesh to support decarbonisation (Carbon Clean, 2022). However, adoption of CCUS technologies in India is still at a nascent stage and its role in sustainable scenarios in India remains uncertain.

In the industry sector, there is a decrease in CO_2 emissions between the NDC and low-carbon scenarios due to the intensification of energy-efficient technologies in energy-intensive industries through the Perform, Achieve and Trade (PAT) scheme. The transport sector accounted for about 11 per cent of total carbon emissions in 2010, and this is expected to increase to about 12 per cent in 2050 in the BAU scenario and 14 per cent in the NDC scenario. However, in the 1.5°C scenario, it decreases to almost 9 per cent of total carbon emissions. This reduction is due to a combination of policy measures, including technological changes driving a shift in energy sources (e.g., electric vehicles [EVs]), a modal shift to low-carbon modes (e.g., metro systems) and behavioural changes affecting mobility demand (e.g., telecommuting).

In 2000, the industrial and residential sectors accounted for about 85 per cent of final energy consumption. In the future, under both the BAU and NDC scenarios, the share of the residential sector is expected to fall while the share of the transport sector will increase. The share of the agricultural sector is expected to remain constant. In the NDC scenario, overall final energy consumption (FEC) is projected to fall by 7 per cent in 2030 and 14 per cent in 2050 compared to the BAU scenario.

India's energy system is largely based on the use of coal for power generation, oil for transport and industry, and biomass for residential heating and cooking (IEA, 2020a). The industry sector accounts for the largest share of India's total final energy consumption, followed by the residential sector, transport sector, agriculture sector and service sector. Recent policy trends suggest a faster-than-expected transition from coal to renewable electricity, with electricity generated from coal and renewables converging at 30 per cent by 2040 (IEA, 2021). At the same time, demand for electricity is set to increase significantly due to large-scale electrification of end-use demand and rising demand for air conditioning, vehicles and buildings.

5.2.1. Energy

Coal remains the largest energy source in India's primary energy mix across all scenarios except the 1.5°C scenario (Table 5.1). Most of this coal is used for power generation. In the BAU scenario, the share of coal increases significantly from 42 per cent in 2005 to 68 per cent in 2030 (Shukla et al., 2017). Conversely, coal demand declines substantially in the 2°C scenario, reducing to one-third of the reference scenario's level by 2030. In the NDC scenario, there is no major change in the primary energy mix compared to the BAU scenario (Mittal et al., 2018).

Biomass consumption grows in the 2°C and 1.5°C scenarios, when supported by CCS. However, its share decreases in the NDC scenario. Biomass usage also drops significantly in the sustainable 2°C scenario where CCS is assumed to be non-implementable (Gupta et al., 2020). The share of non-biomass renewables rises from 1 per cent in the reference scenario to 3 per cent in the NDC scenario and 7 per cent in the 2°C scenario, primarily contributing to power generation.

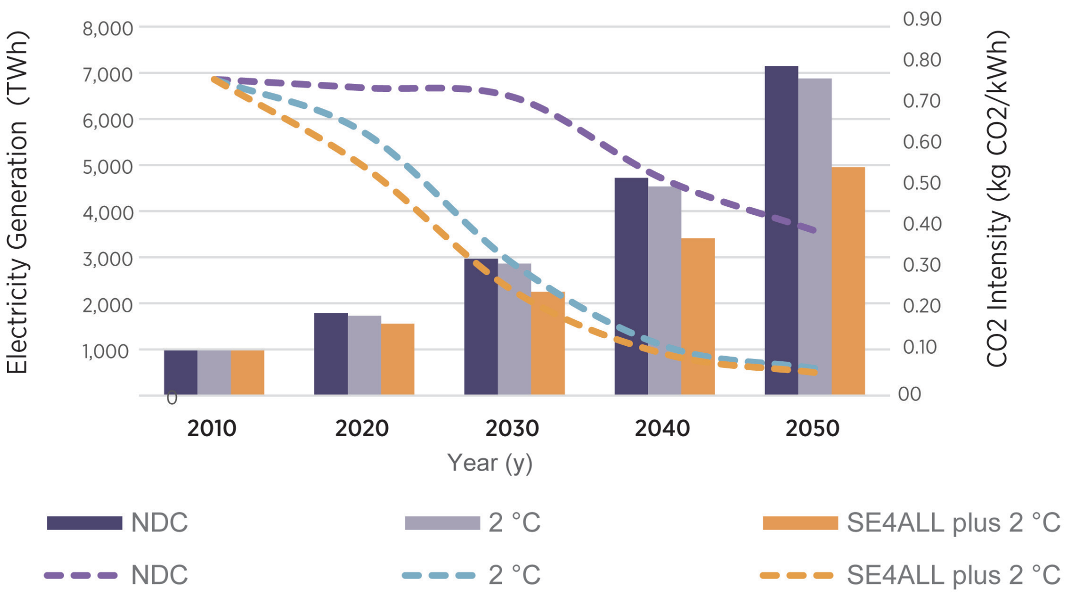
When comparing conventional and sustainable 2°C scenarios, dependence on fossil fuels is higher in the conventional scenario. Nuclear energy contributes

Table 5.1: Share of total primary energy demand (all sectors) and total primary energy of supply (only power sector) in per cent

Sector	BAU			NDC		1.5°C		Source
	2016	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	
Coal	45	40	40	31	31	31 – 34	31 - 34	[1]
	47.4	37.8	47.5	36.4	45	19.3	18.4	[2]
Oil	25	23	23	22	22	21 – 23	21 - 23	[1]
	23.7	23.6	24.7	21.9	26.2	29.3	22.8	[2]
Bioenergy	22	18	18	10	10	11 – 14	9 - 10	[1]
	21.5	18.4	7.6	18.8	7.8	21.3	13.8	[2]
Gas	5	10	10	19	19	16 – 19	16 - 19	[1]
	4.7	12.6	9.9	12.9	8.8	18.2	12.9	[2]
Renewables	1	6	6	15	15	10 – 13	10 - 13	[1]
	0.4	6	8.9	7.7	9.5	8.5	21.8	[2]
Other (hydro, nuclear)	3	3	3	3	3	3- 4	3 - 4	[1]
	2	1.4	1	1.9	2.5	3.2	10	[2]
Total Energy (EJ/year)	36	55	84	51	73	52 - 54	73 - 76	[1]
	28.7	49.5	81.8	48.1	79.6	40	53.7	[2]

Notes: EJ = Exajoule. NDC = Nationally Determined Contributions. [1] Vishwanathan & Garg, 2020NDC scenario, 2 °C scenarios (early and late actions. [2] Zhou et al., 2020. For Vishwanathan and Garg (2020), the 'well below 2°C' scenario is taken as equivalent to the 1.5°C scenario. The range presented denotes the estimates for early action in 2°C, late action 2°C, and well below 2°C scenarios.

Figure 5.3: Electricity generation and CO^2 intensity of electricity in India under different scenarios



Note: SE4ALL plus 2°C = This scenario follows the 'sustainability' rationale, similar to the IPCC SRES B1 global scenario (IPCC, 2000) or the pathway one of the shared socio-economic pathways (SSP1).
Source: *Dhar et al., 2018*

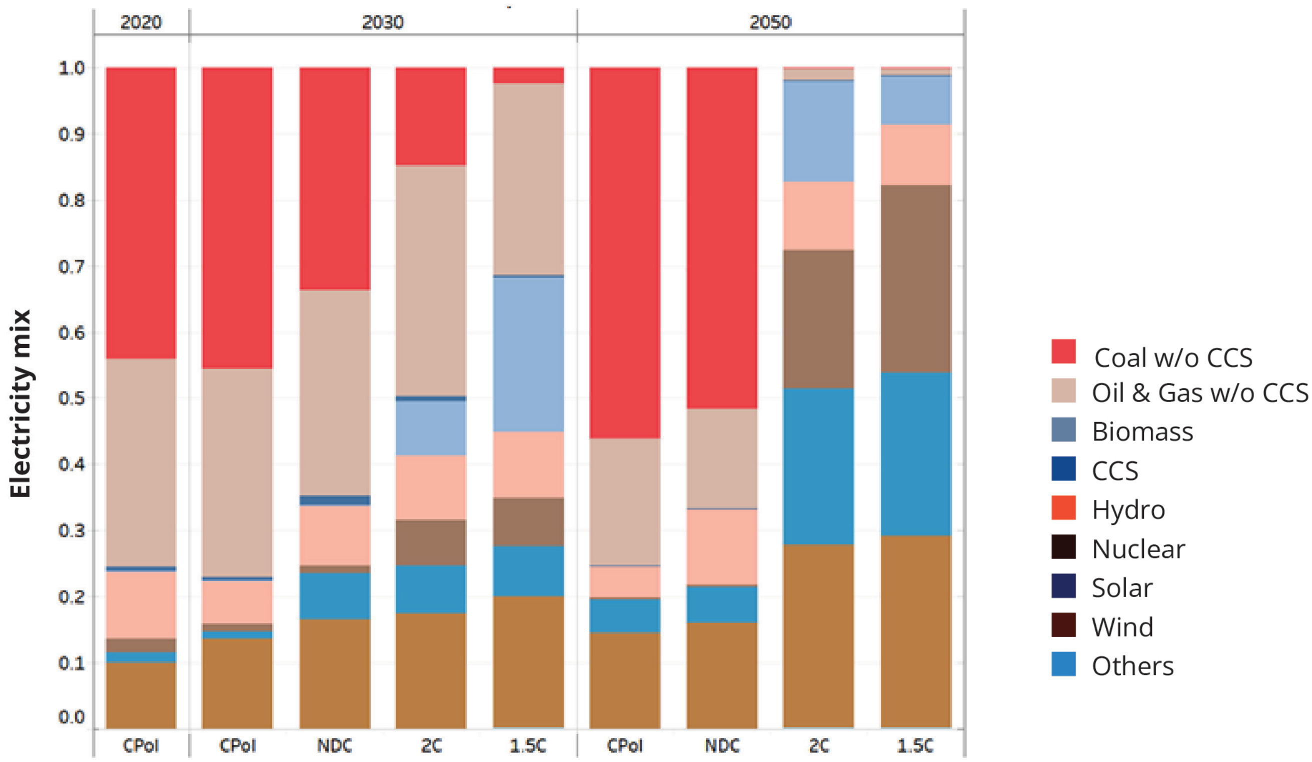
more to the conventional scenario (6 per cent in 2050) compared to the sustainable 2°C scenario (3 per cent in 2050) (Shukla et al., 2015). The contribution of renewables to the primary energy mix in 2050 is about 20 per cent in the conventional scenario and 33 per cent in the sustainable scenario.

In the low-carbon scenarios, there is a significant decoupling between economic growth and energy use and emissions, partly due to the high deployment of renewable energy. In the 1.5°C scenario, renewables like solar PV and hydropower gain a significant share (to 9 per cent) in the energy mix by 2050, compared to the 2°C scenario (Mittal et al., 2018).

On the demand side, overall energy demand is expected to increase (Mittal et al., 2018; Shukla et al., 2017). In the baseline scenario, the demand for electricity is estimated to rise in India due to increasing incomes, achieving universal electrification, and the electrification of transport, residential and industrial sectors. Electricity generation is projected to rise seven-fold between 2010 and 2050 (Shukla et al., 2015). The higher penetration of intermittent renewables causes a marginal rise in energy consumption by the power sector in the NDC scenario by 2025 due to network losses (Shukla et al., 2017). However, in the low-carbon scenarios, energy reduction is driven by changes in fossil fuel prices, resulting in fuel switching and demand reduction. In the NDC scenario, energy demand is marginally lower (3 per cent) compared to the reference scenario in 2030. Compared to the BAU scenario, overall energy demand is 13 per cent lower in 2020 and 43 per cent lower in 2030 in the 2°C scenario (Shukla et al., 2017).

Power from coal reaches its peak value much earlier in the sustainable 2°C scenario compared to the conventional 2°C scenario (Gupta et al., 2020). This is due to the reduced demand for electricity in the sustainable scenario. Sustainable low-carbon pathways, such as the SE4ALL plus 2°C scenario (Dhar et al., 2018), are estimated to have the least electricity generation and the lowest CO_2 intensity of electricity generation. Decoupling of electricity generation from CO_2 emissions is the fastest in sustainable scenarios. Driven by global sustainability goals, the SE4ALL scenario displays higher energy efficiency in fossil fuel generation and greater diffusion of clean energy sources, including renewables and nuclear sources.

Figure 5.4: Electricity generation mix in India under four scenarios



Notes: CCS = Carbon Capture and Storage. CPol = Current Policies. NDC = Nationally Determined Contributions; it denotes a climate scenario with policies of 2015.
Source: *Zhou et al., 2020*

In the electricity generation mix, coal is currently the main source in India (Figure 5.4). In 2016, the power generation mix was 78 per cent coal, 2 per cent oil, 4 per cent each for gas and hydro, 3 per cent nuclear, 7 per cent bioenergy, and 2 per cent other renewables (Vishwanathan et al., 2018). However, low-carbon scenarios show limited growth in coal-based power generation, with increasing reliance on renewable energy. In these scenarios, the share of renewables exceeds 30 per cent, and even reaches 50 per cent in the sustainable 2°C scenario, compensating for the phase-out of coal power (Gupta et al., 2020).

Shukla et al., (2015) estimated that renewable energy would constitute 58 per cent of electricity generation capacity in 2050 in the conventional 2°C scenario and 71 per cent in the sustainable 2°C scenario. The conventional scenario includes a higher share of nuclear energy and the use of coal and biomass with CCS. Coal-based power generation might re-enter post-2030 with CCS. The share of nuclear energy in power generation is expected to increase in both conventional and sustainable 2°C scenarios, with a significantly higher share in the conventional scenario (Shukla et al., 2015). Increased use of nuclear energy in the 2°C and 1.5°C scenarios, compared to the NDC scenario, is also evident (Zhou et al., 2020), though this is inconsistent with projections by Vishwanathan et al., (2018).

In the optimal cost 2°C scenario (conventional scenario), the share of electricity generation from coal declines to 34.5 per cent, while the share of non–fossil fuel-based power generation increases to 39 per cent in 2030 compared to the BAU scenario (Shukla et al., 2017). Within renewables, the composition is expected to change over time as price trends vary among different renewable energy sources. Until 2030, renewable capacity is expected to be predominantly a mix of hydro, wind, solar, and biomass (Shukla et al., 2015). Post-2030, solar power capacity is expected to dominate the mix.

5.2.2. Transport

Transport is the fourth-largest sector contributing to direct GHG emissions in India, accounting for nearly 7 per cent of total emissions (Busby and Shidore, 2017). Due to the sector's high growth rate, it is projected to become the third largest contributor by 2030. Road transport makes up 87 per cent of total emissions within the transport sector, driven by rapid urbanisation, inter-regional trade and expansion of supply chains, and a shift toward more consumerist lifestyles, resulting in significant increases in vehicle use. This trend is expected to continue, particularly in urban areas as rising incomes lead to increased per capita passenger and freight demand. Consequently, the transport sector will consume a growing share of energy in the medium-to-long term.

For instance, passenger transport demand is estimated to be driven by an increase in individual mobility, with p er capita mobility expected to increase by a factor of three from 5,685 passenger km (pkm) in 2010 to 18,837 in 2050 (Dhar et al., 2017). Urban transport demand would witness a transition towards motorisation with increased use of private motorized modes and reduced reliance on non-motorised transport (NMT). The share of rail-based modes e.g., metros, light rail, etc. would increase due to significant investments in public transport including mass transit. Implementation of fuel efficiency norms will facilitate investments in cleaner vehicle technologies including EVs and fuels. The per capita freight demand in India is quite low at 1,464-ton km (tkm) in 2010 compared to nearly 8,000 tkm in EU (EEA, 2013). Economic growth would result in an increase in the overall demand for freight transport from 1,793 x 10 9 tkm in 2010 to 10,052 x 109 tkm in 2050. Investment in dedicated freight corridors will increase the share of rail. Road based transport dominate the share of freight transport (Dhar et al., 2017).

The share of the transport sector in final energy consumption is projected to increase from around 15 per cent in 2010 to about 20 per cent in 2050 in the NDC and 2°C scenarios (Dhar et al., 2018). Transport energy intensity is also expected to rise in these scenarios. However, in the 1.5°C scenario, final energy demand of the transport sector is projected to reduce by 47 per cent by 2050 compared to the NDC scenario. In low-carbon scenarios, a shift towards gas, electricity and biofuels helps reduce the CO_2 intensity of transport energy use (Mittal et al., 2018; Shukla et al., 2015). Despite this, Shukla et al., (2015) estimate that oil will remain the largest transportation fuel source from 2010 to 2050 in both conventional and sustainable pathways to achieve the 2°C target. On the other hand, biomass becomes the most prominent transport fuel in the 1.5°C and NDC 2°C scenarios (NDC till 2030 and 2°C pathway post-2030) (Mittal et al., 2018).

Vishwanathan et al., (2018) estimated that the transport sector accounted for about 11 per cent of total carbon emissions in 2010, with projections to increase to about 12 per cent in 2050 in the BAU scenario and 14 per cent in the NDC scenario. However, emissions from the transport sector are projected to decrease to almost 9 per cent of total carbon emissions in the 1.5°C scenario. This reduction is expected to result from a combination of policy measures, including technological changes driving a shift in energy sources (e.g., EVs), modal shifts to low-carbon modes (e.g., metro rail), and behavioural changes affecting mobility demand (e.g., telecommuting). These projections align with Dhar et al., (2018), which indicates that end-use demand in the transport sector for a 1.5°C pathway will change under the influence of clean fuels and technological innovations.

Electricity demand for transport has traditionally been dominated by rail-based intercity transport (Dhar et al., 2017). In 2010, demand for electricity from transport was 11.6 Terawatt hours (TWh), with 82 per cent from intercity rail. The remaining demand came from metro systems in cities and the transportation of petroleum products through pipelines. Future demand for electricity from rail-based transport is expected to increase due to the expansion of rail networks, increased rail services, creation of dedicated freight corridors and high-speed rail networks.

India's NDCs specifies a target to increase the share of rail in inland transportation from 36 to 45 per cent. Dedicated freight corridors (DFCs) are a move towards this target, expected to ease the load on road freight, which relies on diesel-powered trucks. This shift could result in a cumulative reduction of around 132 $MtCO_2$ between 2015 and 2030, and 625 $MtCO_2$ between 2015 and 2050. Higher reductions can be achieved if electricity is decarbonised. The shift from road to rail will also deliver energy savings and diversify away from oil.

The mix of vehicles and a fuel shift is evolving with the penetration of cleaner technologies and fuels. The electrification of transport is supported by an increasing share of rail for intercity, urban passenger and freight transport. Urban mobility is being encouraged via public transport by expanding existing metro rail systems, Bus Rapid Transit Systems (BRTS), light rail systems and regional rails. Around 754 km of metro rail is in operation, with metro capacity increasing from five cities in 2014 to 18 cities in 2020 and an estimated 25 cities in 2025 (MOEFCC, 2023). Currently, 130 MW of solar power is being used to run the metro rail, which will increase to 600 MW in the coming years.

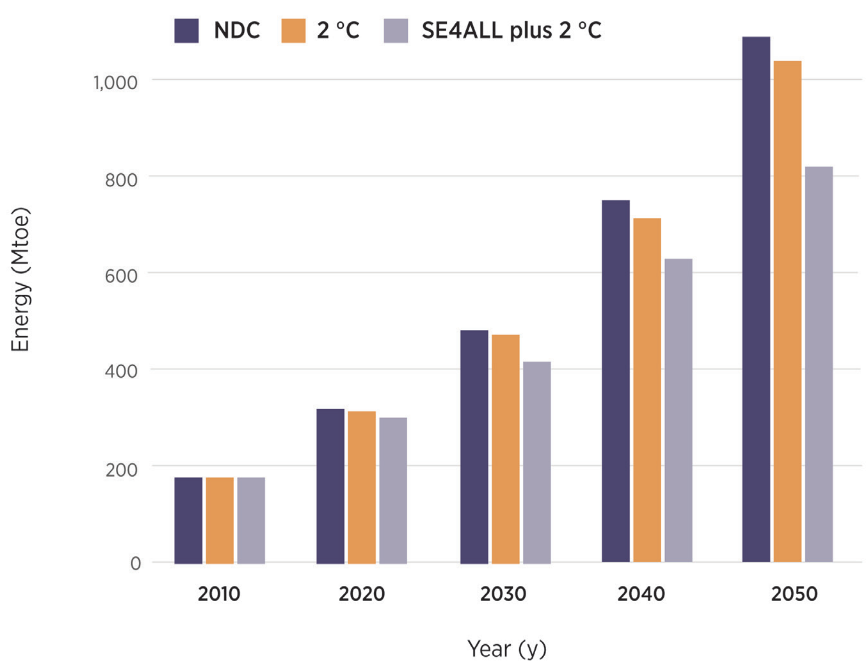
Few metro systems also use regenerative breaking (generating electricity from breaking and supplying it back to the grid), which can lead to emissions reduction. From 2002 to 2016, 0.86 $MtCO_2$ emissions have been avoided with the implementation of metro systems (MOEFCC, 2023). BRTS is being operated in 11 cities.

5.2.3. Industry

Industry is the second largest contributor to GHG emissions in India, accounting for about 25 per cent of total emissions, and this share is expected to grow. Three sub-sectors: steel, cement and chemical, dominate industrial emissions, making up nearly 80 per cent of net industrial direct emissions (Busby and Shidore, 2017). Energy consumption in these sectors is estimated to increase by 4 per cent annually due to rising energy demand for cement, brick manufacturing, and iron and steel (Vishwanathan et al., 2017). Key drivers of this demand include rising urbanisation and increased demand for residential and commercial buildings and infrastructure construction.

Dhar et al., (2018) estimate the energy demand of the industrial sector to increase steadily under all climate scenarios: NDC, 2°C and sustainable 2°C (SE4ALL plus 2°C). The sustainable scenario anticipates the lowest rate of energy demand growth for the industrial sector due to simultaneous interventions in transport, buildings and infrastructure, which collectively reduce net demand. Shukla et al., (2015) also indicate that a sustainable low-carbon scenario has a 22 per cent lower energy demand compared to the conventional scenario. While final energy demand in the conventional low-carbon scenario

Figure 5.5: Energy demand from the industrial sector under different scenarios



Source: *Dhar et al., 2018*

is expected to increase six-fold by 2050, relative to 2010, the energy intensity of the sector is projected to improve over the same period.

In the NDC scenario, emissions from the steel sector are projected to reach around 1,000 $MtCO_2$ by 2050, while emissions from the cement sector will reach around 380 $MtCO_2$ (Dhar et al., 2018). Although CO_2 emissions in the steel sector are lower in the 2°C scenario, they do not peak by 2050. In the cement industry, a reduction in CO_2 emissions growth can be achieved through the widespread deployment of CCS, with 45 per cent of cement plants expected to utilise CCS by 2050.

Both the steel and cement industries, under the sustainable 2°C and 1.5°C scenarios, are projected to achieve peak emissions by 2050, indicating a decoupling of emissions from economic growth. These sustainable scenarios anticipate lower demand for materials and energy-intensive products due to higher levels of dematerialisation, recycling, waste reduction and reuse (Dhar et al., 2018).

Apart from directly reducing final energy demand, another crucial factor for decarbonising the industrial sector is the changing fuel mix, which reduces the CO_2 intensity of energy use (Shukla et al., 2015). In 2017, the industry consumed a mix of coal, oil, natural gas, electricity and biofuels, with fossil fuels collectively representing 56 per cent of total consumption, excluding electricity production (IEA, 2020a). Coal is extensively used, both as a fuel and as a raw material in certain processes, such as non-coking coal in iron and steel production and in cement manufacturing. Coal constitutes more than 50 per cent of the industrial fuel mix, followed by diesel, natural gas and electricity (Vishwanathan et al., 2017). However, sectors such as iron and steel, paper, and textiles are increasingly moving towards electrification, while the fertiliser industry is shifting towards natural gas.

CO_2 intensity is projected to decrease from 3.92 tCO_2 per toe in 2010 to 1.49 tCO_2 per toe in 2050 under low-carbon scenarios (Shukla et al., 2015). The fuel mix is expected to shift away from coal, with coal's share dropping from 40 per cent in 2010 to 38 per cent (35 per cent) in 2050 in the conventional low-carbon scenario (sustainable low-carbon scenario). The deployment of CCS is anticipated to increase in the steel and cement industries, further reducing CO_2 emissions. The role of natural gas is projected to rise in the industrial fuel mix, contributing to lower CO_2 intensity, along with an increasing share of electricity as it becomes progressively decarbonised.

To manage energy consumption in the industrial sector, India implemented the National Mission for Enhanced Energy Efficiency in 2008, which includes the PAT scheme, a market-based energy efficiency improvement programme. Under the PAT scheme, industries must meet energy-saving targets by either implementing energy efficiency measures or offsetting excess energy consumption through the purchase of energy-saving certificates. In its first cycle (2012–2015), the scheme covered eight energy-intensive industries and achieved energy savings of 8.67 million tonnes of oil equivalent (Mtoe), surpassing the target of 6.68 Mtoe, leading to avoidance of 31 $MtCO_2$ emissions (BEE, 2023a). In the second PAT cycle (2016–2019), the scheme covered 11 sectors (including three new sectors - refineries, railways and Power Distribution Companies (DISCOMs) and resulted in total energy savings of about 14.08 Mtoe, translating into avoidance of about 68 $MtCO_2$ emissions. The third PAT cycle led to energy savings of about 1.75 Mtoe. Eight PAT cycles have been rolled out so far; from the third cycle onwards, the roll-out has been happening on an annual basis with new designated consumers (DCs) and new sectors being added in some cycles. The cycle duration continues to be of three years with no interim targets. As of date, PAT covers 1,343 DCs from 13 sectors (Chunekar & Apte, 2023). However, an assessment shows that the PAT scheme's first cycle was not significantly effective in contributing towards the NDC as the energy-saving targets were not more stringent than those set for BAU scenarios (Bhandari and Shrimali 2017). Another assessment also called for stricter target setting under the scheme, pointing to oversupply of energy saving certificates in the market and modest targets, and recommending greater transparency and compliance monitoring of the scheme (Chunekar & Apte, 2023).

5.2.4. Buildings

Residential and commercial buildings are significant contributors to electricity consumption and are responsible for approximately 12 per cent of emissions (Busby and Shidore

2017). The building sector accounts for about 30 per cent of India's final energy consumption (BEE, 2023a).

In the residential sector, urban energy demand for cooking is primarily met through liquefied petroleum gas (LPG), with low-income populations using kerosene and biomass, while rural households predominantly rely on traditional biomass. However, there is a shift away from traditional biomass towards gas and electricity, driven by governmental initiatives. This transition reduces local air pollution but increases CO_2 emissions. Vishwanathan et al., (2018) found that as reliance on biomass declines, building sector emissions tend to rise. Under a deep decarbonisation scenario, the CO_2 intensity of energy use is projected to decrease from 3.92 tCO_2 per toe in 2010 to 1.49 tCO_2 per toe in 2050 (Shukla et al., 2015). In commercial buildings, direct electricity consumption is the primary source of emissions.

Electricity consumption in both residential and commercial buildings is expected to grow, especially due to the rapid expansion of air conditioning in Indian homes and offices (Phadke et al., 2014; Chaturvedi and Shukla 2014). It is projected that nearly 70 per cent of the buildings that will exist in India by 2030 are yet to be built. The housing gap amounts to about 19 million units in urban areas (NBO, 2013) and at least 43 million in rural areas (MoRD, 2011), which has significant implications for climate mitigation. The choice of technology, design and materials, and the implementation of energy-saving options can significantly impact the cost and CO_2 emissions of the impending building stock (Khosla and Janda, 2019).

Buildings consume 33 per cent of total electricity in the country, and this share is estimated to rise to 55 per cent by 2047. Electricity demand in the residential and commercial buildings sectors is predicted to rise fivefold and threefold, respectively, by 2032 (BEE, 2023). Traditional use of biomass for heating and cooking is the largest component of residential energy consumption. Under the BAU scenario, energy demand in the building sector could increase by as much as 700 per cent by 2050, compared to 2005 levels (GBPN, 2014). The technical potential from this unprecedented growth includes a 30 per cent reduction in energy use in new residential buildings and 40 per cent in new commercial buildings through energy efficiency measures.

To achieve the goals of the Paris Agreement, the Indian building sector must reduce final energy demand by 40 per cent compared to BAU. Current interventions are inadequate. The International Energy Agency (IEA) notes that India has access to cooling technologies with efficiencies higher than 400 per cent. Improving residential cooling equipment performance could save 3.5 EJ of energy by 2025, which was nearly equivalent to the total electricity use in India in 2015 (IEA, 2017). Delaying improvements in building envelope performance by a decade could result in an additional 50 EJ of final energy demand by 2060 (Abergel et al., 2017).

India's initiatives to improve building energy efficiencies include the Energy Conservation Act, 2001, the establishment of the Bureau of Energy Efficiency (BEE) in 2002, and the development of the Energy Conservation Building Code (ECBC) for commercial buildings in 2007 (updated in 2017) and for residential buildings (ECBC-R or Eco Niwas Samhita) in 2018. Despite some improvements in building energy intensity, the Indian building sector is not yet decarbonising (Graham and Rawal, 2019). The sector offers a GHG mitigation potential of 0.3 $GtCO_2e$ by 2050; about 8 per cent of the global GHG mitigation potential of the building sector (GBPN, 2012).

Approximately 90 per cent of this potential is related to energy savings in new buildings, while retrofitting existing buildings offers just under 10 per cent of the total energy savings potential (BEE, 2020). Without significant improvements in new building energy performance, the rate of new construction, coupled with increasing electricity demand, will lock out opportunities to realise the mitigation potential of India's building sector (Graham and Rawal, 2019).

About 70 per cent of the growth in energy demand from buildings is driven by the residential sector (Graham and Rawal, 2019), which currently lacks mandatory building energy performance regulations (IEA, 2017). Eco Niwas Samhita, launched in 2018, sets minimum performance standards for building envelopes to limit heat gains and losses and ensures adequate natural ventilation and daylighting. The code applies to residential building projects on plots larger than 500 sq. m.

Table 5.2: Fuel shares in buildings energy consumption under BAU and advanced NDC scenarios (in per cent)

Sector	2015	2030 BAU	2030 Adv. NDC
Biomass	68	46	29
Coal	4	0	0
Gas	3	3	5
Oil	12	11	17
Electricity	12	34	40
Solar	1	6	10

Source: *Vishwanathan et al., 2018*

New construction and increased air conditioning in India have led to a 500 per cent increase in electricity demand in the building sector since 2010 (IEA, 2017). Air conditioning currently accounts for 40–60 per cent of summer peak load in large Indian cities and is projected to contribute to around 30 per cent of national peak demand (approximately 140 GW) by 2030 (Abhyankar et al., 2017). Transitioning to cleaner appliances like LEDs, cleaner cook stoves, solar water heaters and energy-efficient cooling systems is expected to improve energy use in the sector.

However, overall energy demand will remain high due to increased use of air conditioners and other electric technologies. Smart grids will face technical challenges with constantly changing technologies, business challenges in servicing end-use providers, and financial risks (Vishwanathan et al., 2019). A better understanding of demand load curves will be essential for the smooth implementation of smart and microgrids in residential, commercial, and industrial areas.

In the advanced NDC scenario, India achieves both its NDC targets for 2030: a reduction in the carbon intensity of GDP and a 40 per cent non–fossil fuel share in generation capacity (Vishwanathan et al., 2019). In this scenario, the fuel share composition shifts in favour of electricity compared to biomass in the baseline scenario, with solar energy emerging as a prominent energy source. Post-NDC policies promote household access to cleaner cooking, which will lead to increased fossil fuel consumption and, consequently, higher CO_2 emissions in the building sector in the short and medium terms. However, this increase will allow for a better quality of life for many more Indians during the country's transition.

The rise in carbon emissions from the building sector is offset by reduction in emissions from other sectors, primarily power generation. This reduction is driven by the switch to energy-efficient thermal plants and the scaling up of renewable energy sources (Vishwanathan et al., 2019).

5.2.5. Agriculture

Agriculture faces the triple challenge of increasing production to meet the growing food demand, adapting to changing climatic conditions and reducing GHG emissions.

While the agriculture sector has less CO_2 emission intensity than the industrial and service sector, it emits methane (CH_4) and nitrous oxide (N_2O), contributing about 13 per cent of GHG emissions in the country; a decrease of 1 per cent compared to 2016 (MOEFCC, 2023). Key emission-intensive activities include rice cultivation, livestock production (enteric fermentation), fertiliser use and burning of crop residue. Increasing use of fertilisers and rising livestock population are major drivers of methane and nitrous oxide emissions. Within the different categories in this sector, 53 per cent of GHG emissions were from enteric fermentation, followed by 21 per cent from agricultural soils, 17 per cent from rice cultivation, 6.54 per cent from manure management and 1.99 per cent from field burning of agricultural residues in 2019.

States like Uttar Pradesh, Andhra Pradesh, Madhya Pradesh, Maharashtra, Rajasthan and West Bengal exhibit higher total emissions due to extensive crop areas and large livestock populations. Andhra Pradesh, West Bengal and Punjab have higher crop emissions due to significant rice cultivation, while Maharashtra, Madhya Pradesh and Uttar Pradesh show higher emissions from cotton and sugarcane cultivation. States like Himachal Pradesh, Uttarakhand, Jharkhand and Chhattisgarh have higher crop emission intensities due to lower crop yields.

Emissions from agriculture in India are expected to increase further in the future as food demand rises with increasing population and per capita income. Hence, India has identified agriculture as one of the priority sectors for GHG emissions reduction in its NDCs. Identifying emission hotspots and cost-effective mitigation options in agriculture can help prioritise efforts to reduce emissions without compromising food and nutrition security.

Sapkota et al., (2017) estimated that by 2030, business-as-usual GHG emissions from the agricultural sector in India would be 515 $MTCO_2e$ per year, with a technical mitigation potential of 86 $MtCO_2e$ per year through the adoption of various mitigation practices. About 80 per cent of this technical mitigation potential could be achieved by adopting cost-saving measures like efficient use of fertilisers, zero tillage and rice water management.

5.3 Mitigation Options on the Demand and Supply Sides

Decarbonisation (transitioning from BAU to NDC scenarios) and deep decarbonisation of the economy (transitioning from NDC to low-carbon pathways) require focused attention in several key areas: increased energy efficiency in both supply and demand sectors, enhanced deployment of renewable energy, demand reduction in end-use sectors through dematerialisation, recycling, reuse and behaviour change, and deployment of CCS where feasible (Vishwanathan et al., 2018). Vishwanathan et al., (2018) further suggest that energy efficiency and renewable energy will play nearly equal roles in CO_2 mitigation under the NDC scenario. However, for low-carbon scenarios, lifestyle changes and CCS will be more relevant.

Supply-side interventions are primarily within the energy sector, whereas demand-side interventions include demand reduction or substitution, efficiency improvements, and behavioural changes. Effective emissions mitigation necessitates a combination of both sets of options.

NITI Aayog (2017) provides a schematic division of possible intervention areas on both the supply and demand sides. On the supply side, areas are classified according to the energy source (coal, oil, gas or renewable) or form (electricity) and the stage of the value chain (Table 5.3). Stages of the value chain are divided into upstream, midstream and downstream. For instance, the upstream stage of electricity is generation, while midstream and downstream stages are transmission and distribution. Similarly, exploration and production define the upstream stage of oil while refining and distribution are midstream and downstream stages. Final energy consumption is captured in demand-side areas and is categorised into major consumption sectors like businesses, households, transportation, industries and agriculture (Table 5.4).

Decarbonisation on the demand side includes policy measures that support the reduction and stabilisation of demands in energy-intensive industries, significant increases in energy-efficient technologies in the building sector, rise of EVs in the transport sector, enhanced deployment of smart grids and changes in consumer behaviour (Vishwanathan & Garg, 2017).

Roy et al., (2018) find that demand-side actions alone cannot be effective enough. Optimising mitigation actions requires acknowledging the interconnectedness across sectors. For example, demand-side mitigation actions in the transport sector heavily depend on city planning and infrastructure, and the construction sector is integral to the building sector. There can also be trade-offs between demand-side mitigation options in different sectors. In the industrial sector, some demand-side actions in other sectors have trade-offs in the industrial production process.

Table 5.3: Supply-side interventions

	Stages of Value Chain		
	Upstream (Generation)	Midstream (Transmission)	Downstream (Distribution)
Oil and Gas	Enhancing E&P by adopting best R&R practices. Attracting private capital by offering a stable regime. Instituting a robust regulatory regime.	Enhancing refining and distribution through increased infrastructure. Determining fuel prices on market price basis. Achieving universal clean cooking coverage through multiple fuel options.	
Coal		Efficient transportation and distribution through better rail infrastructure. Value addition of raw coal through washeries. Pursuing technologies to establish commerciality of Indian coal.	
Renewable Energy	Enhancing capacity and generation, including of nuclear power, large hydro, biomass and offshore wind. Higher adoption of ultra-supercritical/IGCC. Policy support for decentralised generation or CCS. Promoting uranium exploration.	Increased grid integration of renewables and adoption of battery and pumped storage. Efficient market for uptake of renewable electricity. Achieving flexibility in coal power plants.	
Electricity		Need for a robust transmission and distribution infrastructure, efficient electricity market and improved financial status of DISCOMs. Achieving universal electrification.	
Cross-border trade	Fostering cross border trade of petroleum products and electricity especially with neighbours (Nepal, Bhutan, Bangladesh, Myanmar, Sri Lanka, China and Pakistan), which would enhance energy security.		

Note: IGCC = Integrated Gasification Combined Cycle.
Source: *NITI Aayog, 2017a*

The IEA (2020) notes that in 2018, efficiency gains were largely achieved in industrial and service sectors, as well as in residential buildings, avoiding nearly 300 $MtCO_2e$ in emissions. However, total energy efficiency improvements were almost completely offset by factors boosting energy use, such as increases in residential building floor area and appliance ownership, shifts to less efficient modes of transport and decreasing vehicle occupancy rates. Therefore, a cross-sectoral framework is essential for positive net benefits in demand-side mitigation.

Feasibility assessments of mitigation options in different sectors (Busby & Shidore, 2017) suggest that road transport is the most favourable sector for emissions mitigation, followed by petrochemicals. Cement and fertilisers are already at or near the global efficiency frontier. Buildings possess strong techno-economic feasibility but face challenging political and organisational feasibility. Electricity, agriculture and steel represent hard cases in both political/organisational and techno-economic feasibility. (A feasibility assessment of mitigation options is discussed in the Chapter 7).

Table 5.4: Demand-side interventions

	Energy Efficiency/ Decarbonisation	Investment	Infrastructure
Industry	Rolling out PAT scheme cycles. Encouraging fuel switching towards reduction in solid fuel use by electrifying processes.	More investment required in efficient manufacturing technologies in cement, iron and steel, and other sectors.	Higher capex in plants and infrastructure to inducting efficient technologies.
Cooking	Improving the efficiency of biomass cook stoves and gas stoves. Moving towards cleaner fuel, including electric cook stoves.	Investing in induction cookers/LPG bottles or efficient biomass cook stoves, pellet manufacturing and electricity distribution infrastructure to shift to cleaner cooking fuels.	Setting up refineries and pipeline infrastructure to deliver LPG, enhance the use of electric stoves.
Transport	Raising CAFÉ standards and switching to EVs and public transport.	Investing in manufacturing of efficient vehicles/EVs/ hybrids and higher spends on fuel-efficient vehicles.	Electric charging stations, hydrogen filling stations for FCVs and more CNG stations.
Buildings	Improving energy efficiency of all electrical appliances and adhering to the for all buildings with high energy use, including retrofits. Raising thermal efficiency of buildings.	Higher investment in buildings and domestic appliances with higher energy efficiency	Enhancing use of better insulation and construction materials.
Agriculture	Better efficiency of pumps and tractors.	Investment in efficient irrigation pumps, including solar/electric pumps for irrigation.	Laying sub-transmission infrastructure to electrify irrigation pumps and solar pumps and build efficient tractors.

Notes: BAT =. CAFÉ = Corporate Average Fuel Economy. CNG = Compressed natural gas. EV = Electric vehicle. FCV =. LPG = Liquefied petroleum gas. PAT = Perform, Achieve and Trade.
Source: *NITI Aayog, 2017a*

5.3.1. Energy sector

Key strategies for mitigation in India include decarbonisation of electricity, electrification of end-uses and improvement in energy efficiency. Mitigation options in the energy sector are crucial as they influence the mitigation potential of most other sectors.

Enhancing energy efficiency by retrofitting energy-efficient coal technologies across sectors, implementing supercritical coal combustion technology for all new power plants and phasing out relatively inefficient plants older than 20–30 years will lead to a decrease in overall demand (Vishwanathan & Garg, 2020). Between 2011 and 2050, the overall energy demand is estimated to decrease by 78 EJ under the NDC scenario, and by 38–71 EJ in deep decarbonisation scenarios (the inclusion of CCS increases overall energy demand in the power sector).

Supply-side options: The energy mix needed to meet the chosen level of energy demand should reduce import dependence and transition towards cleaner and sustainable supply options (NITI Aayog, 2017). The commercialisation of newer, cleaner technologies such as ultra-supercritical and Integrated Gasification Combined Cycle (IGCC) technologies in coal-based generation will lead to their increased penetration. Enhanced gas-based power generation capacity is acknowledged for encouraging cleaner power sources and balancing renewable energy capacities. The potential for CCS in coal and gas-based generation capacities in the medium-to-long term should also be considered (NITI Aayog, 2017).

While the continued use of coal and gas with CCS is an option, renewable energy is expected to be the key driver of mitigation in the energy sector. Achieving 175 GW of renewable energy capacity by 2022 and creating a market and facilitative mechanism for renewable energy post-2022 will lead to its increased adoption through autonomous growth (NITI Aayog, 2017). Concentrated Solar Power (CSP) and offshore wind capacities will contribute to renewable energy generation alongside solar PV, distributed Solar Photo Voltaic technology and onshore wind.

Areas of intervention: NITI Aayog (2017) identifies several areas of intervention:

- Energy consumption by businesses, households, transportation and agriculture.
- Energy efficiency/decarbonisation measures on the demand side.
- Production and distribution of coal.
- Electricity generation, transmission and distribution.
- Augmenting the supply of oil and gas through domestic exploration and production, and acquisition of overseas acreages.
- Refining and distribution of oil and gas.
- Installation, generation and distribution of renewable energy.

CCS is crucial for well below 2°C and 1.5°C scenarios (Shukla et al., 2015), especially if there is delayed mitigation action (Vishwanathan et al., 2018). CCS becomes economically viable at sites with high storage potential and low transportation and sequestration costs, such as depleted oil and gas wells. The main enabler for CCS is carbon price, which is expected to increase steadily. According to Anandarajah & Gambhir (2014), India can meet its emission reduction targets without CCS technology, but with greater contribution from renewables. However, CCS technologies can reduce long-term mitigation costs, as the unavailability of CCS triples the marginal abatement cost by 2050 when comparing scenarios with and without CCS.

Demand-side options: Demand-side options for emissions reduction in the energy sector primarily involve improving efficiency and energy usage patterns in end-use sectors. With end-use energy efficiency improvement policies in industries, buildings and transport, final energy consumption is estimated to decrease by 5 per cent in 2030, 8 per cent in 2050 and 16 per cent in 2090. Primary energy consumption is expected to similarly decline (Chaturvedi & Shukla, 2014).

High code compliance rates are critical to achieving intended savings, despite existing policies in different end-use sectors (Yu et al., 2017). Technical efficiency alone is not sufficient; alternative strategies focused on behavioural changes enabled through planning and policies are also necessary. In the transport sector, strategies like mobility management, shortening trip lengths and increasing vehicle occupancy are more effective than merely increasing vehicle fuel efficiency (Chaturvedi & Shukla, 2014). Emissions from the transport and building sectors can also be reduced through the spatial organisation of urban areas, particularly the geometric characteristics established by the relationship between roads, buildings, public structures, green spaces, land use distribution and the relative location of activities (Creutzig et al., 2016).

Smart grids are expected to play a crucial role in monitoring and conserving energy in urban areas (Vishwanathan et al., 2017). Power distribution relies on utilities to maximise efficiency and optimise the network to deliver power to consumers at minimal cost. Smart grid technologies offer promising solutions for dynamic optimisation of grid operations and resources, metering, and distribution automation in response to demand (Shamim & Rihan, 2017).

5.3.2. Transport

In 2050, electricity is projected to comprise 18 per cent of the transport energy mix in the 2°C scenario and 24 per cent in the 1.5°C scenario (Mittal et al., 2018). With expected increases in population and GDP, significant rise in vehicles and demand for road transport is anticipated. In 2019–20, about 21 million two-wheelers, 3.4 million passenger vehicles and 0.75 million commercial vehicles and were produced in India (Bazaz et al., 2022). Between 2001 and 2011, the percentage of households owning two-wheelers increased by 2.5 times. The National Transport Development Policy Committee (NTDPC) estimates that travel demand served by road transport will increase to 163 trillion passenger-kilometres by 2031, nearly 17 times that of 2011 (NTDPC, 2014).

Transport energy demand is expected to increase from 1.7 EJ in 2010 to 12 EJ by 2050 under the NDC scenario (Dhar et al., 2018). In a conventional scenario, this demand rises to 15 EJ by 2050, while in a sustainable scenario, it reaches only 8 EJ (Shukla et al., 2015). The sustainable scenario, which includes population and demand-side interventions, aims to lower end-use demand. India's transport strategy focuses on sustainability, reducing dependency on imported energy and mitigating environmental impacts. Mass transit and urban planning will play a vital role in the transport mitigation strategy.

Significant CO_2 reductions in transport can be achieved through a combination of sustainable mobility strategies and fuel economy standards, with EVs playing a more substantial role post 2030 (Dhar, Shukla, et al., 2017). Improving service efficiency, such as ride-pooling or car sharing, and fuel switching to options like hydrogen buses and EVs can also reduce emissions (Creutzig et al., 2016). A holistic strategy involving planned interventions in both demand and supply is necessary for a decisive shift towards sustainable transport modes (TERI, 2015).

Supply-side options: Clean vehicle technologies and fuels are central to supply-side strategies. Upgrading fuel quality and efficiency can reduce emissions significantly (TERI, 2015). Alternatives like biofuels can aid in transitioning away from carbon-based fuels. India's National Policy on Biofuels (2018) sets blending targets for ethanol (20 per cent by 2030) and biodiesel (5 per cent by 2030). The 20 per cent ethanol blending target has now been advanced to 2025-26, with India achieving 10 per cent ethanol blending in 2022–23 (Mukherjee, 2024).

Fuel economy standards are regulated by the Central Pollution Control Board. In 2012, fuel mileage standards and labelling for new cars were introduced, requiring manufacturers to display certified efficiency labels on each car. The National Electric Mobility Mission set a sales target of 6–7 million EVs by 2020, potentially reducing emissions by 98 $MtCO_2$ between 2015 and 2030, and by 1,155 $MtCO_2$ between 2015 and 2050 (Gupta et al., 2018). India aims to make 30 per cent of its total vehicle stock electric by 2030 (Fekete et al., 2021).

Direct financial incentives and infrastructure investments are crucial for increasing EV adoption in the short-to--medium term (Dhar, Pathak, et al., 2017). There is significant potential for scaling up the share of electric two-wheelers in the short term (Dhar et al., 2017). This would also be an opportunity for India to develop the domestic EV industry and create an enabling environment, including charging infrastructure, which can facilitate diffusion of larger EVs. For EVs, policy support in terms of financial aid (subsidies), infrastructure (charging stations and proper roads) and training facilities for drivers are crucial in market penetration (Ahmed & Karmaker, 2019; Tu & Yang, 2019; Zhang et al., 2018)it has also caused tremendous damage to the global ecological environment. Therefore, humans are thinking seriously about the environment and its sustainable development. One of the solutions to environmental problems is new energy vehicles. Since the promulgation of the "Energy Saving and New Energy Vehicle Industry Development Plan (2012–2020.

Demand-side options: Demand-side strategies for passenger and freight transport include reducing the need for travel and shifting to low-emission modes (Sims et al., 2014). Enhancing conditions for walking and cycling, increasing public transport provision, and integrating urban planning with transport can significantly reduce emissions. Investments in high-speed rail and dedicated freight corridors are crucial for altering transport trends. Many cities are investing in mass transit systems like metros and bus rapid transit (BRT).

Integrated land use and transport planning can reduce travel demand and associated costs (TERI, 2015). Promoting non-motorised transport can be particularly beneficial in Indian cities due to short trip lengths and mixed land use structures. Innovation and strategies to reduce the cost of hybrid and electric public transport vehicles are also essential.

Spatial planners and policymakers play a significant role in reducing the demand for mobility services. Long-term housing near work hubs, improving last-mile connectivity and better service delivery in public transport can facilitate a shift towards sustainable modes. Comprehensive mobility plans in cities like Kolkata, Pune and Delhi aim for a 90 per cent modal share in public transport (Roy et al., 2018). Developing a user-friendly public transport environment and encouraging non-motorised modes are crucial. Innovation and intervention in service delivery can reduce the need for private transportation and facilitate mass transit (Roy et al., 2018). A supporting infrastructure provisioning is also an important enabler in reducing transport demand and affecting modal choices.

Policymakers and planners need to facilitate a user-friendly environment to use public transport (e.g., by providing information on bus routes, timetables, easy ticket payment and collection) and non-motorised modes of transport (e.g., specific lanes for walking and biking). Private players can also influence transport demand by changing their employees' transport allowances, which in turn can change the behaviour of commuters (Ahmad & Puppim de Oliveira, 2016; Roy et al., 2018).

Overall, demand-side policies have great potential in shaping the transport sector (Creutzig et al., 2016). Projections for the transport sector show a marked difference between the conventional scenario (supply-oriented policies) and the sustainability scenario (both supply- and demand-oriented policies). Under the sustainable scenario, the share of transport sector CO_2 emissions in 2050 reduces to 16 per cent, compared to 28 per cent in the conventional scenario (Shukla et al., 2015).

5.3.3. Industry

Mitigation in the industry sector can be achieved through interventions in industrial processes, management and technologies. Key strategies include raw material management, process improvements, installation of systems such as waste heat recovery and reducing output wastage through better quality control. Reducing emissions intensity and improving energy efficiency can be accelerated through cap-and-trade mechanisms like the PAT scheme, which targets large energy-intensive consumers to reduce energy intensities and overall energy consumption. Fuel switching to gas from coal, automation and electrification of industry, modernisation of old plants, and CCS in steel and cement plant clusters are measures that can enhance energy efficiency (Vishwanathan & Garg, 2020).

Allwood et al., (2010) suggest four strategies for improving material efficiency: reducing material intensity, extending product life and usage, re-manufacturing and reuse of components, and recycling. Reducing material intensity can be achieved by adopting lightweight design principles, upgrading material properties and material substitution. Studies indicate that applying lightweight design principles can reduce steel and aluminium requirements by 25–30 per cent (Seyfried et al., 2015). Substituting low-energy materials in construction can reduce cement consumption by 5 per cent. Overall, material intensity reductions through lightweighting and material substitution can lower product demand by 10 per cent for steel and 15 per cent for cement by 2050, compared to conventional scenarios (Dhar et al., 2018).

Adequate investments in building and infrastructure are essential, as lack of investment translates to lower quality and shorter lifespan. Prolonging the service life of buildings and infrastructure through maintenance and reinvestment is a useful strategy to reduce steel and cement consumption and CO_2 emissions (Shi et al., 2012).

Electricity will play a crucial role in decarbonising the steel sector. In other words, the decarbonisation of steelmaking will rely heavily on the decarbonisation of electricity (Dhar et al., 2018). The reduction in CO_2 intensity in steel and cement will also depend on the uptake of CCS, which will require stringent carbon policies such as levying a high carbon tax or a cap on CO_2 emissions. NITI Aayog (2017) noted that electricity demand in their ambitious scenario would be more than the BAU scenario, since the technology employed in the former is more electricity-intensive rather than hydrocarbons-intensive. Hence the composition of electricity generation mix is an important determinant of the mitigation potential in the industry sector. Dhar et al., (2018) found that major contributors to decarbonisation in the steel sector include a larger share of electricity due to greater diffusion of electric arc furnace (EAF) technology and the rapid decarbonisation of electricity. In the cement sector, technological advancements like more efficient dry cement technology and CCS, are expected to have a larger impact than decarbonisation alone.

Establishing linkages between manufacturing and construction industry policies can amplify demand-side reductions. National and sub-national building codes and urban building by-laws could specify performance standards and waste management policies, such as the use of fly ash from power plants in the brick and cement manufacturing industries.

5.3.4. Buildings

The buildings sector primarily operates on the demand-side, with minimal on-site fuel consumption, mainly for cooking, and the use of diesel generators in high-end commercial or residential buildings during frequent power blackouts. Most energy consumption comes from centralised grid electricity. Demand reduction strategies in this sector focus on minimising building footprint and lowering energy usage for heating/cooling, lighting, cooking and appliances (Creutzig et al., 2016).

One approach to reducing energy-intensive materials like cement involves substituting them with alternatives such as fly ash, wood, or bamboo (Roy et al., 2021). Environmentally sustainable designs that incorporate natural daylight and efficient management of circulation areas can significantly lessen the need for heating, cooling, and artificial lighting (Lourenço et al., 2019). Research indicates that information and communication technology (ICT) and Internet of Things (IoT) devices that provide real-time consumption data can encourage energy-saving behaviors, particularly among environmentally conscious consumers (Fabi et al., 2017).

India is addressing mitigation options through initiatives such as upgrades to the ECBC, promoting green building ratings, energy certification and stimulating markets for low-carbon/high-efficiency technologies. NITI Aayog (2017) suggests that periodic revisions to the ECBC, improved urban planning, and the promotion of high-efficiency lighting and appliances can significantly enhance energy efficiency in both commercial and residential buildings.

High Performance Buildings (HPBs) that focus on maximising efficiency in form and function, can play a crucial role in transforming India's carbon-intensive real estate sector. HPBs are designed to be resource and cost-efficient, using only 50 per cent to 25 per cent of the energy and water benchmarks established by current Indian codes (IIHS, 2024). They incorporate advanced technologies like high-performance windows, insulation, efficient HVAC systems, smart controls, and water-efficient designs to enhance thermal comfort, indoor air quality, and resilience throughout the building's life cycle.

A recent initiative, the Accelerating Sustainable and Super Efficient Real Estate (ASSURE) program, supported by Infosys, the Indian Institute for Human Settlements (IIHS), and the Alliance for Energy Efficient Economy (AEEE), aims to decarbonize commercial real estate in India by achieving 100 million square feet of high-performance commercial buildings by 2030 (ETTech, 2024). It is projected that if half of the projected commercial building stock for 2030 is built or retrofitted according to HPB principles, it could save businesses $432 billion in energy costs, create 10 million skilled green jobs, and prevent 600 million tons of CO_2 emissions (IIHS, 2024).

Capacity-building is vital to harness the energy-saving potential of regulatory and voluntary energy performance policies (Graham & Rawal, 2019). The fragmented nature of the building value chain necessitates on-the-ground support for stakeholders, requiring collaboration among industry, government, and experts to create a conducive policy and finance environment.

Encouraging energy-saving behaviors among occupants through smart thermostats and digital interfaces that provide feedback on energy use is a critical scaling-up strategy (Graham & Rawal, 2019). However, challenges such as inadequate documentation of design decisions, alterations during construction, informal building operations, and limited access to performance evaluation tools complicate the landscape (Khosla & Janda, 2019). Addressing these issues requires a new generation of third-party evaluators, architects, and engineers to bridge the energy and carbon savings gap.

Monitoring actual building energy consumption is essential for evaluating the impact of building energy codes and refining policies aimed at achieving energy savings and emissions reductions (Khosla & Janda, 2019). Disclosing energy performance at the point of sale or lease change can effectively stimulate markets for energy-efficient building renovations.

Vishwanathan et al., (2017) highlight several high-impact opportunities (HIO) in the building sector. LEDs stand out as promising HIOs in the short term, while medium-term prospects include space-cooling appliances and the transition to clean energy stoves. Smart metering through ICT is expected to become a significant opportunity post-2025. Until 2030, key technologies for the Indian building sector include LED lights, efficient fans, air conditioners, and cleaner stoves (Vishwanathan et al., 2017).

5.3.5. Agriculture

Mitigation of GHG emissions from agriculture can be achieved by sequestering carbon and reducing emissions of methane and nitrous oxide through improved land use management and enhanced input–use efficiency. A win-win solution involves developing strategies that aid in climate change adaptation while promoting sustainable agricultural development.

Improved management of agricultural land and livestock offers mitigation possibilities through three mechanisms: reducing or displacing emissions and enhancing removal (Sapkota et al., 2017). These mitigation activities often affect multiple gases in different ways, with the net benefit depending on the combined effects on all gases. Several practices in agro ecosystems have been advocated for emissions mitigation. Crop abatement options include a range of improved agronomic practices that increase crop yield, promote soil carbon storage, and ensure good management practices for fertilisers, water and other resources. These practices increase resource-use efficiencies, thereby reducing emissions associated with production inputs.

Sapkota et al., (2017) estimate that just three mitigation options—efficient fertiliser use, zero tillage, and rice water management—could deliver more than 50 per cent of the total technical abatement potential. Using slow-release fertiliser forms or nitrification inhibitors and applying fertilisers at the optimal time and place for plant uptake increases nutrient-use efficiency. This reduces fertiliser-induced field emissions and consumption, thereby decreasing emissions related to fertiliser production and transportation.

Livestock-related mitigation options are broadly identified as increased green fodder and concentrate feeding for lactating cattle and buffaloes, improved diet management for pigs and small ruminants, and enhanced manure management. Restoration of degraded land for crop production and vegetation establishment has the potential to increase carbon storage through enhanced photosynthesis and reduced soil erosion loss. Additionally, growing bioenergy crops on restored land can reduce dependency on fossil fuels, making this a viable mitigation practice (Jat et al., 2016; Olsson & Ardö, 2002).

Adopting zero tillage in crop production offers GHG mitigation by enhancing carbon sequestration and reducing fuel consumption (UNEP, 2013). Since soil disturbance stimulates soil carbon losses through enhanced decomposition and erosion, reducing tillage operations often results in soil carbon gain, although the effects may be small and variable (Baker et al., 2007; Powlson et al., 2016). Avoiding burning of crop residue also prevents the emission of aerosols and GHGs generated from fire, while enhancing soil carbon (Sapkota et al., 2017), all of which contribute to mitigation.

Effective irrigation management in crops contributes to GHG mitigation by reducing water consumption and the associated energy use for irrigation, increasing yields and residue returns (Lal, 2004), and directly reducing methane emissions from rice fields (Wassmann et al., 2004). Other water management options, such as sprinkler or micro-sprinkler irrigation and fertigation, offer a technical mitigation potential of approximately 5.5 $MtCO_2e$ but involve a large initial capital investment.

5.3.6. Technology as an enabler

New low-carbon, renewable energy sources and technologies will be crucial for mitigation, primarily led by the private sector. Demand-side management in domestic and commercial appliances and agriculture, will become more prominent as market penetration and greater adoption of available technologies takes place. These can be achieved through appropriate pricing policies, labelling and awareness-raising strategies, and attractive financing schemes, many of which are currently underway (Pahuja et al., 2014).

For most supply-side options, it is important to develop new technologies and facilitate market penetration by enabling policies and building institutional capacity. Supercritical power plants, ultra-supercritical power plants, IGCC and CCS are promising technologies for emissions abatement. In renewable energy, the government is pursuing solar power as a critical technology to achieve long-term energy security and low-carbon growth. Options to reduce industrial emissions, especially in cement, iron and steel, and oil and gas, hinge on the development, adaptation and adoption of new technologies. Industry efforts have been instrumental in driving the development of technologies for emissions reduction. For example, India's cement industry, among the largest producers globally, is also one of the most technologically advanced (Riccardi et al., 2012). In recent years, facilities have gradually transitioned to dry process technology during cement production to replace the less efficient wet process dominant in the industry during the 1960s (Dutta & Mukherjee, 2010).

Table 5.5: High impact opportunities across different sectors

Sector	**Short Term** 2015–2020	**Medium Term** 2020–2030	**Long Term** 2030–2050
Agriculture	Energy-efficient pumps		Energy-efficiency, solar pumps
Transport	Metro	Metro, EVs	
Residential	LED, advanced space cooling systems, cleaner cooking	Energy-efficient fans, LED, advanced space cooling systems, cleaner cooking	Advanced space cooling systems (air conditioner with cool roof), solar concentrators for cooking, city/housing complexes–based heating and cooling systems.
Industry	PAT	PAT with enhanced sectoral and plant coverage	
Power	Transmission and commercial loss reduction, supercritical coal-based power plants	Supercritical and ultra-mega power plants, transmission and commercial loss reduction, solar and wind energy, and smart grids	Supercritical and ultra-mega power plants, solar, wind and other renewables, and smart grids

Source: *Vishwanathan et al., 2017*

Box 5.1: Green Hydrogen

Outlook: Green hydrogen is set to play a crucial role in decarbonizing hard-to-abate sectors such as iron, steel, cement, fertilizers, and refining, which collectively emit substantial CO_2. Several countries, including India are developing strategies to harness green hydrogen for its low-carbon transition. Green hydrogen is an important component of India's Long Term Low Emissions Development Strategy (LT-LEDS) and its updated NDCs. As part of LT-LEDS, India aims to set up a green hydrogen hub and increase its electrolyser manufacturing capacity, targeting a production capacity of 5 MMT (million metric tonnes) per annum by 2030 (MOEFCC,2022). Adoption of green hydrogen is estimated to reduce 3.6 giga tonnes of cumulative CO 2 emissions, save energy imports worth USD 246 billion to 358 billion between 2020 and 2050, and generate 6 lakh jobs (NitiAyog, 2022; RBI, 2023).

Current status: As of 2023, low-emission hydrogen accounted for just 1 MMT of the 97 MMT global hydrogen demand (IEA, 2024). The majority still relies on fossil fuels, particularly in refining and chemicals. Projections suggest low-emissions hydrogen production may reach 49 MMT per year by 2030, supported by approximately 520 GW of announced electrolysis capacity (IEA, 2024). Current projects with final investment decisions (FID) could yield 3.4 MMT of capacity, split between electrolysis (1.9 MMT) and fossil fuels with carbon capture (1.5 MMT). China currently leads in electrolysis capacity, while India has emerged as a significant player with a 1.3 GW FID (IEA, 2024). Approximately 115 green hydrogen projects have been announced in India across sectors like mobility and steel production, including NTPC's hub in Andhra Pradesh and plants in Noida, Ladakh, Gujarat, and Tamil Nadu (MNRE, 2024).

Challenges: Green hydrogen production costs range from $4.10 to $7 per kilogram, significantly higher than brown or grey hydrogen (NITI Aayog, 2022). To foster a competitive domestic and international market, India must lower these costs. Additionally, hydrogen's low density and flammability complicate storage and transportation, necessitating investments in new pipelines or repurposing natural gas lines, which only becomes feasible when demand reaches a critical level. Estimates suggest that green hydrogen could compete with grey hydrogen by 2030, with potential prices dropping to approximately $1.60 per kilogram by 2030 and $0.70 by 2050 under favorable conditions (NITI Aayog, 2022). Building a robust hydrogen economy will require clear standards, regulations, and significant financing, which are still in development.

The iron and steel industry, which provides key resources to sectors including construction, transportation and power transmission, has had mixed success in reducing emissions. Some Indian steel producers have indigenised and improvised on imported technology, and competition among domestic industries is likely to increase the energy efficiency of techniques used during the production process (Dutta & Mukherjee, 2010). However, there has been limited policy support for the formalisation of research and development (R&D) in this sector.

In the oil and gas sector, capturing fugitive emissions from industrial activities has recently emerged as a significant issue (India produced 21 $MtCO_2e$ methane emissions in 2010, or 1.3 per cent of the global total).

For example, the country's largest producer, the Oil and Natural Gas Corporation (ONGC), is working to reduce methane emissions through awareness-raising workshops and capacity building initiatives. Since 2008, ONGC has been conducting measurement studies across seven company facilities with the greatest potential for emissions reductions. The company also mapped fugitive emissions from their facilities and is looking to develop a fugitive emission inventory (Global Methane Initiative, 2011).

Looking ahead, such industry-led improvements in technology mix and implementation of existing policies such as the PAT scheme will likely bring some reduction in emissions intensity. Nonetheless, technology transfer support, R&D to facilitate technology development and adaptation, using new technologies that suit Indian conditions, and the timely adoption of these technologies will be crucial for achieving the 'aggressive effort' targets in the industry (Planning Commission, 2011).

India is looking at setting up an ecosystem for green hydrogen production to slowly replace coking coal and natural gas in iron and steel production and act as chemical feedstock in production of fertilisers and chemicals (Srinivasan et al., 2023). The Union budget announced a Green Hydrogen Mission in 2023 with an outlay of INR 19,744 crore from 2023–24 to 2029–30 to make India a global hub for hydrogen production (GOI, 2023). However so far, the production and supply chain of green hydrogen is yet to take any kind of concrete shape (see Box 5.1).

The sharp decline in the prices of wind and solar technologies in recent years by about 60 per cent and 52 per cent, respectively, between 2010 and 2015 (in kWh terms) has led to a change in the relative importance of energy sources (NITI Aayog, 2017). Advancement in these technologies was one of the main reasons for reducing tariffs. EVs based on advanced battery technologies can achieve a faster reduction in costs; however, they would require large investments in R&D, demonstration projects and technology transfer (Dhar et al., 2017). They are found to be highly impactful opportunities in the medium-to-long term (Table 5.5).

5.4 Conclusion

India faces a pressing challenge as its greenhouse gas emissions continue to rise, having increased by 4.6 per cent from 2016 to 2019 and by approximately 115 per cent since 1994. The energy sector is the predominant contributor, accounting for about 76 per cent of total emissions and 93 per cent of CO_2 emissions in 2019. This underscores the critical need to decarbonise the energy sector, which not only impacts emissions but is also integral to India's broader development goals, such as poverty alleviation, increasing per capita income, employment generation, and boosting GDP growth.

Total CO_2 emissions must decline by about 46 per cent and 62 per cent by 2050 for the sustainable 2°C and 1.5°C scenarios to be realised, compared to a business-as-usual trajectory (Vishwanathan et al., 2017). This study estimates only 20 per cent CO_2 emissions reduction in Nationally Determined Contribution (NDC) scenario, highlighting the urgency for more ambitious national action. Achieving these reductions requires an average annual decrease in carbon intensity of 1.3 per cent for the 2°C scenario and 1.9 per cent for the 1.5°C scenario, compared to 0.15 pe cent under the NDC.

Transitioning to low-carbon pathways will need significant improvements in energy efficiency across both supply and demand, increased reliance on renewable energy, and demand reduction strategies through dematerialisation, recycling, and behavioural changes. Effective mitigation must incorporate supply and demand strategies across key sectors such as energy, urban development, land use, and industry, with technology serving as a crucial enabler of these transformations.

Renewable energy can drive mitigation efforts in the country. However, while India has made strides in expanding its renewable capacity, continuous policy efforts are essential for its grid integration and facilitating a supportive market for renewable electricity. Studies indicate that energy efficiency and renewable energy will play nearly equal roles in CO_2 mitigation under the NDC scenario, with lifestyle changes and carbon capture and storage (CCS) becoming increasingly relevant for deeper decarbonisation.

Supply-side strategies should include advancements in clean fuel technologies, such as biofuels and electric vehicles, along with the development of low-carbon building materials. On the demand side, interventions like enhancing energy efficiency in transportation, industry, and buildings are vital. This can be achieved through smart grid technologies, well-designed public transport systems, and sustainable urban planning. Recognising the interconnectedness of various sectors is key to optimizing mitigation actions. For instance, effective demand-side measures in transportation depend heavily on urban spatial planning and infrastructure, while construction practices impact the building sector.

Finally, fostering new low-carbon technologies, particularly those led by the private sector, will be essential for India's mitigation strategy. As seen with solar energy, technological advancements can reduce tariffs and offer several high impact opportunities across sectors. Innovations such as supercritical and ultra-supercritical power plants, integrated gasification combined cycle (IGCC) technologies, and CCS are promising avenues for emissions reduction. Additionally, the government's commitment to solar power and the development of green hydrogen are critical for decarbonising hard-to-abate sectors, ensuring both energy security and low-carbon growth for India's future.

6.

Feasibility Assessment of Adaptation and Mitigation Options

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6. Feasibility Assessment of Adaptation and Mitigation Options

- There is sufficient evidence on a range of feasible adaptation and mitigation strategies that are being and/or can be implemented at various scales across the country to achieve a 1.5°C-compatible climate future in India.
- Adopting the Climate Resilient Development (CRD) framework, this chapter assesses 23 adaptation and 16 mitigation options across key systems: land, oceans and ecosystems, urban and infrastructure, energy, industrial, and cross-cutting categories.
- In land, oceans and ecosystems transitions, suites of options are available, such as climate-resilient agriculture production (e.g., changing crop varieties or improved irrigation efficiency), sustainable and climate-proofed food supply chains, and incentivising food waste reduction.
- In urban and infrastructure systems, green and blue infrastructure-based options can meet adaptation and mitigation goals as well as Sustainable Development Goals (SDG), creating healthier and more liveable cities while reducing disaster risk and creating urban carbon sinks.
- In energy systems, solar photovoltaics (PV) and wind energy emerge as highly viable mitigation options, scoring high-to-medium feasibility across all the six assessed parameters. Other mitigation options, such as electricity storage, smart grids and power sector Carbon Capture and Storage (CCS), have medium feasibility due to institutional and technological challenges.
- Cross-cutting options—such as early warning systems, public health systems and, social security nets like the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) and the Public Distribution System (PDS)—that reduce vulnerability to climate change also offer high feasibility across multiple parameters. However, significant policy attention is required for options that are politically and geophysically challenging, such as planned relocation and migration.

6.1 Introduction

India needs a new development paradigm to chart its future growth trajectory and combat the twin challenges of development and climate action. This paradigm must help meet the country's aspirations to become an advanced economy while creating jobs, providing climate protection, and ensuring social and income security for its people. As discussed briefly in Chapter 3, the Climate Resilient Development (CRD) framework, negotiated by the Intergovernmental Panel on Climate Change (IPCC) across 193 countries in its Sixth Assessment Report (AR6), offers a new development framework to integrate sustainable development, climate adaptation, mitigation and biodiversity goals (IPCC 2022; 2023). The CRD provides a clear menu of mitigation and adaptation options that can be implemented within both national and local contexts. It can be operationalised through a systems approach that calls for simultaneous transitions across five key systems—energy, land, oceans and ecosystems, urban

Box 6.1 What is feasibility?

Feasibility denotes the possibility and the conditions that shape the possibility for specific climate actions (Allen et al., 2018). In mitigation, feasibility refers to the range of possibilities for an option. For example, studies discuss the feasibility of meeting long-term climate targets, such as limiting global warming to 1.5°C by 2030 and achieving net-zero emissions by 2050.

In adaptation, there are relatively fewer assessments of feasibility due to the disparate and highly localised nature of adaptation evidence, contradictory metrics for assessing adaptation possibilities, outcomes and effectiveness (Ford et al., 2013), and inadequate data on several aspects of feasibility such as adaptation costs, limits and behavioral constraints (Klein et al., 2014).

The feasibility assessment approach adopts a 'barriers perspective', which argues that low barriers to a certain adaptation option can indicate high feasibility (Singh et al., 2020). Notably, the feasibility of adaptation is distinct from adaptation effectiveness, which focuses on the goals and outcomes of planned and implemented adaptation.

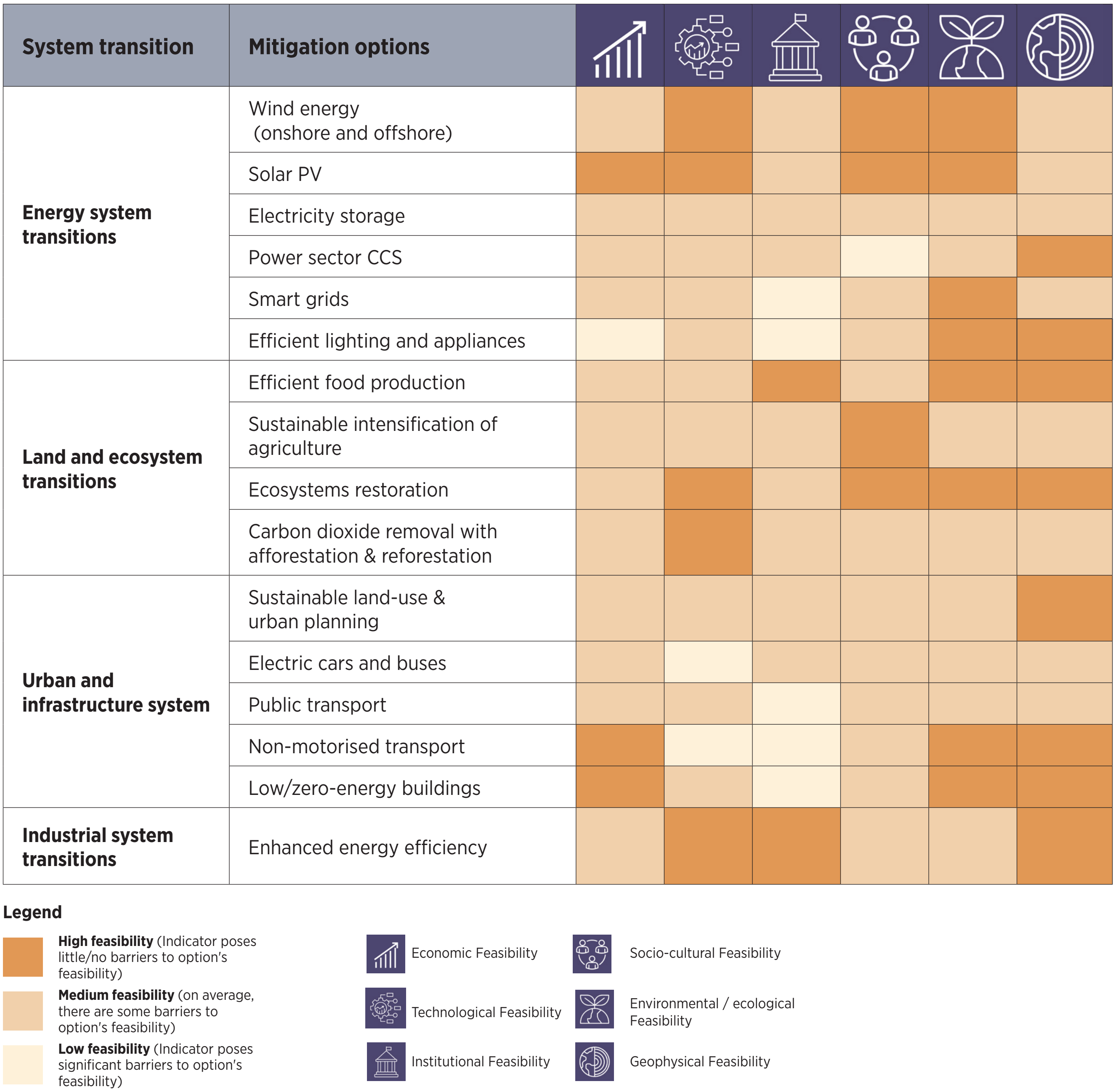
and infrastructure, industry, and societal—instead of siloed sectoral action. Using the CRD framework, this chapter undertakes a multidimensional feasibility assessment of 16 mitigation options and 23 adaptation options at the national scale, using the systems-framing approach across the first four transitions. We consider all the systems, except societal, for mitigation assessment, and for adaptation assessment, we consider land, oceans and ecosystems, urban and infrastructure, and a 'cross-cutting options' category. This category includes options such as disaster management, climate information services and health sector interventions, which are being planned and implemented across systems transitions.

Our feasibility assessment offers evidence-based, actionable pointers to policymakers and funders to implement adaptation and mitigation actions and their varied combinations to chart out the climate action trajectory for India to achieve the 1.5°C climate goal. This chapter synthesises a large but scattered literature on adaptation to offer insights on a subject that continues to be underplayed and underfunded in climate action. First, the chapter summarises the feasibility of 16 mitigation and 23 adaptation options across systems in section 6.2 with the help of Figures 6.1 and 6.2 and Table 6.1, highlights key findings, policy implications and knowledge gaps. Section 6.3 delineates the 16 mitigation options across key systems transitions, followed by a detailed feasibility assessment of the 23 adaptation options in section 6.4.

6.2 Feasibility of Mitigation and Adaptation Options

In this assessment, 16 mitigation options and 23 adaptation options relevant to India are considered within systems transitions. This assessment can help draw on combinations of these actions to best limit global warming and adapt to 1.5°C. Figure 6.1 summarises the feasibility assessment of 16 mitigation options relevant for the country across the four systems under study: energy, land, oceans and ecosystems, urban and infrastructure, and industrial. Figure 6.2 summarises the feasibility assessment of 23 adaptation options relevant to India, across two systems—land, oceans and ecosystems, urban and infrastructure—along with a 'cross-cutting options' category that runs across systems like public health and climate services. Table 6.1 summarises the key takeaways from these assessments along with policy implications and knowledge gaps.

Figure 6.1: Feasibility assessment of 16 Mitigation options



Note: CCS = Carbon capture and storage

Source: *Authors' assessment*

Figure 6.2: Feasibility assessment of 23 Adaptation options

System transition	Adaptation options	Economic Feasibility	Technological Feasibility	Institutional Feasibility	Socio-cultural Feasibility	Environmental / ecological Feasibility	Geophysical Feasibility
Land and ecosystem transitions	Conservation agriculture	High	Medium	Medium	Medium	High	High
	Agricultural diversification	High	Medium	Medium	High	High	Medium
	Improved cropland management	High	Medium	Medium	LE	LE	LE
	Improved grazing land management including reduced grassland conversion to cropland	High	High	Medium	High	High	LE
	Integrated soil management (soil salinization, mitigating soil erosion, reducing soil compaction, etc.)	High	Medium	LE	Medium	LE	LE
	Water use efficiency and water resource management	High	LE	Medium	Medium	High	Medium
	Efficient livestock	High	Medium	Low	Medium	Medium	High
	Agroforestry	High	High	Medium	High	High	High
	Biodiversity management, conservation	Medium	High	Medium	Medium	Medium	Medium
	Integrated coastal zone management including wetland, mangrove conservation	Medium	Medium	Medium	Medium	High	High
	Coastal defence and hardening	Medium	Medium	Medium	Medium	Medium	LE
	Sustainable aquaculture	High	Medium	Medium	High	Medium	Medium
Urban and infrastructure system transitions	Sustainable land-use & urban planning	Medium	Medium	Low	Medium	Medium	Medium
	Sustainable water management	NE	High	Low	Low	Low	Low
	Green infrastructure & ecosystem services	Medium	High	Medium	High	Medium	High
	Building codes & standards	Medium	High	Medium	NE	Medium	High
Crosscutting options	Disaster risk management	Low	Low	Low	Medium	Medium	Low
	Risk spreading, and sharing	Medium	Medium	Low	Medium	Medium	Low
	Climate services, including EWS	Medium	Medium	Medium	Low	High	Medium
	Indigenous knowledge	Low	High	Low	Medium	Medium	Medium
	Public health systems	High	High	Medium	Low	High	Medium
	Social safety nets (e.g., MGNREGA, PDS)	High	Low	Medium	High	Medium	Medium
	Resettlement, relocation and migration	Medium	Low	Low	Low	Low	Low

Legend

- **High feasibility** (Indicator poses little/no barriers to option's feasibility)
- **Medium feasibility** (on average, there are some barriers to option's feasibility)
- **Low feasibility** (Indicator poses significant barriers to option's feasibility)
- **NE** - No Evidence
- **LE** - Low Evidence
- Socio-cultural Feasibility
- Economic Feasibility
- Institutional Feasibility
- Environmental / ecological Feasibility
- Technological Feasibility
- Geophysical Feasibility

Note: EWS = Early warning system; MGNREGA = Mahatma Gandhi National Rural Employment Guarantee Act; PDS = Public Distribution System

Source: *Authors' assessment*

Table 6.1: Key takeaways on feasible options

System	Key Findings on Feasibility	Policy Implications	Knowledge Gaps
Energy	• All options demonstrate moderate-to-high feasibility, with solar PV and wind energy scoring high overall feasibility. Governance and institutional barriers remain in bioenergy, smart grids and efficient lighting/appliances.	• Strengthening governance and institutional enabling environment for energy systems is critical.	• No notable knowledge gaps reported, though more evidence on institutional and social barriers to energy options can improve feasibility and implementation.
Land, Oceans and Ecosystems	• Several adaptation options show moderate-to-high feasibility, notably agricultural diversification into climate-resilient crops/ varieties, conservation agriculture (including interventions such as climate-smart agriculture and zero-budget natural farming), agroforestry and improved grazeland management. • Reducing food wastage is a highly feasible option with mitigation and SDG co-benefits. • Ecosystem restoration emerges as a highly feasible strategy for meeting adaptation and mitigation goals.	• Existing government interventions on climate-smart agriculture, agroforestry and horticulture have resulted in high feasibility of these options, providing lessons for scaling up. • Certain measures such as integrated soil management face barriers of governance and public acceptance, and can be enabled by strengthening institutional capacity and public awareness. • Targeted action is needed in certain options such as livestock efficiency and coastal defenses to address geophysical barriers.	• There is low evidence on the environmental feasibility of grazeland and soil management, which requires evidence on how these options impact resilience and adaptive capacity. • Evidence exists on how dietary shifts have sociocultural and gendered barriers, but its link to climate resilience/ greenhouse gas footprints in the Indian context needs further research.
Cross-cutting Adaptation Options	• National and state policy thrust on providing social security and public services through MGNREGA, public health infrastructure, climate services and early warning systems are notable, driving the high feasibility of these options.	• Significant policy attention is required for options that are politically and geophysically challenging such as planned relocation and migration. • Dedicated policy and practice attention is needed to reimagine how scientific and indigenous knowledge systems can be leveraged collaboratively for inclusive and contextual risk management.	• Despite growing evidence on the climate change and migration nexus, gaps remain on almost all feasibility dimensions, especially on social, institutional and geophysical aspects.

Urban and Infrastructure	• Highly feasible adaptation options include green infrastructure options such as strengthening urban waterbodies, green spaces and building codes. • Energy-efficient buildings and non-motorised transport show high feasibility.	• There is a suite of feasible adaptation and mitigation strategies that can be mainstreamed into existing sectoral urban programmes such as 100 Smart Cities, National Urban Livelihoods Mission, Swachh Bharat Mission and Pradhan Mantri Awas Yojana. • Critical barriers include inadequate finance, poor political acceptability and thrust, and institutional capacity. These are severe gaps considering India's urban transition. • Climate-proofing key infrastructure is also an important intervention, where finance, technical capacity and context-appropriate interventions need immediate attention.	• Economic feasibility of sustainable water management and sustainable land use planning requires further evidence and quantification. • Certain infrastructural sectors such as aviation and shipping require more evidence on technological feasibility.
Industrial	• Improving industrial energy efficiency is a highly feasible option.		• Negligible evidence on the environmental and sociocultural feasibility of bio-based and circularity-based options as well as electrification and switching to hydrogen.

Note: MGNREGA = Mahatma Gandhi National Rural Employment Guarantee Act; SDG = Sustainable Development Goal

Source: *Vishwanathan et al., 2017*

6.3 Feasibility of Mitigation Options across Systems

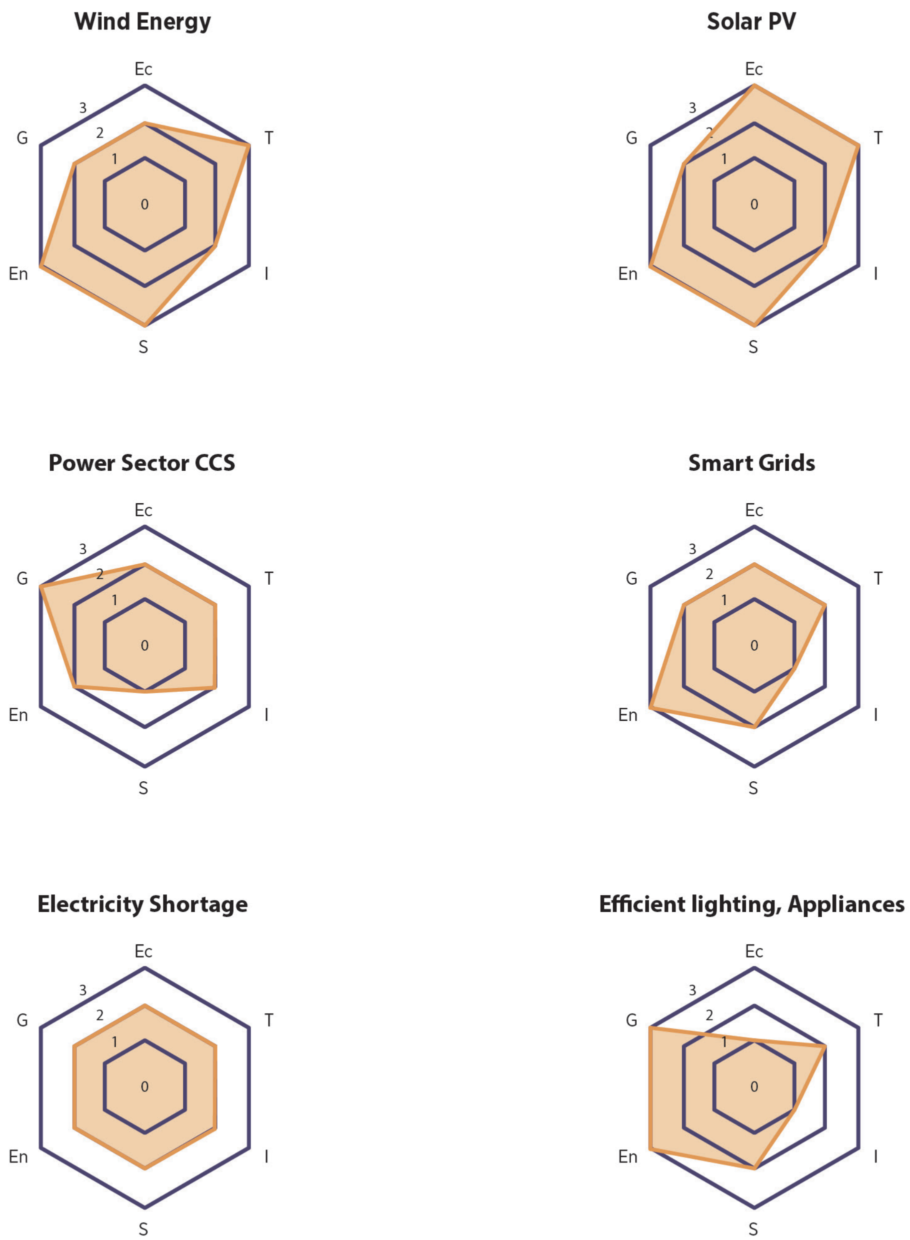
This section assesses the feasibility of 16 mitigation options relevant for India across four systems: energy, land, oceans and ecosystems, urban and infrastructure, and industrial (see Figure 6.1). The assessment shows high-to-medium feasibility for various mitigation options across systems, including for renewables like solar and wind under energy systems; ecosystem restoration under land, oceans and ecosystems; low-energy buildings and non-motorised transport (NMT) under urban and infrastructure systems; and energy efficiency under industrial systems. The assessment is discussed within the four systems transitions and six feasibility parameters: economic, technological, institutional, sociocultural, environmental and geophysical.

6.3.1 Energy systems

This section details eight options under the energy systems transition such as renewable energy and various aspects of power generation. While renewables such as wind energy and solar PV show high-to-medium overall feasibility, bioenergy has medium-to-low feasibility. Electricity storage has medium feasibility overall. The feasibility of power sector CCS and smart grids ranges from medium to low, and efficient lighting and nuclear energy show mixed scores, ranging from high to low across different indicators. These will be discussed further in the following sections.

Mitigation actions in India's power sector prioritise energy security by providing modern energy resource access and affordability for all, diversifying energy resources, and enhancing renewable energy contributions (Ministry of Environment, Forest and Climate Change [MoEFCC], 2021). As of 31 March 2024, India has achieved total installed renewable capacity of 138 gigawatt (GW; excluding hydropower) out of the 500 GW energy capacity target set for 2030 (Ministry of New and Renewable Energy, 2024). The adoption of various energy-efficient programmes, such as the UJALA LED scheme, Perform, Achieve and Trade (PAT) scheme, and Building Energy Efficiency Programme (BEEP), has led to an overall emission reduction of 44 Mtoe or about 6 per cent of the total primary energy supply of the country for the year 2021–22 (MoEFCC, 2023). The equivalent reduction in carbon dioxide (CO_2) emissions is around 281 million tonnes annually.

Figure 6.3: Feasibility of mitigation options under energy systems



Ec: Economic | **T:** Technological | **I:** Institutional | **S:** Social | **En:** Environmental | **G:** Geophysical

Note: CCS = Carbon capture and storage

Source: *Authors' compilation*

6.3.1.1 Wind energy

Wind energy is cost-effective in many locations (IRENA, 2018). The feasibility of renewable energy options largely depends on the geophysical characteristics of the area where the option is implemented. However, technological advances and innovative policy instruments are making renewable energy options increasingly attractive in almost all areas (Renewable Energy Agency, 2017).

By 2011, India had become the world's fifth-largest market for wind energy (BP, 2012), accounting for 10 per cent of the total 416 GW installed capacity in the country (MOEFCC, 2023). Many areas across India, such as Gujarat and Rajasthan, have high wind capacity, capable of generating up to 4 GW. However, there is considerable daily and seasonal flux due to variability in climatic conditions. This, combined with the lack of demand projections and advanced scheduling techniques, makes transmission difficult and results in significantly lower output (Sareen, 2018). Institutional feasibility for wind energy is medium, as small businesses looking to install wind turbines often face bureaucratic inconsistencies (Sareen, 2018).

6.3.1.2 Solar PV

Solar PV forms a significant part of India's target of achieving 500 GW of installed renewable power capacity by 2030 (MoEFCC, 2023). The economic feasibility of solar PV is high as the fuel cost is zero compared to other sources like coal, and variable costs such as operations and maintenance (O&M) are minimal (Council on Energy, Environment and Water [CEEW], 2019b). The levelized cost of electricity (LCOE) is therefore low, driven primarily by the capital cost (CEEW, 2019b; Shakti Sustainable Energy Foundation, 2020a). Currently, solar power makes for 17 per cent of the total non-renewable power capacity in the country.

India has adopted a hybrid approach to enhance solar power, balancing grid-connected and off-grid solutions. Off-grid solutions are largely tied to a specific demand, such as the Ministry of New and Renewable Energy's Off-grid and Decentralised Solar PV Applications Programme, which promotes the installation of LED-based solar street lights throughout the country (MoEFCC, 2021). More recently, in February, 2024, the government announced the PM Surya Ghar: Muft Bijli Yojana, a rooftop solar programme that aims to provide INR 7,500 crore in subsidies to install grid-connected rooftop solar systems for nearly one crore homes, enabling consumers to reduce their electricity bills and allowing them to earn money by selling excess power to the grid (Press Information Bureau [PIB], 2024; Reuters, 2024). This was envisaged to help India meet its commitment to triple renewable energy capacity by 2030.

There has been considerable innovation in the governance and institutional dimensions of solar power development in India. These advancements are largely due to an impressive target-oriented approach (i.e., the National Solar Mission), dedicated budgetary support to offset viability gaps (capital subsidies and other incentives like the Production Linked Incentive schemes (PLI), and substantial institutional backing through the enhanced capacity of institutions like the Solar Energy Corporation of India (SECI), Power Grid Corporation of India and Rural Electrification Agency (Haldar et al., 2024; Sovacool et al., 2021). A range of policy instruments aimed at price discovery have also been tested and progressively stabilised, such as auction mechanisms (Bose & Sarkar, 2019; Thapar et al., 2018).

The socioculturalfeasibility of solar PV is high, with broad social acceptability of solar appliances. However, challenges remain with larger installations, particularly regarding land acquisition and ensuring just transitions (International Energy Agency (IEA), 2020; Mohan, 2017; Stock, 2022; Yenneti et al., 2016;). Environmentally, solar PV is beneficial in many ways, including having a lower water footprint than other comparable alternatives (Shakti Sustainable Energy Foundation, 2020a).

6.3.1.3 Electricity storage

Electricity storage has medium feasibility overall. While the costs and technical maturity of battery storage are increasingly positive, challenges of resource availability and the environmental impact of production remain concerning (Peters et al., 2017). The use of electric vehicles (EVs) as a form of storage has been modelled and evaluated as a promising opportunity, with emerging demonstrations (Dhar et al., 2018; Green & Newman, 2017), but upscaling challenges persist. Institutional and governance arrangements to develop a robust electricity storage ecosystem are still evolving and are linked to ongoing experiments. Although social acceptability is gaining traction, it is constrained by market dynamics and retrofitting requirements in some cases (NITI Aayog, 2021; Parihar & Urele, 2021).

Globally, pumped storage accounts for almost 96 per cent of existing world storage capacity (World Energy Council, 2019). India has identified 63 sites with pumped storage potential of 97 GW, but only 4.8 GW is designed to function as pumped storage units (World Energy Council, 2019). As of March 2020, India has 3,305 megawatt (MW) of installed pumped storage capacity, with 1,480 MW being non-operational, 1,580 MW to be commissioned by 2022–23 and 8,380 MW proposed (Shakti Sustainable Energy Foundation, 2020b). In February 2020, Greenko Group and Renew Power won an auction conducted by SECI for 1.2 GW of solar, wind and energy storage.

Developments in the storage sector have predominantly focused on batteries, mainly due to the rapidly falling costs of lithium-ion (Li-ion) batteries worldwide. The deployment of large-scale battery energy storage in India began in 2017, with Power Grid Corporation of India Limited (PGCIL) commissioning its first pilot project to test different battery performances in Puducherry. Progress has been slow and limited, primarily due to high costs. However, in 2019, India commissioned its first and largest battery storage system of 10 MW in Delhi at the Tata Power Delhi Distribution Ltd. (TPDDL) substation, developed by AES and Mitsubishi Corporation. The same year saw numerous storage tenders, driven by a steep decline in Li-ion battery prices globally, fueled by growing demand for EVs. A report estimated the energy storage requirement for grid support at 17 gigawatt hours (GWh) by 2021 and a total potential of 190 GWh of stationary energy storage from 2019 to 2025, with approximately 16 per cent expected for grid-scale applications and the majority for behind-the-meter applications (Shakti Sustainable Energy Foundation, 2020b). According to the Central Electricity Authority (CEA, 2019), India will require about 34 GW/136 GWh of grid-connected battery storage by 2030 to support the ambitious target of 455 GW of renewable energy (Shakti Sustainable Energy Foundation, 2020b).

6.3.1.4 Power sector CCS

CCS in the power sector can contribute to cost-effective emissions reduction requirements for limiting warming to 1.5°C. CCS may also offer employment and political advantages for fossil fuel–dependent economies (Kern et al., 2016), but it may provide fewer co-benefits compared to other mitigation options that generate power. Therefore, CCS relies on climate policy incentives for its business case and economic feasibility. Evidence suggests that CCS in the power sector has medium feasibility.

CCS has not been realised at scale in India's power sector, primarily due to the incremental costs of capture and the under-development of transport and storage infrastructures, which are not sufficiently compensated for by market or government incentives (IEA, 2017a). In sites with high potential and low transportation and sequestration costs, such as depleted oil and gas wells, CCS is economically viable (Anandarajah & Gambhir, 2014). However, CCS has technological challenges as it has not been widely tested or deployed at a commercial scale and the associated risks are not yet well characterised (Giri & Tiwari, 2013). Therefore, its economic and technological feasibility shows mixed characteristics.

CCS technologies are widely perceived as costly to deploy and are not sufficiently understood by the public, which is further heightened because of gaps in information provided by the government and other institutions (Giri & Tiwari, 2013). As a result, social acceptance is relatively low due to a lack of awareness and information gaps (Giri & Tiwari, 2013).

6.3.1.5 Smart grids

India initiated the National Smart Grid Mission in 2014 (MoEFCC, 2021) to be implemented in two phases. The first phase (2014–2017) focused on deploying smart meters, renovating and modernising substations, implementing GIS, developing microgrids and creating EV charging infrastructure. The second phase aimed to improve equity and justice outcomes, enhance existing infrastructure, and increase efficiency (Ministry of Power, n.d.).

Smart grids are transformative, enabling significant efficiency gains in infrastructure, monitoring power flows, predicting storage requirements and dynamically managing demand responses. However, these benefits could lead customers to reduce or eliminate reliance on the broader grid, potentially increasing utility costs (Tongia, 2015). Thus, smart grids have medium economic feasibility.

The technological feasibility of smart grids is also medium. While technological innovation and advancements are critical for smart grid development, implementing premeditated interventions may lead to non-contextual or unnecessary interventions in new technologies (Kumar, 2019).

Institutional feasibility of smart grids is low, as social, financial and governmental interventions are central to 'smartness'. Multifaceted and relational socio-technical approaches are essential for building cost-effective, just, democratic and sustainable smart grids (Kumar, 2019). Progress is ongoing, with notable advancements through the Smart City Mission (Ministry of Urban Development, 2015).

6.3.1.6 Efficient lighting and appliances

To provide consumers with informed choices about energy savings and cost reduction, the Bureau of Energy Efficiency (BEE) initiated the Standards and Labelling scheme in 2006 (Chunekar, 2014). This scheme includes a star labelling programme for 26 appliances, 10 of which are under a mandatory regime (BEE, 2017; MoEFCC, 2021). In 2018–19, this programme achieved emissions reduction of 46 metric tonnes of carbon dioxide ($MtCO_2$) and energy savings of 56 billion units (MoEFCC, 2021).

In India, the phasing out of incandescent bulbs has been a success story of institutional innovation and market formation. Despite some challenges, India has successfully shifted its lighting load to LEDs (Chunekar et al., 2017), demonstrating economic feasibility for efficient lighting and appliances.

However, challenges remain in certain areas. For example, highly efficient fans with Brushless Direct Current (BLDC) motors and efficient blades are not yet commercially available in India. Barriers such as high purchase prices and lack of information (e.g., absence of labels recognising high efficiency) lead to limited adoption of these options (Shah et al., 2015). This is being addressed through the launch of the Energy Efficient Fans Programme (PIB, Ministry of Power, 2023), indicating growing economic, financial and institutional viability. The market penetration of efficient appliances also faces challenges, particularly in informal settlements. Households in these areas often prefer unrated appliances to save on upfront costs (Dubash et al., 2015). Innovative financing models are increasingly being employed to address this issue.

6.3.1.7 Nuclear energy

As of March 2023, there were 22 commercial nuclear reactors totalling 6.8 GW in India, with nuclear energy contributing about 3 per cent to the total generation of energy in the country over the past decade. By 2027, an additional capacity of 5.8 GW is expected to be commissioned, with the capacity of nuclear power generation to increase to 15.5 GW by 2030. This also means that the share of nuclear energy in the energy mix will continue to remain at around 2 per cent.

While technological feasibility for nuclear power is proven, uncertainties remain around nuclear fuel. Initial capital costs can drive the sellable power price to upwards of ₹7 per unit (Economic and Political Weekly [EPW], 2019), making it less competitive compared to coal and renewable energy. Additionally, the cost of establishing a nuclear plant is exceptionally high and can take decades to complete (EPW, 2019).There are ongoing debates about whether nuclear power is the best option for peak load management compared to hydropower, but the evidence is still evolving and remains inconclusive. Institutional arrangements and governance dynamics, particularly concerning the safe management and operation of nuclear power facilities, are still being strengthened.

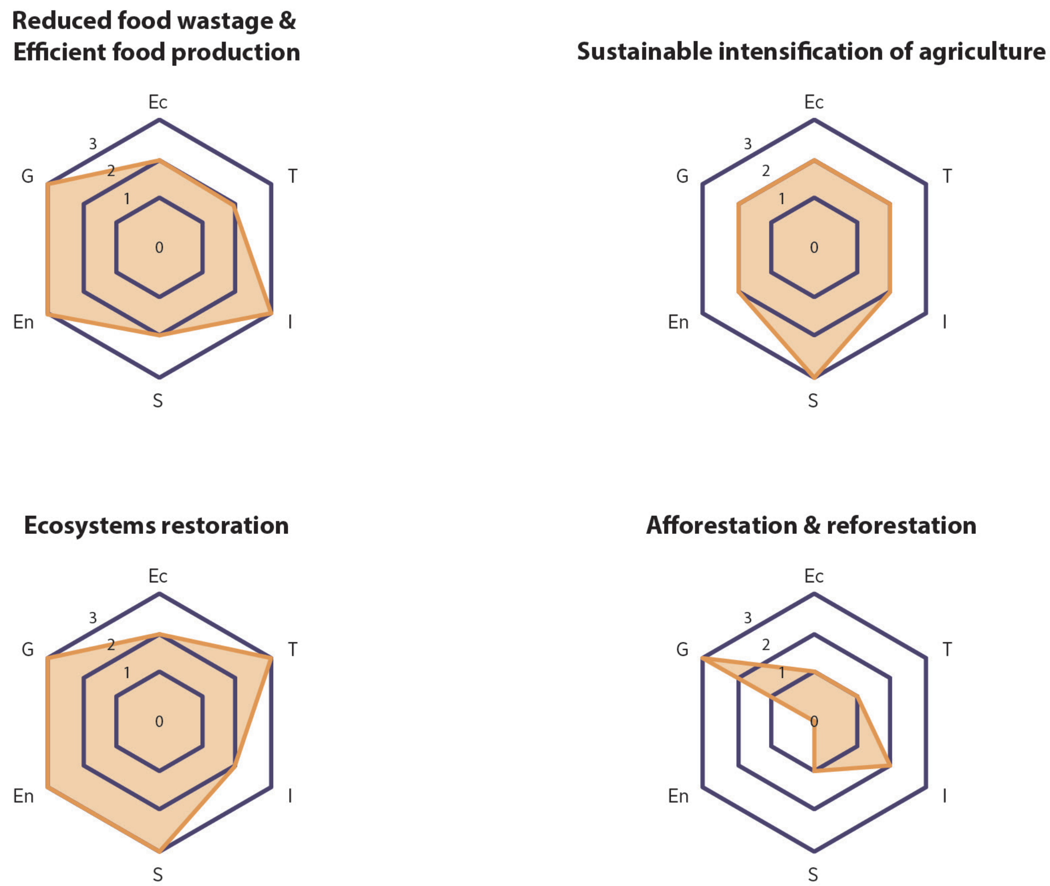
6.3.2 Land, oceans and ecosystems

The land, oceans and ecosystems transition encompasses three mitigation options: efficient food production, agricultural intensification and ecosystem restoration. The feasibility of efficient food production and ecosystem restoration ranges from medium to high overall. Sustainable intensification of agriculture shows mixed evidence, with most dimensions exhibiting medium feasibility.

Mitigation actions within land, oceans and ecosystems transitions include initiatives such as crop diversification, the System of Rice Intensification (SRI), food and nutrition security enhancement, and biodiversity protection. These initiatives contribute significantly to lowering emissions (MoEFCC, 2021). As part of the National Food Security Mission, SRI is being implemented in 24 states (MoEFCC, 2021). Between 2017 and 2019, a total of 33,487 hectares (ha) were brought under SRI (MoEFCC, 2021).

can lead to cost savings in areas such as labour and waste disposal. To lower diet-related disease burdens and reduce the environmental footprint of the food system, it is essential to improve food production efficiency and reduce food waste while promoting healthy diets (Green et al., 2018).

Figure 6.4: Feasibility of mitigation options under land and ecosystems



Ec: Economic | **T:** Technological | **I:** Institutional | **S:** Social | **En:** Environmental | **G:** Geophysical

Source: *Authors' compilation*

6.3.2.1 Efficient food production

Efficient food production and reduced food wastage exhibit medium-to-high feasibility overall. Elevated CO_2 concentration can alter food composition, impacting nutritional security (DaMatta et al., 2010; De Souza et al., 2015; Högy et al., 2009; Loladze, 2014; Taub et al., 2008), with varying effects depending on the region (Medek et al., 2017).

Economic feasibility shows mixed trends. Consumers' awareness of their food purchases and waste reduction

Increased food production has been linked to a decline in groundwater levels (Barik et al., 2017). There is a positive correlation between food production and electricity consumption, indicating a high dependency on groundwater-based irrigation, which leads to higher energy consumption (Barik et al., 2017). Methods such as using treated wastewater for agricultural activities sometimes yield higher productivity but could result in higher emissions than groundwater-based agriculture (Miller-Robbie et al., 2017).

India has consistently focused on improving efficiency across the water–energy–food nexus. Public programmes like PM Krishi Sinchayee Yojana and PM Kisan Urja Suraksha evam Utthaan Mahabhiyan Yojana (KUSUM) have created viable institutional and governance regimes to synergise this nexus, leading to medium-to-high feasibility of these nexus-oriented interventions. Social acceptability has also improved, enabled by agile institutional and governance dynamics (Integrated Research and Action for Development (Integrated RaDE, 2017; Ministry of Finance, 2023).

6.3.2.2 Sustainable intensification of agriculture

Sustainable intensification of agriculture involves increasing production per unit area while managing potential adverse environmental impacts (Pretty & Bharucha, 2014). It can enhance input efficiency, health and food security (Ramankutty et al., 2018). Evidence across economic, technological, institutional, environmental and geophysical parameters shows medium feasibility, with both positive attributes and trade-offs observed in agricultural practices.

Crop intensification of rice fallows with winter crops like chickpea, lentil and safflower and following conservation tillage practices can achieve higher system productivity, economic returns, energy use efficiency and reduced greenhouse gas (GHG) emissions (Kumar et al., 2020). This practice is economically viable and benefits soil health (Sapkota et al., 2019). However, there is often a shortage of skilled labour to implement practices like SRI effectively, increasing labour costs (Geethalakshmi et al., 2016). Water management options like sprinkler or micro-sprinkler irrigation offer viable technical mitigation options but require significant initial capital investment (Wassmann et al., 2004).

SRI has positive implications for livelihood security, improving economic and social conditions (Sapkota et al., 2019). It enhances food security, equitable access to food, effective food utilisation and social stability (Geethalakshmi et al., 2016). Thus, social feasibility is high for sustainable intensification of agriculture.

Environmental feasibility is medium, with evidence indicating both positive and negative impacts. SRI offers numerous benefits such as mitigating methane (CH_4) emissions from flooded rice soils. A study conducted in Tamil Nadu showed that methane emissions from an SRI plot were significantly lower compared to conventional practices (Geethalakshmi et al., 2016). Mitigating CH_4 emissions could improve soil properties by increasing carbon storage. However, nitrous oxide (N_2O) emissions were higher in SRI plots, representing a trade-off (Geethalakshmi et al., 2016). Sustainable intensification could minimise the crop yield gap without imposing environmental burdens, addressing a major challenge in Indian agriculture (Roth et al., 2018).

6.3.2.3 Ecosystems restoration

The feasibility of ecosystems restoration ranges from medium to high. The National Mission on Biodiversity and Human Well-Being exemplifies an integrated approach, combining biodiversity, ecosystem services, climate change, agriculture, health, bio-economy and capacity building. This mission effectively merges biodiversity conservation and management with sustainable development. By emphasising convergence and synergies among various goals, the mission has established an institutional mechanism to facilitate large-scale ecological management, restoration, and conservation agendas (Bawa et al., 2021). Consequently, this approach enhances the institutional and social dimensions of feasibility.

6.3.2.4 Carbon dioxide removal with afforestation and reforestation

Afforestation and reforestation exhibit medium feasibility overall. The National Mission for Green India (GIM), one of the eight national missions under India's National Action Plan for Climate Change (NAPCC), aims to double the area dedicated to afforestation and reforestation in India over the next decade as a primary climate mitigation strategy (MoEFCC, 2018).

The GIM, a part of the NAPCC, targets specific areas for agroforestry: 1.5 million hectares (Mha) of degraded agricultural lands and fallows; 0.8 Mha under improved agroforestry practices on existing lands; and an additional 0.7 Mha of new lands under agroforestry. The majority of India's carbon sequestration potential through afforestation will come from agroforestry on agricultural lands, given extensive cultivation across the country (Murthy et al., 2013).

Various afforestation and reforestation programmes have been active in India including social forestry since the early 1980s, the Joint Forest Management (JFM) programme since 1990, afforestation initiatives under the National Afforestation and Eco-development Board (NAEB) since 1992, and plantation forestry initiated by private farmers and industries (Ravindranath et al., 2008).

To derive economic benefits from afforestation and reforestation initiatives and to enhance their economic viability, a well-crafted strategy is essential. The emerging domestic carbon market presents a viable avenue. Additionally, in urban areas, afforestation efforts need to align with urban transformation initiatives. For instance, the Government of India's recent urban infrastructure improvement programme, the Atal Mission for Rejuvenation and Urban Transformation (AMRUT), incorporates provisions for urban greening. This is particularly valuable in light of increasing heat risks in cities, necessitating coordinated efforts across multiple institutional frameworks.

6.3.3 Urban and infrastructure systems

The urban and infrastructure systems transitions detail six mitigation options across urban planning, transportation (both motorised and non-motorised) and low/net-zero energy buildings. The feasibility of sustainable land use and urban planning ranges from medium to high overall, while energy-efficient transport options mostly show medium feasibility, with some parameters indicating low feasibility. Non-motorised transport options exhibit a mixed feasibility score, ranging from low to high based on context.

India's mitigation actions in the transport sector have focused on both structural and fuel-oriented strategies. For example, India progressed from Bharat Stage (BS) IV emission norms to BS VI norms in 2020 (MoEFCC, 2021). Notable interventions and programmes in the transport sector include the National Green Highways Mission, the Bus Rapid Transit programme and the National Electric Mobility Mission Plan. In aviation, the adoption of the Carbon Accounting and Management System (CAMS) aims to reduce GHG emissions at airports and facilitate the quantification and reporting of these emissions (MoEFCC, 2018; 2021). In the buildings sector, regulatory codes such as the National Building Code (NBC), which sets standards for construction activities across the country, and the reformed and updated Energy Conservation Building Code (ECBC) have been established (MoEFCC, 2021).

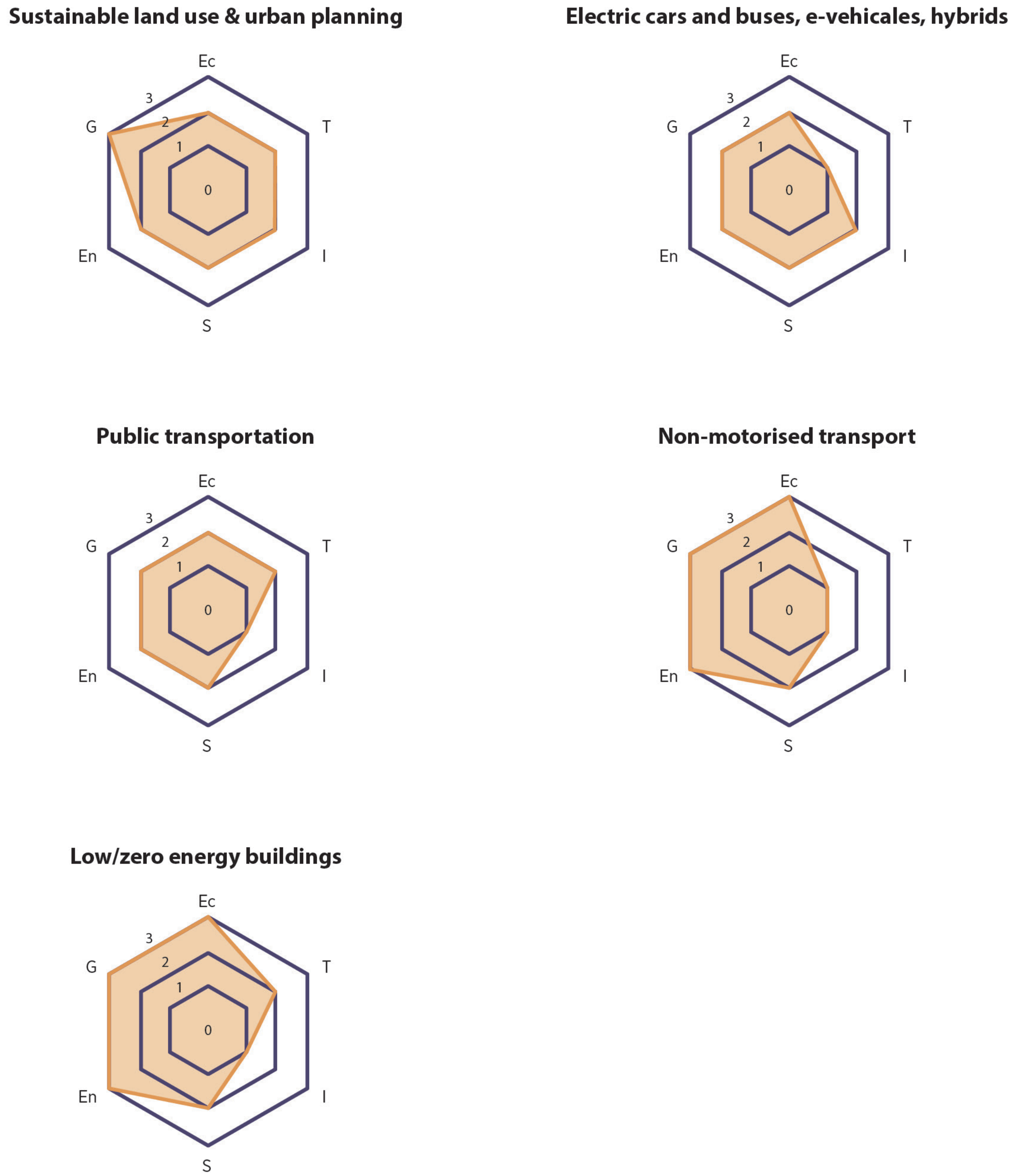
6.3.3.1 Sustainable land use and urban planning

Land use and urban planning exhibit medium overall feasibility. Designing public transit–oriented urban settlements offers multiple economic, social and environmental benefits, which are well documented. Indian cities have experienced considerable densification of urban regions, resulting in increased mobility demand due to ongoing structural transformations. This shift needs to be appropriately managed, particularly from a GHG mitigation perspective. Evidence around enhancing public transport and mass transit facilities is encouraging but requires expansion (Doll & Balaban, 2013; Grazi et al., 2008; Jain et al., 2016; Li, 2011; Maitra & Sadhukhan, 2013; Yang et al., 2020).

The literature on low-carbon transitions shows that population and infrastructure concentration in cities can foster innovative approaches to energy consumption and grassroots mitigation technologies. However, these efforts are challenged by mismatches between jurisdictional and ecological boundaries (Cook & Chu, 2018). Many climate actions require collaboration across jurisdictional boundaries, but most cities are fragmented with political boundaries dividing contiguous metropolitan regions (Cook & Chu, 2018).

Urban climate actions are often driven by immediate and local development needs (Khosla et al., 2019; Sethi & Puppim de Oliveira, 2018), partly because city leadership tends to prioritise development (Khosla et al., 2019). However, city-level actions in India depend largely on state and national directives (Khosla et al., 2019; Sharma & Tomar, 2010). Spatial planning can influence modal choice decisions and subsequently increase the share of public transport or cleaner transport. Cities like Kolkata, Pune and Delhi have set targets of achieving a 90 per cent modal share of public transport through their comprehensive mobility plans and master plans (Roy et al., 2018).

Figure 6.5: Feasibility of mitigation options under urban and infrastructure systems



Ec: Economic | **T:** Technological | **I:** Institutional | **S:** Social | **En:** Environmental | **G:** Geophysical

Source: *Authors' compilation*

A health impact assessment of six cities estimated the effects of alternative land use and transport policy initiatives. Modelling land use changes to enable a compact city with increased density and diversity, and reduced distances to public transport resulted in health gains for all cities (Stevenson et al., 2016). In Bengaluru, studies show that street trees significantly impact microclimatic buffering (Vailshery et al., 2013). Suspended particulate matter (SPM) levels for road segments with and without trees range between 40–60 µg/m3 and 150–300 µg/m3, respectively (Vailshery et al., 2013). In Nagpur, per capita green space of 31 sq. m correlates with lower concentrations of sulfur dioxide (SO2), nitrogen dioxide (NO2) and respiratory suspended particulate matter (RSPM) within permissible limits. Zones with better tree cover showed lower SO2, NO2 and RSPM concentrations as compared to zones with poor tree cover (Avni & Chaudhry, 2016; Murthy et al., 2013).

Sustainable land use and planning have immense potential for GHG reduction but face two structural challenges: centralised planning decisions and persistent institutional coordination efforts. These realities constrain institutional, including governance and social feasibility. Long-term city development plans, like master plans, have been ineffective from a climate perspective. Efforts are underway to create a template for long-term spatial planning and climate concern integration, but this will require effort (Brihanmumbai Municipal Corporation [BMC], 2022; Bruhat Bengaluru Mahanagara Palike [BBMP], 2023).

6.3.3.2 Electric cars and buses

Electric cars and buses show medium feasibility, with both positive and negative aspects across most indicators, except for technological feasibility, which is low. Evidence demonstrates the economic viability of electric cars and buses (Shakti Foundation & India Smart Grid Forum (ISGF(, 2017), with adequate support for viability gap funding (Global Green Growth Institute (GGGI), 2014) and enhanced human well-being through alternative livelihoods (Chandran & Brahmachari, 2015). Electric buses with a 100 kilowatt-hour (kWh) battery are highly cost-effective to own and can operate for more than ten years, with net savings of ₹70 lakh (almost the initial capital cost of a diesel bus) based on net present value.

Technological feasibility is low, with scalability and maturity showing lower trends. The phased adoption of EVs is expected to affect the entire automobile industry supply chain. Major value drivers like batteries, motors, controllers, chargers and other electronics are currently imported, although PLI schemes have altered the landscape (Gupta et al., 2021; Observer Research Foundation, 2024; Ministry of Commerce & Industry, 2024; Tripathy & Dastrala, 2023). Even in the least favourable scenario, where India imports all its li-ion cells and assembles battery packs, 25–40 per cent of the economic opportunity in battery manufacturing for India's EV ambitions can be captured domestically (Federation of Indian Chambers of Commerce and Industry (FICCI) & Rocky Mountain Institute (RMI), 2017). Advanced battery technologies can achieve faster cost reductions but require large investments in research and development (R&D), demonstration projects, and technology transfers (Dhar et al., 2016).

EV batteries are costly, heavy and bulky, and contain hazardous chemicals. The distance between battery factories and assembling units is crucial to keeping logistics, freight and insurance costs under control (BEE & EY, 2019). Battery management systems are critical for all chemical compositions, but they are essential for li-ion batteries as they pose a fire risk at high temperatures. This is particularly relevant for regions in India experiencing extreme summer temperatures, increasing the risk of EV battery fires (Shakti et al., 2019).

The Indian government has announced ambitious targets for vehicle electrification by 2030, with several states responding with sub-national policies, strategies and plans, although results have been mixed across vehicle segments (Dhar et al., 2020). Given the public value of shifting to electric mobility, it presents a strong case for public agencies to formulate supportive policies and regulations. Consequently, various central, state and local governments have initiated policies and plans to increase EV uptake (Shakti et al., 2019). Legal provisions have been made for charging points in residential and commercial properties, indicating modifications to building/property rules to establish a robust public charging infrastructure (Shakti et al., 2019; World Economic Forum, 2019).

According to the International Energy Agency, EVs are expected to have 35–45 per cent lower emissions than conventional internal combustion engines. Introducing EVs as a last-mile connectivity option could significantly reduce local air pollution and associated health issues (ICLEI & Shakti Foundation, 2019).

The shift towards greater adoption of EVs can result in a cumulative reduction of around 98 $MtCO_2$ between 2015 and 2030, and 1,155 $MtCO_2$ between 2015 and 2050 (Gupta et al., 2018). EVs can deliver significant local air quality benefits in the short and medium term (Shukla et al., 2015). In the 2°C and 1.5°C scenarios, EV diffusion will further reduce PM2.5 emissions to less than half of 2015 levels (Dhar et al., 2016). Introducing electric buses in public transportation systems will not only reduce particulate matter concentration in the air, but also reduce congestion and save lives (CSTEP & GGGI, 2016; Dhar et al., 2016; GGGI, 2014; NITI Aayog & Rocky

Mountain Institute, 2017). Significant co-benefits emerge from a strong alignment with electric mobility options (Agora Verkehrswende, GIZ, 2023; Bazaz et al., 2022; Climate Action Tracker, 2020; Kamboj et al., 2022).

6.3.3.3 Public transport

Economic feasibility for public transport shows mixed evidence, indicating medium feasibility. Many studies in India highlight the benefits of a robust public transport system, including social acceptance, equity and local pollution reduction. Despite this, institutional inertia and lack of effective investment have constrained development. An overemphasis on NMT without balancing public transport has increased GHG emissions in the sector. Coordinated actions are needed to expand and densify the sector while reducing its GHG footprint.

Initiatives such as subsidies under the Faster Adoption and Manufacturing of Electric Vehicle (FAME) scheme for 5,595 electric buses encourage clean mobility in public transport (PIB, 2019). Balancing metro-based and bus-based transit systems is essential, as metro rail projects are significantly more capital-intensive than Bus Rapid Transit Systems (BRTS) (Sharma et al., 2013). While BRTS is promoted as a low-cost alternative, it is not yet accessible to the urban poor, particularly women (Mahadevia et al., 2013). The World Bank estimates that 1,000 km of new BRTS corridors in 20 Indian cities could create 50,000–90,000 short-term jobs and 128,000 permanent jobs (Gota & Mejia, 2018).

As EV manufacturing expands in India, jobs will need to adapt to new systems, with state policies focusing on creating new job opportunities (Shakti Sustainable Energy Foundation et al., 2019). Electric buses are already deployed on a large scale globally, with mature and evolving technology (The Centre for Study of Science, Technology and Policy (CSTEP) & GGGI, 2016). The market for EVs is growing, with significant expansion anticipated (IEA, 2020). Technological innovation is crucial to reduce costs of hybrid and electric public transport vehicles (The Energy and Resources Institute (TERI), 2015).

Institutional feasibility remains low despite gains from the National Urban Renewal Mission (NURM) and National Urban Transport Policy (NUTP) agendas, strengthened by subsequent urban programmes (Mahadevia et al., 2013). There is growing interest in rail-based systems to meet the mobility needs of expanding urban populations (Goel et al., 2015). However, other mass rapid transport modes like BRTS, monorail and light rail transit lack legislative support, leading to coordination and integration issues within urban transport governance (IIHS, 2015). The lack of institutional arenas to examine investment, infrastructure maintenance and regulation concerns further hinders the system's responsiveness (National Transport Development Policy Committee, 2014). Innovation and interventions in service delivery can reduce the need for private transportation and facilitate mass transit (Roy et al., 2018).

Early interventions in BRTS and metro corridors can prevent carbon-intensive infrastructure lock-ins and deliver environmental and health co-benefits from improved air quality, like in Ahmedabad (Dhar et al., 2016). Introducing electric buses will reduce particulate matter concentration and congestion, and save lives (CSTEP & GGGI, 2016; Dhar et al., 2016; GGGI, 2014; NITI Aayog & Rocky Mountain Institute, 2017).

6.3.3.4 Non-motorised transport

Promoting NMT such as walking and biking can significantly reduce infrastructure and operating expenses, freeing financial resources (FICCI & RMI, 2017). Substituting 50 per cent of short-distance work trips with NMT could save ₹27 billion in fuel expenses, with most savings from two-wheelers and cars (TERI, 2018). Providing bicycles to unskilled workers could save ₹112 billion in travel time annually, increasing work hours by 23 million (TERI, 2018). Since even subsidised transportation options remain inaccessible to many low-income groups working in the informal sector, cycling and walking are often the only modes of transport available to them (Rahul & Verma, 2018)calculation of the explanatory indicators for the scenarios before and after providing NMT infrastructure, and determination of the sustainability impact. The proposed framework is then used to determine the sustainability impact on providing NMT infrastructure inside the Central Business District (CBD. Strengthening the bicycle industry would create jobs and promote inclusive growth. Hence, economic feasibility and related social dimensions are high for NMT.

Technological feasibility for NMT is low due to multiple risks. Instead, pedestrians face significant risks from buses and cars. Safe crossings and pedestrian infrastructure are essential for road safety (Tiwari, 2015). Despite national policies encouraging walking and cycling, infrastructure like designated lanes and footpaths are often missing, making travel unsafe (Embarq India, 2014). Poor footpath conditions force people to walk on roads, increasing accident risk (Kapoor, 2019; Mahadevia, 2015; Shah et al., 2017). Knowledge gaps also exist in scaling up and maturing NMT technologies.

Institutional feasibility is low despite political acceptability. The NUTP encourages greater use of public transport and NMT, but local authorities lack the decision-making power and financial resources for this (CSTEP, 2015). An analysis of the transport budget shows minimal prioritisation of NMT (Sum Net India & Shakti Foundation, 2017). A review of public transport taxation and expenditures indicates a preference for private cars and rail systems. Despite pro-bus and pro-cycling rhetoric, the NURM allocated most of its funding to road widening and construction of flyovers, with minimal support for NMT infrastructure (IIHS, 2015). Further, urban transport planning and provision suffer from untrained manpower and a shortage of qualified staff (IIHS, 2015).

Social feasibility is medium, with high health benefits but low human capabilities. Providing bicycles can enhance student attendance and academic performance, increase visits undertaken by healthcare workers, and offer a safer mode of transport for women (World Bicycle Relief, 2019). Enhancing income potential, school enrollment rates and women's socio-economic status are notable benefits (TERI, 2018). Promoting healthy lifestyles through active transport options like cycling is critical in countering sedentary lifestyle diseases (TERI, 2018), which has been a focus area for Indian climate action as indicated through the LiFE mission (MOEFCC, 2022). Most state- and city-level agencies dealing with urban transport planning and provision suffer from overstaffing of untrained, unskilled manpower on the one hand and shortage of qualified technical staff and managerial supervisors on the other (IIHS, 2015), indicating a lack of institutional and governance related preparedness.

Environmental and geophysical feasibility is high for NMT. Substituting 50 per cent of two-wheeler and four-wheeler trips could save ₹241 billion over ten years and significantly reduce air pollution (TERI, 2018). NMT infrastructure will benefit all city sizes by reducing fuel consumption and vehicular emissions (Goel et al., 2015).

6.3.3.5 Low/net-zero energy buildings

The United Nations Environment Programme (UNEP) estimates that improving embodied energy, thermal performance and direct energy use of buildings can reduce emissions by 1.9 giga tonnes of carbon dioxide equivalent ($GtCO_2e$) yr−1 (UNEP, 2017), with an additional reduction of 3 $GtCO_2e$ yr−1 through energy-efficient appliances and lighting (UNEP, 2017). Further enhancements in energy efficiency of appliances and improvements in lighting, heating and cooling systems offer substantial potential for savings (Garg et al., 2017; Parikh & Parikh, 2016). Net-zero energy buildings exhibit varying feasibility across indicators, with high feasibility in economic, environmental and geophysical aspects, medium feasibility in technology and social dimensions, and low feasibility in institutional dimensions.

The economic feasibility of net-zero energy buildings is high. Savings primarily arise from reduced operational costs, carbon credits, and potentially higher rental or capital values (Sharma & Rajput, 2017). Building thermally comfortable housing is crucial for resilience, particularly for the urban poor, who are vulnerable to climate impacts like increased temperatures and urban heat islands due to inadequate housing and services (Kumar, 2019; Shakti Foundation, 2018). Significant research highlights barriers such as extended payback periods, attributable to poorly designed incentives and market rules (International Finance Corporation, 2023).

Institutional feasibility remains low in the net-zero energy building sector. Implementation relies on multiple regulatory instruments and departments at state and city levels. Success hinges on existing frameworks, policies, and the capacity of states and cities. Substantial gaps exist due to outdated or absent master plans and city development plans in some states compared to more progressive ones, requiring a medium-to-long-term perspective for resolution (Kumar, 2019; Shakti Foundation, 2018).

The social benefits of low-emission and green buildings are multifaceted, contributing positively across various scales. Improved working conditions enhance occupant productivity and reduce health issues (Sharma & Rajput, 2017). While research on thermally comfortable design and construction practices is extensive, integration into policy and housing development projects remains insufficiently mainstreamed (Kumar, 2019; Shakti Foundation, 2018).

Net-zero energy buildings demonstrate high feasibility from an environmental and geophysical standpoint, provided that clear metric systems are in place to account for their diverse environmental benefits (Khosla et al., 2017).

The NITI Aayog (2017) recommends strengthening the ECBC through periodic revisions in order to promote its wider adoption, enhance urban planning, and encourage transitioning to high-efficiency lighting technologies and appliances. Failure to significantly improve new building energy performance risks limiting India's building sector's mitigation potential amidst increasing construction rates and electricity demand (Graham & Rawal, 2019).

6.3.4 Industrial systems

The feasibility of mitigation options in industrial system transitions focuses on energy efficiency as a means to reduce emissions. Transitioning to low-carbon industrial production in hard-to-abate industries such as steel, cement, and chemicals requires new technologies that are still being explored. In India, regulatory and legislative initiatives for energy efficiency, including the Energy Conservation Act (ECA), the PAT scheme, and the National Mission for Enhanced Energy Efficiency (NMEEE) have been fairly successful.

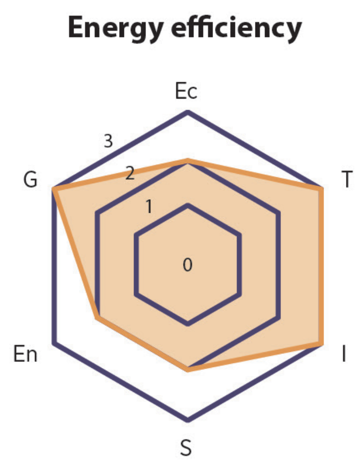
6.3.4.1. Energy efficiency

The feasibility of energy efficiency initiatives varies from medium to high across economic, social, environmental, technological, institutional and geophysical aspects. The ECA, 2001 underwent significant amendments in 2010, and more recently in 2022, introducing stringent compliance norms to enhance energy efficiency. The operational framework of the revised ECBC has been actively implemented since then. For instance, through energy efficiency lighting programmes, sales of compact fluorescent lamps (CFLs) increased from 7.8 per cent of total lighting requirements in 2005 to 37 per cent in 2014 (MoEFCC, 2018).

The NMEEE serves as a comprehensive framework, guiding energy efficiency improvements in India. It aims to bolster the energy efficiency market through conducive regulatory and policy measures, and fostering innovative and sustainable business models. NMEEE encompasses four key initiatives: PAT scheme; Energy Efficiency Financing Platform; Market Transformation for Energy Efficiency; and Framework for Energy Efficient Economic Development. The PAT scheme, launched under NMEEE in 2008 to enhance energy efficiency in the industrial sector in its first three cycles, achieved significant energy savings of 24.5 Mtoe and avoidance of approximately 99 $MtCO_2$ emissions (MOEFCC, 2023).

Energy efficiency in the industrial sector demonstrates high feasibility on economic, environmental and geophysical dimensions, while scoring medium on institutional, governance and social dimensions. To fully realise the dual benefits of energy savings and carbon reduction, a coordinated approach is crucial and remains a work in progress. This necessitates aligning regulatory and institutional frameworks, alongside addressing social dynamics such as generating incremental employment across production and consumption value chains.

Figure 6.6: Feasibility of mitigation options under industrial systems



Ec: Economic | **T:** Technological | **I:** Institutional | **S:** Social | **En:** Environmental | **G:** Geophysical

Source: *Authors' compilation*

6.4 Feasibility of Adaptation Options across Systems

This section assesses the feasibility of 23 adaptation options relevant for India across two systems: land, oceans and ecosystems, and urban and infrastructure, as well as a cross-cutting category with options that span across systems (see Figure 6.2). The assessment shows high-to-medium feasibility for many of the 12 adaptation options under land, oceans and ecosystems, including conservation agriculture, agroforestry and agriculture diversity, that are being practised with some success in various states. The four options examined under urban and infrastructure systems—sustainable land use planning, green infrastructure, sustainable water management and building codes—have high technical feasibility but are constrained due to institutional barriers. Green infrastructure has high feasibility across technical, economic and environmental parameters. Under the cross-cutting category, seven adaptation options are analysed, of which social safety nets like MGNREGA and PDS as well as early warning systems have overall high-to-moderate feasibility across parameters.

6.4.1 Adaptation options for land, oceans and ecosystems transitions

This section assesses 12 adaptation options for land, oceans and ecosystems transitions, which include agriculture, forest and coastal ecosystems, against a set of six parameters, that is, economic, technological, environmental, social, institutional and geophysical. Agricultural options such as conservation agriculture, agricultural diversification, grazing land management and agroforestry have high-to-medium overall feasibility (see Figure 6.4). The efficient management of resources such as water offers multiple co-benefits including higher income, disaster risk reduction and livelihood diversification. Biodiversity management and coastal adaptation options have medium feasibility, with evidence suggesting that a mix of infrastructural and nature-based interventions are most feasible.

6.4.1.1 Conservation agriculture

Conservation agriculture is a set of farming practices that promotes minimum soil disturbance (no/low tillage), maintenance of permanent soil cover and diversification of plant species (Food and Agriculture Organization [FAO], 2017). In India, these practices include zero-budget natural farming, permanent bed and zero tillage, and zero tillage dry-seeded rice/wheat (Bhan & Behera, 2014).

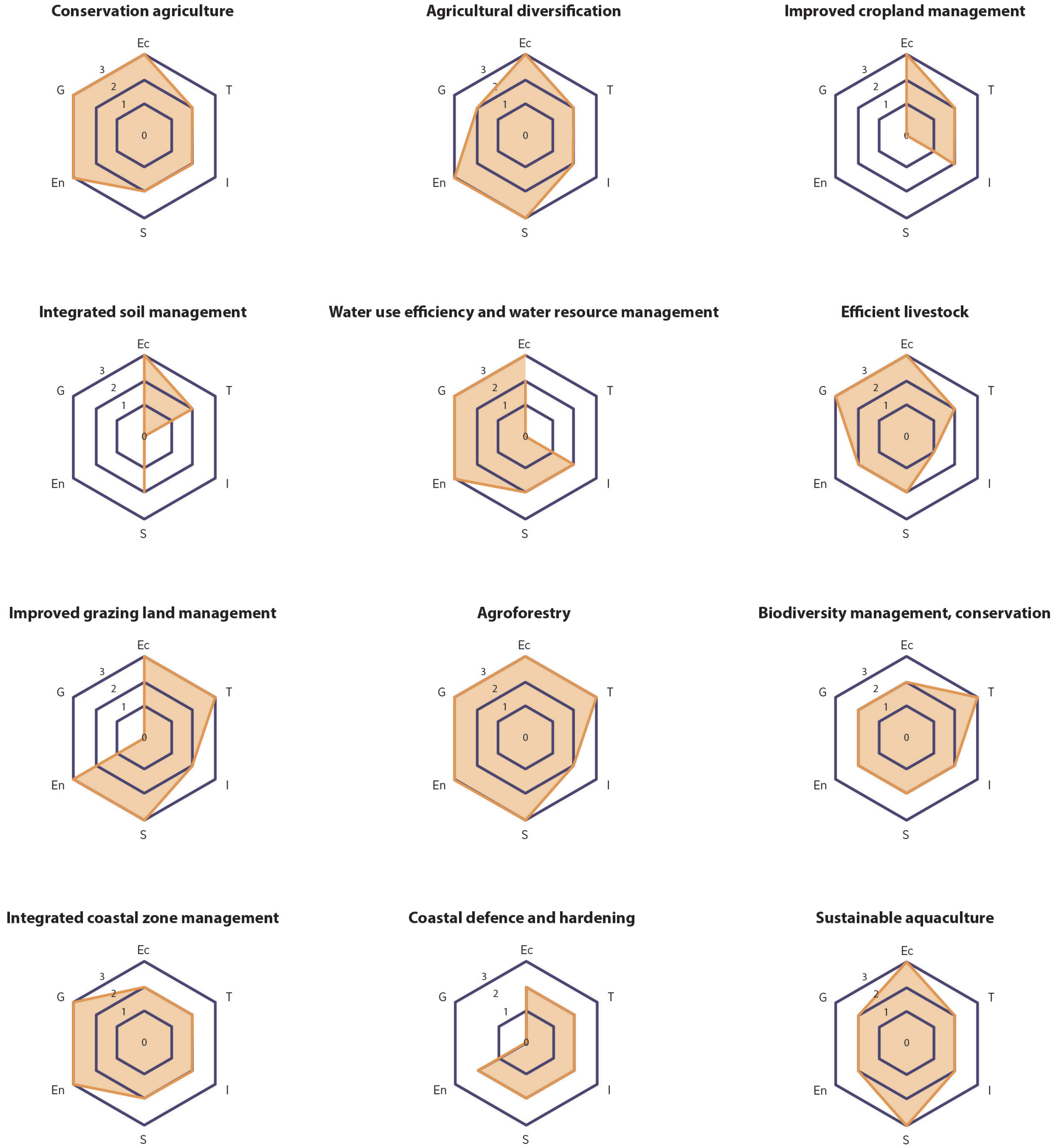
Overall, conservation agriculture practices have high economic feasibility due to higher net profits from reduced production costs, significant water, energy and labour savings, and higher yields (Bharucha et al., 2020; Jat et al., 2014b). Evidence from the Indo-Gangetic Plains, the North Eastern Region, north-western India and Andhra Pradesh highlights these economic benefits (Ghosh et al., 2010; Jat et al., 2014b; Parihar et al., 2016).

However, its adoption is constrained by gaps in locally relevant technical know-how and inadequate extension services such as farmer training and on-farm demonstrations (Kumar et al., 2011b). State extension services are often understaffed or inadequately trained to address the diverse social-ecological challenges faced by smallholders, particularly in dryland systems (Bharucha et al., 2020; Sapkota et al., 2015). Political acceptability is high at both national and state levels (e.g., Haryana and Andhra Pradesh), with dedicated programmes incentivising conservation agriculture, though these policies need scaling up (Aryal et al., 2016).

There is strong evidence that conservation agriculture improves nutrition, reduces health hazards and environmental pollution, and has intergenerational benefits by contributing to future income needs and sustainable resource use (Parihar et al., 2016; Pradhan et al., 2016). Sociocultural acceptance varies, with farming communities in north-western India and the Indo-Gangetic Plains being more receptive than those in Haryana (Aryal et al., 2016; Bhan & Behera, 2014; Pradhan et al., 2016).

Conservation agriculture also restores natural resources, improves soil health, and reduces soil erosion and water use (Bhan & Behera, 2014; Bharucha et al., 2020; Ghosh et al., 2010). It has strong mitigation synergies as it has reduced the use of fossil fuels, pesticides and other pollutants (Jat et al., 2019; 2011; Naresh et al., 2013). Additionally, it builds adaptive capacities in farming systems, especially for extreme events such as droughts and excessive rainfall. Adoption of these practices has

Figure 6.7: Feasibility of adaptation options under land and ecosystems transitions



Ec: Economic | **T:** Technological | **I:** Institutional | **S:** Social | **En:** Environmental | **G:** Geophysical

Source: *Authors' compilation*

been increasing over the past 8–10 years in India (Bhan & Behera, 2014), with zero tillage being a success story in north-western India, although uptake remains uneven (Aryal et al., 2016).

6.4.1.2 Agricultural diversification

Agricultural diversification includes practices such as diversifying crop types and cropping practices (e.g., intercropping and crop rotation). It also involves agricultural income diversification and resource diversification (Jha et al., 2015).

Overall, agricultural diversification enhances incomes and reduces poverty (Jat et al., 2012; Khatri-Chhetri et al., 2016; Mandal & Bezbaruah, 2013). However, its impact diminishes beyond a threshold due to constraints such as limited capital for smaller farms and limited labour for larger ones (Birthal et al., 2015). Local ecology, crop choice and farmland size influence the income gains from crop diversification. The shift from paddy to pulses, oilseeds and high-value crops in upland rainfed areas shows the most promise (Reddy, 2013). In specific regions like the Eastern Ghats and the Northern Plateau of Odisha, and in the hard rock areas of south India, larger farms, owner-operated farming and diversified cropping patterns yield higher average profit efficiencies (Manjunatha et al., 2013; Reddy, 2013).

There is limited evidence on the technical viability of agricultural diversification due to inadequate infrastructure such as reliable water supply, markets, fertiliser availability and post-harvest facilities (Acharya et al., 2011; Manjunatha et al., 2013). The feasibility of agricultural diversification is strongly influenced by institutional capacity and policy support, with increasing state and national policy support. For example, in Himachal Pradesh, the Horticultural Produce Marketing and Processing Corporation along with agricultural universities in the state have facilitated crop diversification by providing technical assistance and farmer advisories on cultivating high-value cash crops (Sharma, 2011). Improved irrigation coverage and credit access in Odisha and Assam have also enabled agricultural diversification (Reddy, 2013).

Crop diversification offers positive co-benefits for ecosystem services, such as improved soil quality (Jat et al., 2012) and human well-being through better nutrition, poverty alleviation and employment generation (Bhattacharyya, 2008). It also builds resilience against weather shocks and is an important adaptation measure to climatic risks (Birthal & Hazrana, 2019; Khatri-Chhetri et al., 2016).

6.4.1.3 Improved cropland management

Improved cropland management includes strategies such as SRI, improved seed management and laser land levelling. Despite high input costs in some cases, there is robust evidence that these strategies provide multiple economic benefits, including reduced input costs for water, seeds, fertilisers and energy; increased net returns; and higher crop productivity (Aryal et al., 2015b; 2018b; Aryal et al., 2020a; Barah, 2009; Jat et al., 2009; Jat et al., 2014b; Khatri-Chhetri et al., 2016).

In the Indo-Gangetic Plains, studies show that different combinations of cropland management techniques can more than double the net returns on initial investment in rice–wheat cropping systems (Aryal et al., 2015a;Aryal et al., 2015b; Jat et al., 2009; Khatri-Chhetri et al., 2016). In Maharashtra, improved technologies in the production of sorghum have increased net returns (170 per cent), grain yield (58 per cent), quality (78 per cent) and fodder yield (26 per cent) (Chapke & Tonapi 2018). In Uttar Pradesh, sustainable land management has tripled cropping intensity, increasing rice yields from 0.9 to 3.5 tonnes/ha and wheat yields from 0.4 to 3.0 tonnes/ha (Satapathy et al., 2011). Laser land levelling in the Indo-Gangetic Plains offered 97–120 per cent internal rate of return for service providers, with estimates showing that one laser unit can create employment opportunities of 270 to 330 person-days/year.

Climate-smart agriculture has emerged as a highly feasible strategy to adapt to climatic risks such as drought and floods, although it entails significant costs. For example, drought-tolerant rice can increase production by over 8 million tonnes by 2035 but would require investment of approximately US$ 206 billion (2015–2030) (Aryal et al., 2019). These options would also generate local employment and higher incomes (Aryal et al., 2015b; Gill, 2014; Jat et al., 2014b; Mula & Sarker, 2013).

While technological capacity for improved cropland management is high, some strategies are expensive and constrained by low awareness, ineffective implementation and lack of equipment (Bhatta et al., 2017; Khatri-Chhetri et al., 2016). However, increasing farmer awareness, government subsidies, better custom-hire services, extension and training services, and ICTs can improve uptake (Aryal et al., 2018a).

Numerous policies, schemes and institutions promote improved cropland management at national and state levels, such as the National Initiative on Climate Resilient Agriculture (NICRA), Weather-based Crop Insurance Scheme, Kisan Sanchar Samuha, Tamil Nadu Precision Farming Project, National Agroforestry Policy and National Mission for Sustainable Agriculture (Amjath-Babu et al., 2019; Aryal et al., 2020a; Chapke & Tonapi, 2018; Mondal & Basu, 2009; Satapathy et al., 2011). However, many existing policies suffer from transparency and accountability challenges, which can inadvertently incentivise maladaptive practices and cause lack of institutional flexibility (Aryal et al., 2019).

Improved cropland management provides social benefits such as improved food security, new investment opportunities, employment and reduced health impacts from chemical inputs (Agarwal & Pandey, 2017; Aryal et al., 2015b ; Aryal et al., 2018b; Gill, 2014; Jat et al., 2014a;). However, the acceptance and penetration of these practices depend on factors such as land tenure, literacy, caste and gender (Aryal et al., 2018a; 2018c). Farmers with larger farm areas are more willing to adopt climate-smart agriculture practices compared to smallholders (Aryal et al., 2014; 2018a; 2018b). There is mixed evidence on the gender inclusiveness of these options. While there are more employment opportunities for women in specialised operations like SRI (Barah, 2009), many new technologies have not adequately addressed the unequal workload of women farmers (Bhatta et al., 2017). For instance, in Haryana and Bihar, women were reported to have had less awareness of improved agricultural practices (Aryal et al., 2014).

Environmentally, improved cropland management has positive impacts. In Uttar Pradesh, sustainable land management practices promote organic farming, reduce pests and diseases, and increase floral and faunal diversity as well as microbial biomass (Aryal et al., 2019; Barah, 2009; Satapathy et al., 2011). Seed banks in Uttar Pradesh, Bihar, West Bengal and Odisha have enhanced resilience against floods, increased productivity and diversified local food systems (Satapathy et al., 2011). Even small improvements in rice cropland management positively impact groundwater availability and water savings (Aryal et al., 2015b; Barah, 2009; Dourte et al., 2014; Gill, 2014; Jat et al., 2014a). Such practices mitigate the effects of high temperatures, thereby adapting agriculture to drought and heat stress (Aryal et al., 2014; 2018c).

Improved cropland management is physically feasible across most of India (e.g., more feasible in the north-east due to the climate, soil type, and existing practices of organic food production in the region; Das et al., 2017). However, there are barriers to land availability and tenure as well as the challenge of declining field sizes in some regions such as the Indo-Gangetic Plains (Aryal et al., 2018c; DeFries et al., 2016). Practices such as laser land levelling and climate-smart agriculture have mitigation co-benefits by reducing GHG emissions and substantially reducing the demand for irrigation water and energy for pumping water (Jat et al., 2014a). A combination of improved cropland practices, including reduced or no tillage, nutrient management and residue recycling, has a higher rate of soil organic carbon sequestration (427.9 kg/ha/year under the rice–rice system; Yadav et al., 2019). Laser land levelling reduces ~0.15 Mg of CO_2 eq/ha/year by decreasing water pumping and cultivation time (Aryal et al., 2020b).

6.4.1.4 Integrated soil management

Integrated soil management includes practices such as site-specific nutrient management, soil health and fertility management, and zero or minimum tillage. These practices offer substantial economic benefits by reducing input costs and cultivation expenses while increasing productivity, yield and net returns (Aryal et al., 2019; Phonglosa et al., 2015; Sharma et al., 2015). For example, compared to conventional tillage, a zero tillage–based rice–wheat cropping system can save input costs and increase net revenue by approximately ₹7,000/ha (Aryal et al., 2015c; Aryal et al., 2019; Gathala et al., 2011; Jat et al., 2014b; Keil et al., 2015; Khatri-Chhetri et al., 2016; Phonglosa et al., 2015; Sapkota et al., 2014; Sapkota et al., 2015). On-farm vermicompost and manure, ridge and furrow systems, zero tillage, and soil test–based balanced nutrition technologies also improve productivity and net returns (Chander et al., 2013; Keil et al., 2015; Parihar et al., 2012; Pathak, 2010; Sharma et al., 2015). However, some nitrogen management technologies can increase expenses and reduce net incomes (Pathak, 2010).

Adoption of soil management practices is constrained by low awareness, insufficient training, high equipment costs, lack of technology, and socio-economic incompatibility (Bhatta et al., 2017; Bhattacharyya et al., 2016;). Institutions such as the Cereal Systems Initiative for South Asia in Bihar (Keil et al., 2015), State Department of Agriculture in Karnataka (Kannan & Ramappa, 2017), Central Soil Water Conservation and Training Institute in Ooty (Bhattacharyya et al., 2016), and Central Soil Salinity Research Institute in West Bengal have developed, trained and driven the adoption of integrated soil management practices. Support from agricultural departments, panchayati raj institutions, watershed associations (Kannan & Ramappa, 2017) and access to credit (Aryal et al., 2018c) have enabled adoption in some regions, although lack of coordination remains a significant barrier (Bhattacharyya et al., 2016).

Integrated soil management provides significant health and socio-economic benefits. For example, it reduces infant mortality and morbidity in poor households by decreasing womens' exposure to fertiliser-derived toxins in paddy fields (Farnworth et al., 2017). It benefits marginal farmers who cannot afford expensive chemical fertilisers (Jat et al., 2015). Factors such as farm size, access to credit, caste and literacy of the household head influence adoption rates. For instance, in the Indo-Gangetic plains, these four factors influence the adoption of zero tillage and site-specific nutrient management, with educated, higher-caste farmers with larger landholdings adopting these practices more frequently (Aryal et al., 2018a; 2018c; Keil et al., 2017; 2019).

Integrated soil management enhances soil microbial activity (Parihar et al., 2020; Patra et al., 2020), improves soil water-holding capacity (Parihar et al., 2020; Srinivasarao et al., 2013), increases nutrient availability (Batabyal et al., 2017; Parihar et al., 2020; Patra et al., 2020; Sarkar et al., 2018) and boosts carbon sequestration potential in north-west India (Aryal et al., 2015c), Andhra Pradesh (Wani et al., 2014) and Central India (Kumar et al., 2018a). These impacts collectively build local resilience through improved soil health, leading to yield benefits in subsequent seasons (Chander et al., 2013).

The physical feasibility of soil management practices depends on geography, location, farm size and soil type (Kannan & Ramappa, 2017; Keil et al., 2017). Practices like zero tillage are more beneficial in rainfed agricultural systems and must be combined with residue retention and crop rotation to realise these benefits (Keil et al., 2015). Techniques such as contour grass barriers vary with grass types and site conditions; for instance, buffel grass in Andhra Pradesh or guinea grass in Uttarakhand (Mandal et al., 2017).

Most soil management practices increase soil carbon sequestration and reduce GHG emissions compared to conventional farming (Pathak, 2010; Sarkar et al., 2018; Yadav et al., 2019). For instance, zero tillage–based wheat production in Haryana reduced GHG emissions by 1.5 Mg CO_2 eq/ha/wheat season (Aryal et al., 2015c; 2019). In central India, reduced tillage increased soil organic carbon sequestration (Kumar et al., 2018a). Ridge and furrow systems and integrated fertiliser application in Indian conditions reduced the carbon footprint of pearl millet–mustard cropping systems and increased net returns, sustaining soil health and higher farm profitability (Parihar et al., 2012). A meta-analysis showed that using grasses can reduce soil carbon loss by 83 per cent in the Indian tropics (Mandal et al., 2017). In Andhra Pradesh, applying Jatropha de-oiled seed cake enhanced carbon sequestration on degraded wastelands in semi-arid tropic regions (Wani et al., 2014).

6.4.1.5 Water resource efficiency and water resource management

Improving irrigation efficiency through demand and supply management, along with integrated water management practices, is crucial for agricultural adaptation. These practices offer clear economic benefits by improving crop productivity, cropping and irrigation intensity, and achieving more sustainable yields (Gray & Srinidhi, 2013; Manjunatha et al., 2011; Sharma et al., 2010; Singh et al., 2009; Thind et al., 2010).

While technical barriers are low, institutional barriers persist, such as inadequate capacity to fully leverage watershed programmes (Dhawan, 2017), ineffective community participation (Gray & Srinidhi, 2013) and limited local capacity to improve farm-level water efficiency (Senthilkumar et al., 2012). There is no universal institutional arrangement for water resource efficiency, but different states offer lessons in successful technical solutions and institutional design.

Furrow irrigation in Punjab and drip irrigation in Tamil Nadu and Karnataka are popular among farmers, with high adoption rates (Palanisamy et al., 2010; Thind et al., 2010). Greater efforts are needed to make water efficiency interventions more gender-sensitive. Water resource efficiency and management practices have high ecological feasibility. For example, in the Kumbharwadi watershed programme, efficient water use has enabled afforestation and carbon sequestration, and reduced land degradation (Gray & Srinidhi, 2013; Singh et al., 2009). However, physical characteristics of basins and sub-basins can constrain water resources management, as seen in southern India's Upper Bhima River basin, where upstream watershed development impacts downstream farmers' access to water (Surinaidu et al., 2013).

6.4.1.6 Efficient livestock

Enhancing livestock efficiency involves optimising breeding, rearing and feeding practices, and improving animal health. Studies consistently show that improving livestock systems can boost incomes, promote sustainable livelihoods and empower poor households (Birthal & Negi, 2012; Hegde, 2019; Ranade & Mishra 2015). Notably, poorer households benefit more from livestock diversification than wealthier ones (Deshingkar et al., 2008). Current constraints on livestock productivity include low technology adoption, feed and fodder scarcity, and poor animal health (Birthal & Negi, 2012; Deshingkar et al., 2008; Rathod, 2017).

Barriers to improving livestock efficiency are multifaceted. Economically, practices like stall-fed dairying and intensive poultry production may be unaffordable for poorer households (Hegde, 2019). Technically, there is limited reach of ICT for animal health management, disease control, feeding, herd management and milk marketing (Meena & Singh 2013). Institutionally, livestock often receives low priority in national policy (Birthal & Negi, 2012; Deshingkar et al., 2008; Rathod, 2017). Although small landholders can scale up dairy production, they face production and marketing constraints, along with shrinking community pasture lands (Birthal, 2008; Deshingkar et al., 2008). There is an urgent need for institutional and policy support to improve livestock efficiency through investment, credit, insurance, extension services and market access (Birthal, 2008; Birthal & Negi, 2012; Deshingkar et al., 2008; Rathod, 2017). While livestock rearing is often managed by women, leading to potential income benefits (Birthal & Negi, 2012; Kristjanson et al., 2010), decision-making remains male-dominated in some contexts (Mishra et al., 2008). Additionally, caste-based inequalities can result in exclusion, such as high-caste households refusing to buy milk from marginalised caste groups (Deshingkar et al., 2008).

The environmental feasibility of efficient livestock systems, particularly integrated crop-livestock systems, is mixed. While there are negative impacts on natural resources, GHG emissions and community grazing lands (Deshingkar et al., 2008; Hegde, 2019), there are also positive outcomes such as manure nutrient cycling, reduced erosion, increased crop yields and enhanced soil biological activity (Gupta et al., 2012). Given India's large livestock population and low productivity, improving efficiency can offer significant economic and environmental co-benefits (Blummel et al., 2009).

6.4.1.7 Improved grazeland management

India's grasslands are biophysically diverse, serving as critical wildlife habitats and the foundation of pastoral livelihoods (Kumar et al., 2015). Improved grazing land management includes practices like rotational and controlled grazing, managed silvopasture systems, controlled or prescribed burning, sustainable use of common property resources, fodder management, improved grass varieties, and the cut-and-carry system. These practices effectively increase land productivity, livestock carrying capacity and fodder production (Pathak & Dagar, 2016; Satapathy et al., 2011).

Grazing land management programmes can economically benefit local communities, as seen in Madhya Pradesh (Tetra Tech, 2017) and Gujarat (Kumar et al., 2015). Both formal and informal technologies are available to improve pasture land management (Kumar et al., 2011a; Kumar et al., 2015; Satapathy et al., 2011; Tetra Tech, 2017), with various research and academic institutions developing, refining and testing multiple grassland management technologies, supported by government agencies (Roy & Singh, 2013).

Despite government and local agency efforts to incentivise improved grazing land management across India, significant barriers include the lack of a comprehensive policy, ineffective implementation, lack of ownership and political inefficiency. Although India has one of the world's largest livestock populations, there is no national grazing policy, and forest regulations only address grazing restrictions, leading to conflicts. Some states, like Madhya Pradesh, Karnataka and Andhra Pradesh, have limited grazing policies, but they lack comprehensive management plans (Roy & Singh, 2008). For example, a special programme launched in Rajasthan's desert districts in 2003–2004 for community land improvement was discontinued by the subsequent government (Chaudhry et al., 2011). Government agencies often focus on temporary relief supplies rather than developing permanent solutions (Kumar et al., 2015). Traditional village-level institutions that ensured sustainable grassland management have deteriorated, and no agency is currently responsible for overseeing management issues (Roy & Singh 2013). The Government of India's Task Force on Grasslands and Deserts highlighted the importance of rotational grazing, controlling free-ranging animals, protecting selected grassland plots, securing tenure for pastoralists and improving livestock genetics. However, these measures have not been integrated into national animal husbandry programmes (Kumar et al., 2011a).

There are some successful grassland management programmes. Multipurpose programmes like JFM aim to balance tree products and herbaceous fodder (Roy & Singh, 2008). The Kangayam region in Tamil Nadu has sustained grassland production systems for over a century through technological and social practices (Kumar et al., 2011a). Traditional grazing governed by informal institutions has supported pastoral adaptations in Arunachal Pradesh, showing that local pastoralists can sustain ecosystems through rangeland management (Singh et al., 2018c).

Effective implementation of improved grassland management practices offers social co-benefits, including increased income, better health, gender equity and cross-cultural knowledge exchange (Kumar et al., 2011a; Singh et al., 2018c). Involving local communities at the planning stage enhances the acceptability of these programmes (Joshi et al., 2009).

Improved grazing land management can restore ecosystem services by enhancing forest health, restoring flora and fauna in Madhya Pradesh (Tetra Tech 2017), reducing run-off and erosion (Mandal et al., 2017), and maintaining swamp plant communities in endangered wetland ecosystems (Mohandass et al., 2016). Silvopastoral components reduce temperatures, increase soil moisture and humidity, enhance dry matter production for understory grasses and legumes, and improve fodder availability and livestock health (Pathak & Dagar, 2016). Moderated grazing enhances soil microbial biomass (Devi et al., 2014), increases drought resilience (Satapathy et al., 2011), and improves grassland productivity (Pathak & Dagar, 2016). While these management options yield several ecological benefits, careful planning and assessment are required to avoid unintended consequences, such as large-scale fires (Sriramamurthy et al., 2020) or the introduction of invasive species (Joshi et al., 2018).

The feasibility of integrated grazing land management depends heavily on local ecology, and most evidence recommends developing site-specific management plans (Tetra Tech, 2017). Grasses can reverse land degradation and reduce soil carbon loss by 83 per cent (Mandal et al., 2017). Silvopastoral systems enrich soil carbon and nitrogen pools, with grasses and trees on degraded lands sequestering 1.9 petagram of carbon in seven years, compared to 2.27 Pg of emissions in the same period, thereby slowing global warming (Pathak & Dagar, 2016). Adopting high-density silvopasture systems on at least 3 Mha can help meet half of India's carbon emission reduction target under the Intended Nationally Determined Contributions (INDC) commitment over ten years (Varsha et al., 2017).

6.4.1.8 Agroforestry

Agroforestry holds significant economic promise, offering higher incomes, income security in case of crop failure and robust livelihood support, especially in states as diverse in agro-ecology as Punjab, Haryana, Uttarakhand, western Uttar Pradesh, arid Rajasthan, and Northeast India (Basu, 2014; Chavan et al., 2015; Parihaar et al., 2015; Roy & Tewari, 2012; Sharma et al., 2015). Technical challenges to agroforestry include gaps in scientific knowledge and operational capabilities (Murthy, 2013; Sharma et al., 2015).

The political acceptability of agroforestry is bolstered by national policies like the National Agroforestry Policy (2014), which underscores the tree–crop interface as pivotal for promoting climate-smart agriculture (Chavan et al., 2015). Strengthening existing institutions such as Krishi Vigyan Kendras, Regional Agricultural Research Stations of Indian Council of Agriculture Research (ICAR), Indian Council of Forestry Research and Education (ICFRE) and State Agriculture Universities (SAUs), and R&D extension institutions under state bodies is crucial for fostering locally suited agroforestry models (Chavan et al., 2015).

The uptake of agroforestry is influenced by ecological, institutional and sociocultural factors as well as market development levels. For instance, in north-western India, poplar-based agroforestry has gained popularity due to significantly higher economic returns from timber as compared to traditional rice–wheat rotations (Sharma et al., 2015). In the commercialised regions of western and southern India, farmers opt for woodlots over risk-prone crops like groundnut or cotton (Basu, 2014). In rural Kashmir, the tangible benefits of agroforestry influence community attitudes positively (Islam et al., 2015).

Agroforestry offers substantial socio-economic and ecological co-benefits, including improved local water quality, increased fodder availability, enhanced timber for fuel and construction, and strengthened food security (Basu, 2014; Chavan et al., 2015). Extensive evidence suggests that agroforestry enhances land use efficiency through microclimate regulation, biodiversity conservation, water source protection, erosion control and substantial carbon storage potential (Murthy, 2013; Nandy & Kumar Das, 2013; Roy & Tewari, 2012; Sharma et al., 2015; 2016). Agroforestry also enhances farming system resilience by sustaining production during dry periods (Roy & Tewari, 2012).

6.4.1.9 Biodiversity conservation and management

Biodiversity conservation enhances the trade of non-timber forest products (NTFP), creates wage labour opportunities, and boosts incomes for forest-dependent populations (GIM-MOEFCC, 2016). Valued at ₹100 billion (US$ 1.4 billion) based on carbon sequestration potential, the Western Ghats forests play a crucial role in climate mitigation efforts (Ramachandra & Bharath, 2019). Forest regeneration activities, including afforestation and soil conservation, generate substantial employment through community-based forest management initiatives (Singh, 2008). Forest conservation also contributes to income generation through sustainable forest product use and eco-tourism (Satapathy et al., 2011).

India has established robust legal and institutional frameworks for biodiversity management, encompassing multiple central and state regulations, policies, and schemes. Key legislations include the Wildlife (Protection) Act, 1972; Environment Protection Act, 1986; Joint Forest Management Policy 1993; Biological Diversity Act, 2002; Biological Diversity Rules, 2004; and National Environment Policy 2006 (GIM-MOEFCC, 2016; Iftekhar, 2008). State Biodiversity Boards have been set up across India post the enactment of the Biological Diversity Act, further bolstering conservation efforts (Kumar et al., 2020a). Apart from these, the Compensatory Afforestation Fund Management and Planning Authority (CAMPA) Act, 2016 supports the establishment of a permanent National Compensatory Afforestation Fund in order to enhance afforestation initiatives (Bhan et al., 2016). GIM is a pivotal component of India's climate change strategy, focusing on enhancing forest cover and quality. Furthermore, revenue distribution from forest tax revenues incentivises states to protect and restore forests (Busch & Mukherjee, 2017).

Inadequate capacity of state governments to implement and monitor afforestation activities; lack of viable long-term institutional framework conducive to the objective of increased biomass for the poor; social equity and resource sustainability; and underutilisation of funds accrued under CAMPA threaten long-term biodiversity conservation (Bhan et al., 2016; Singh, 2008). There is also variable implementation of forest management policies in different states (Das & Behera, 2019).

Biodiversity management offers co-benefits for health, food security (Mishra, 2019), education and environmental awareness (Ramadoss & Moli, 2011), preservation of cultural heritage (Satapathy et al., 2011), and overall human well-being (Kumar et al., 2020a; Mallick & Chakraborty, 2018a). While several policies target stakeholder engagement and participatory conservation, exclusionary management practices hamper public acceptability and overall feasibility (Dhanapal, 2019; Faizi & Ravichandran, 2016).

Biodiversity management and conservation enhances ecosystem services significantly (Mallick & Chakraborty, 2018a), contributes to maintenance of nutrient and water flow, aids habitat conservation of forest plants and animal species (Das & Behera, 2019; Hussain et al., 2016; Pradhan et al., 2019; Saniotis, 2011), causes less erosion, and stabilises degraded areas (Agarwal et al., 2017; Satapathy et al., 2011). However, focusing on monocultures (e.g. teak in Central India or *Casuarina equisetifolia* and *Acacia auriculiformis* in Odisha) can constrain effectiveness (Dhanapal, 2019; Hussain et al., 2016; Roy & Datta, 2018).

Land availability, location, transaction costs and landscape properties influence the physical feasibility of biodiversity management. For instance, identifying and earmarking land for afforestation is challenging due to finite land resources and competing demands. Unclear land tenure and difficulties in complying with land acquisition procedures further hinder implementation (Bhan et al., 2016). Location and connectivity also play crucial roles; for instance, Forest Protection Committees located close to local forests experience lower transaction costs (Ray & Bhattacharya, 2011).

Shifting land use through biodiversity conservation can achieve significant carbon sequestration and restore soil carbon stocks (Kumar et al., 2020a; Satapathy et al., 2011). Indian plantations from 2000 to 2050 have the potential to sequester up to 7 billion tonnes of carbon credits, with 153 Temperature guage/year expected by 2030 (Singh, 2008). Conservation efforts in the Western Ghats forests could increase carbon sequestration potential to 1.5 million gigagrams (MGg) by 2031 with enhanced protection and minimal disturbances (Ramachandra & Bharath, 2019). In Northeast India, substantial carbon stock recovery was observed as secondary forests regenerated, with a 30-year fallow storing approximately half the carbon of an old-growth forest. Preserving old-growth forests through protected areas and intensifying cropping in the remaining shifting cultivation areas represents the optimal strategy for carbon storage (Borah et al., 2018).

Forest conservation and planned vegetation contribute significantly to maintaining nutrient and water flows, preventing landslides, conserving flora and fauna habitats, reducing erosion, enhancing availability of wood and other forest products, and stabilising degraded areas (Gupta & Nair, 2012; Satapathy et al., 2011). While scientific biodiversity management practices can mitigate environmental hazards, ineffective implementation may prove to be counterproductive.

6.4.1.10 Integrated Coastal Zone Management

Integrated Coastal Zone Management (ICZM) encompasses multiple adaptation strategies, including mangrove management, coastal zoning and vulnerability assessments, and socio-economic interventions for coastal communities. In India, ICZM activities are notably concentrated in states such as West Bengal, Odisha, Tamil Nadu, Maharashtra and Gujarat.

ICZM delivers significant economic benefits through livelihood generation (Ghosh, 2015; Pitchaikani, 2020; Roy & Datta, 2018), income generation from mangrove products like fish, dyes and medicines, improved employment opportunities, and enhanced food security (Satapathy et al., 2011). It is supported by various legislative and institutional frameworks across India (DasGupta & Shaw, 2013; Iftekhar, 2008; Kathiresan, 2010; 2018), including GIM, Coastal Regulation Zone (CRZ) Notifications, and initiatives like JFM and Eco-Development Committees (Datta, 2017; Datta & Deb, 2017). Further, ICZM is enabled by strong civil society and funder attention (DasGupta & Shaw, 2013; Jayakumar et al., 2019; Portman et al., 2012).

Despite this, ICZM faces institutional constraints such as inadequate financial and human resources, poor infrastructure, and insufficient political will (Kathiresan, 2018). Additionally, challenges like environmental factors originating outside the coastal zone (e.g., reduced freshwater flow upstream) remain unaddressed (Krishnamurthy et al., 2014), along with weak monitoring and enforcement processes (Iftekhar, 2008; Panigrahi & Mohanty, 2012; Puthucherril, 2011; Roy & Datta, 2018).

Technological feasibility of ICZM is moderate, with GIS-based technologies being employed in specific regions such as Udupi in Karnataka, the Chennai coast in Tamil Nadu and Subarnarekha River in eastern India (Dwarakish et al., 2009; Kankara et al., 2014; Roy & Datta, 2018).

ICZM yields numerous social co-benefits, including poverty alleviation and improved livelihoods through programmes like Joint Mangrove Management (Kathiresan, 2018), increased catches of mangrove-dependent fish (Das, 2017), and higher incomes from forestry and fisheries (Hussain & Badola, 2010). However, it also faces socio-economic challenges such as human–wildlife conflicts and diseases like malaria (Badola et al., 2012).

Participatory resource management is integral to ICZM across India, emphasising public awareness and local capacity building for sustainable resource use (Panigrahi & Mohanty, 2012). Despite the health, livelihood and sociocultural benefits of ICZM, public acceptability is mixed, influenced by factors such as community reluctance to protect areas that restrict fishing rights and use of NTFPs (Badola et al., 2012; Chouhan et al., 2016;DasGupta & Shaw, 2013; Ghosh, 2015). ICZM initiatives can also inadvertently increase vulnerability among certain social groups; for example, in Bhitarkanika, Odisha, restrictions associated with ICZM have disproportionately excluded women from resource use (Badola et al., 2012), while in the Sundarbans, insufficient involvement of economically marginalised groups in decision-making has hindered inclusive mangrove management (Datta, 2017), contributing to widening income disparitiy (Ghosh, 2015).

Mangroves and other coastal ecosystems, such as seagrass beds and coral reefs, provide a wide array of ecosystem services, including biodiversity conservation (Chouhan et al., 2016; Datta & Deb, 2017; Satapathy et al., 2011) and risk mitigation benefits such as flood buffering, cyclone protection and storm surge attenuation (Badola et al., 2012; Coppenolle & Temmerman, 2020; DasGupta & Shaw, 2013; Parthasarathy, 2011). They also play crucial roles in preventing soil erosion, stabilising shorelines, and enhancing habitat conservation for flora and fauna (Chouhan et al., 2016; Datta, 2017). Despite covering only 0.3 per cent of India's coastal area, mangroves are estimated to sequester carbon 50 times more effectively than tropical forests, contributing significantly to carbon sequestration efforts (Kathiresan, 2010).

However, significant physical barriers exist against converting mangroves for commercial purposes. In the Sundarbans, for instance, the high costs associated with land use conversion in tidal, saline environments, coupled with international administrative boundaries and the presence of endangered species like the Royal Bengal Tiger, pose formidable challenges to ICZM (Iftekhar, 2008).

6.4.1.11 Coastal defence and hardening

Coastal defence options across India include constructing seawalls, groins, breakwaters, and revetments; establishing bio-shields such as mangrove plantations; deploying Multipurpose Artificial Surfing Reefs (MPASRs); and implementing innovative structures like bamboo pile walls.

Coastal defences such as bio-shields offer economic benefits, providing daily wages, fuelwood, and small timber to local communities when they participate in planting efforts (Feagin et al., 2010; Mukherjee et al., 2015). The multipurpose Kovalam Reef in Kerala, for instance, protects the shore and promotes quality surfing, boosting tourism and enabling small businesses centered around surfing (Asian Development Bank [ADB], 2017).

Innovative coastal defence structures can result in substantial cost savings, though effectiveness varies by type. Bamboo pile walls are both economically and environmentally advantageous, while sand dykes are costly due to the need for large amounts of sand, often transported from distant locations (Harihar & Verhagen, 2017). The unit cost of sea dikes in India is approximately €5.7 million per km or ₹45–48 crore (at 2019–2020 rates), one of the highest in the world (Nicholls et al., 2019). While seawalls are relatively inexpensive and easy to construct, the Swaminathan Committee Report on the CRZ warns against 'hard engineering options' like seawalls, identifying them as serious threats to coastal ecosystems and livelihoods (Rodriguez et al., 2008).

Over the past two decades, India has implemented various coastal defences with the involvement of government and civil society. The techniques used include bio-shields, geotextile tubes and other site-specific designs, showing varying degrees of effectiveness (Chinchmalatpure & Thakor, 2020; Noujas & Thomas, 2018). Strong political will is evident through numerous national and state-level projects along India's coastline. Institutional support from national and international agencies, as well as public and private organisations, is available for such practices. However, challenges like poor management, inappropriate methods and insufficient maintenance budgets constrain the feasibility of coastal protection efforts.

Sociocultural acceptance of coastal defences is mixed. While some techniques offer livelihood support (e.g., additional income from tree plantations), others face issues like inappropriate locations (e.g., seawalls hindering boat movement), negative impacts (e.g., saltwater intrusion due to embankments, planting of exotic species such as *Casuarina*), inequitable benefit distribution, and poor maintenance (ADB, 2017; Feagin et al., 2010; Rodriguez et al., 2008).

Environmental feasibility of coastal defences also varies. While interventions like MPASRs have restored beaches, enhanced ecological capacity, mitigated land degradation, reduced saline water intrusion and enabled recreational activities (Lokesha et al., 2013), issues like poor maintenance, discontinuous protection and planting of exotic species have caused significant ecological and socio-economic damage (Jebarathanam et al., 2014; Mukherjee et al., 2015; Murthy et al., 2020). Conventional shore protection measures such as groins and seawalls often fail to restore lost beaches and may exacerbate erosion (Nair et al., 2018; Selvan et al., 2016). Seawalls, in particular, have been shown to cause beach loss across India (ADB, 2017).

A mix of infrastructural and ecosystem-based interventions often provides greater benefits, though feasibility depends heavily on local geomorphology. For example, in West Bengal, a mangrove belt in front of a dyke offers more ecological benefits compared to conventional dykes with a rock revetment (Verhagen, 2019). In Gujarat, however, mangrove plantations for erosion control were counterproductive, likely due to discontinuous planting (Das, 2020).

Land ownership and coastal morphology influence the feasibility of protection interventions. Seawalls along dynamically stable and accreting beaches do not significantly alter morphology, but on eroding beaches, they are prone to toe scouring and slumping, leading to the disappearance of frontal beaches (Thankappan et al., 2018). Both infrastructural and ecosystem-based interventions are effective in reducing the impacts of tsunamis, cyclones and storm surges (Sonak et al., 2008; Verhagen, 2019). While the efficacy of seawalls remains debatable due to high economic, aesthetic and environmental costs (Rodriguez et al., 2008), MPASRs are increasingly being adopted for coastal protection (Lokesha et al., 2013). Sand dunes are notably effective in protecting against wave inundation and saltwater intrusion (Namboothri et al., 2008).

6.4.1.12 Sustainable aquaculture

Sustainable aquaculture involves the implementation of better management practices in fish and seafood farming. This includes integrating aquaculture with agriculture (e.g., shrimp and rice cultivation), improving nutrient management, clustering small-scale farmers and reorienting the aquaculture supply chain towards low-input, organic practices.

The economic feasibility of sustainable aquaculture is high, as it can enhance income, particularly during th elean fishing season (Apine et al., 2019; Babu et al., 2012; Edwards, 2008). Integrating native fish cultures with SRI practices (Bunting et al., 2014) and reducing feed and fertiliser costs (Chakrabarty et al., 2009) can further support economic viability. Organic shrimp farming with eco-labelling and certification mechanisms also offers high potential financial returns (Knowler et al., 2009).

Sustainable aquaculture is supported by state-led and non-governmental legal, institutional and financial mechanisms. Examples include the Coastal Aquaculture Authority Act, 2005, and the National Centre for Sustainable Aquaculture (Bunting et al., 2014; Puthucherril, 2016; Salunke et al., 2020; Valderrama et al., 2014).

Key constraints to sustainable aquaculture include high input costs, timely supply of quality fish seed and disease prevalence (Bhuyan et al., 2017; Valderrama et al., 2014). Additionally, there are challenges such as lack of follow-up, multi-ownership of waterbodies (Bhuyan et al., 2017; FAO/NACA, 2012; Valderrama et al., 2014), inadequate infrastructure and capacity building along the supply chain, and poor transfer of technology (Apine et al., 2019; Bhuyan et al., 2017; Valderrama et al., 2014). Another critical barrier to uptake is a lack of local experience, knowledge and skills, as well as the availability of quality fish seed from local stocks of indigenous species (Bunting et al., 2014; Umesh et al., 2009).

Sustainable aquaculture offers numerous social benefits, including the transfer of ecological knowledge, livelihood generation, stronger social networks and increased community cohesion (Bunting et al., 2014; Umesh et al., 2009). It also enhances nutritional security (Edwards, 2008) and mitigates disease risks (Valderrama et al., 2014).

Environmentally, sustainable aquaculture provides benefits such as reduced stocking densities, decreased pollution, increased environmental awareness, enhanced nutritional security, improved water management, chemical-free aquaculture and reduced dependency on external nutrients (Bunting et al., 2014; FAO/NACA, 2012; Umesh et al., 2009). However, environmental feasibility can be constrained by exceeding carrying capacity and introduction of invasive species (Bunting et al., 2014; Knowler et al., 2009).

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Physical constraints such as land type, water availability and market linkages limit aquaculture to certain regions. Nevertheless, these constraints are gradually being addressed through better institutional support and capacity building. Key regions with potential for offshore mariculture include Gujarat, Maharashtra, Kerala, Tamil Nadu, Odisha, Andaman and Nicobar Islands, and Andhra Pradesh (Jha et al., 2017).

Overall, sustainable aquaculture can enhance carbon sequestration potential (Adhikari et al., 2012) while reducing the risk of diseases and viral outbreaks (Valderrama et al., 2014), solid waste management issues (Edwards, 2008), and wastewater management problems (Umesh et al., 2009). However, main constraints to feasibility include topographic challenges, land tenure issues, improper maintenance and input cost–related issues.

6.4.2 Adaptation options for urban and infrastructure system transitions

This section evaluates the feasibility of four adaptation options for urban and infrastructure systems transitions: sustainable land use planning, sustainable water management, green infrastructure, and building codes and standards (Figure 6.8). Overall, the technological feasibility of all these options is high. However, governance and financial constraints significantly limit their implementation.

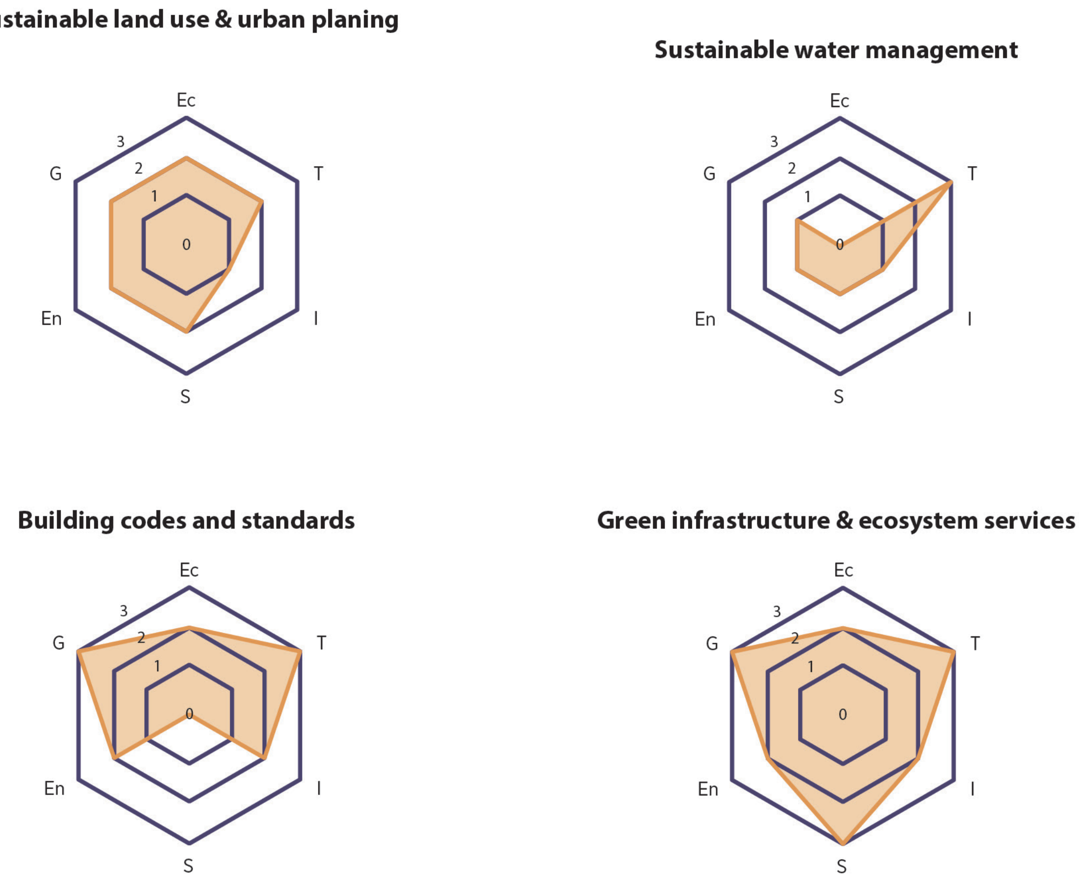
6.4.2.1 Sustainable land use and urban planning

Sustainable land use and urban planning involve integrating climate considerations into urban planning through infrastructure strategies, land development and management tools such as zoning regulations.

Experience from the ground shows that over the years, urban planning and investment projects have frequently neglected participatory and comprehensive planning. Operating with limited local revenue and conflicting objectives, the design and implementation of urban projects often lack connection to larger infrastructure networks or policy frameworks (Mahadevia & Pathak, 2020). In Kolkata and Bengaluru, overlapping administrative boundaries and undefined institutional roles and responsibilities result in ineffective service delivery and poor accountability (Rathee, 2017).

Meanwhile, in Surat, land use redevelopment measures have primarily focused on protecting economically valuable assets, such as textile mills, from flood risks. However, this has led to the displacement of communities from floodplain regions. Although these communities

Figure 6.8: Feasibility of adaptation options under urban and infrastructure systems transitions



Ec: Economic | **T:** Technological | **I:** Institutional | **S:** Social | **En:** Environmental | **G:** Geophysical

Source: *Authors' compilation*

are often relocated to less vulnerable areas, the new locations are typically far from economic opportunities (Anguelovski et al., 2016). Surat's resilience strategy has attempted to integrate local strategies into development planning, but poor and disadvantaged communities continue to lack sufficient access to resilience schemes (Chu, 2016).

Vulnerability is also exacerbated by expansion onto high-risk land, with anthropogenic activities significantly contributing to extreme events (Chandel et al., 2016). Inaccurate implementation of these measures could expose people to hazards. For example, in Chennai, encroachment and construction on wetlands, which act as sinks for excess rainwater, exacerbated flooding during the heavy rains of December 2015 (Jain et al., 2017a).

Sustainable land use faces significant institutional barriers, including low political acceptability and challenges in implementing land use adaptation measures. For example, in Kerala, policy barriers for agricultural land use aim to restrict unsustainable land transitions, but weak implementation and monitoring due to the growing population undermine these efforts (Jose & Padmanabhan, 2015). Furthermore, inadequate land use regulations based on land suitability (Dutta, 2012) and poor coordination among urban planning actors (Rathee, 2017) impede progress.

In rapidly urbanising transition zones, such as peri-urban areas, governance challenges and barriers to sustainable land use planning are more pronounced (Roth et al., 2018; Vij & Narain, 2016). While cities like Surat and Indore have received technological assistance to integrate climate change adaptation into urban planning (Cook & Chu, 2018), smaller, rapidly growing cities often lack evidence of long-term sustainable land use planning.

6.4.2.2 Sustainable water management

Sustainable water management involves maintaining sustainable water supply through practices such as rainwater harvesting, urban flood management (e.g., integrated flood management systems) and upgrading urban stormwater drainage infrastructure. Effective water management systems are crucial for ensuring long-term household water security, as the impact of poor management is typically experienced through repeated droughts (Srinivasan, 2015).

Traditional and indigenous water management technologies in India were often designed with consideration for the region's topography, hydrology and ecosystems (Seenivasan, 2014). In contrast, colonial water management systems, such as canals, prioritised perennial water supply and flood management (D'Souza, 2006). However, unchecked and irregular urbanisation has rendered many of these systems ineffective in large cities like Chennai and Bengaluru (Revi, 2008).

While sustainable water management can have socio-economic co-benefits, such as improved household water security, it is important to undertake interventions specific to household conditions. Adoption of these technologies at the household level can be encouraged through incentives or subsidies. For instance, in Dehradun, rainwater harvesting schemes were difficult for many households to adopt due to affordability and installation challenges (Barthwal et al., 2013).

Institutional barriers, such as overlapping government agencies with minimal interaction, constrain sustainable water management (Randliawa & Marshall, 2012). Although the public water supply system requires comprehensive institutional, administrative, managerial and financial reforms, the existing political economy of urban water and lack of administrative will remain significant barriers (Bassi & Kumar, 2012).

Economic costs of sustainable water management can be reduced through innovative measures. For example, expenses for manhole covers incurred by conventional sewer technologies can be mitigated by using simplified local sewerage systems (Kurian & Reddy, 2013). The cost of operating and maintaining these systems can be recovered by increasing the surcharge on the water bill. Cost recovery could also be supported by the effective reuse of domestic wastewater in secondary towns that support peri-urban agriculture (Kurian & Reddy, 2013).

6.4.2.3 Building codes and standards

Building codes and standards include technical interventions to increase resilience, such as stilt housing to protect from floods, and passive heating and cooling technologies to adapt to rising temperatures. Adhering to these codes and standards is essential to ensure safety of buildings and mitigating the risk of hazards like earthquakes, cyclones, landslides and fires (Mehta et al., 2018).

While technical measures to strengthen and retrofit buildings are cost-effective (ranging from 5–15 per cent of the initial investment), their implementation in India has been limited due to the need for institutional and financial innovation, as well as structured incentives (Revi, 2008). The high capital cost associated with green buildings is a significant barrier to investment in such projects (Abraham & Gundimeda, 2017). Nevertheless, there have been attempts at more affordable interventions. For example, the Ahmedabad Heat Action Plan (2017) includes an initiative to provide affordable cool roofing technology to people vulnerable to heat stress.

In terms of environmental feasibility, non-compliance with building regulations for environmental protection impacts the sustainability and ecological appropriateness of hill towns (Kumar & Pushplata, 2013; Sharma & Singh, 2016). This non-compliance can have devastating consequences, as evidenced in Uttarakhand, where poor enforcement of building codes led to the destruction of many houses during a cloudburst in 2013 (Uniyal, 2013).

6.4.2.4 Green infrastructure and ecosystem services

Green infrastructure and ecosystem services aim to improve human well-being and reduce exposure to climate risks, such as the urban heat island effect, through interventions like rainwater harvesting, green roofs, bioswales, and urban parks and gardens.

These interventions create opportunities for local economic development by providing green jobs in urban parks and enhance provisioning of regulatory, sociocultural and supporting ecosystem services (Adegun, 2017). For instance, rainwater harvesting recharges groundwater resources, offering the greatest net present value (₹21,764– ₹38,851), the fastest payback period (0.3– 1 year), and recharges over 40 per cent of onsite rainfall in cities like Bengaluru, Delhi, Hyderabad, Kolkata, Srinagar and Mumbai (Stout et al., 2015). It also provides sociocultural benefits, such as irrigating urban farms and improving food and nutritional security.

Valuation of ecosystem services can support urban decision-making and strategic planning by conserving energy and enhancing the well-being of residents (Dhyani et al., 2018). Evidence from Bengaluru suggests that greenery plays a significant role in the lives of people residing in informal settlements, providing critical social, cultural, religious, medicinal and food-related ecosystem services (Adegun, 2017).

Technical resource availability is crucial for improving adaptation to extreme conditions like drought. In Nagpur, evidence shows that water shortages during the summer can be substantially reduced by ecosystem-based approaches supported through civil engineering. Phytorid technology, which mimics wetland ecosystems for wastewater treatment, combined with rainwater harvesting, can improve groundwater recharge levels (Chavan et al., 2015).

Ecosystem services in cities are also enhanced through various sociocultural practices. For example, practices like protecting culturally valuable species of flora and fauna, aid in ecosystem protection and enhance the resilience of urban green spaces (Nagendra et al., 2013).

6.4.3 Cross-cutting adaptation options

This section assesses the feasibility of seven adaptation options that span various systems transitions (Figure 6.9). These include strategies for adapting to extreme events such as disaster risk management, climate services, leveraging indigenous knowledge, and risk spreading and sharing mechanisms. Several development interventions that have adaptation co-benefits are increasingly recognised as integral to adaptation strategies.

Under this framework, the feasibility of public health systems and social safety nets is evaluated. Both options exhibit high economic feasibility but can be limited by institutional leakages and issues of unequal access. In contrast, adaptation strategies related to resettlement, relocation, and migration exhibit low feasibility, primarily due to socio-institutional barriers, particularly in destination areas.

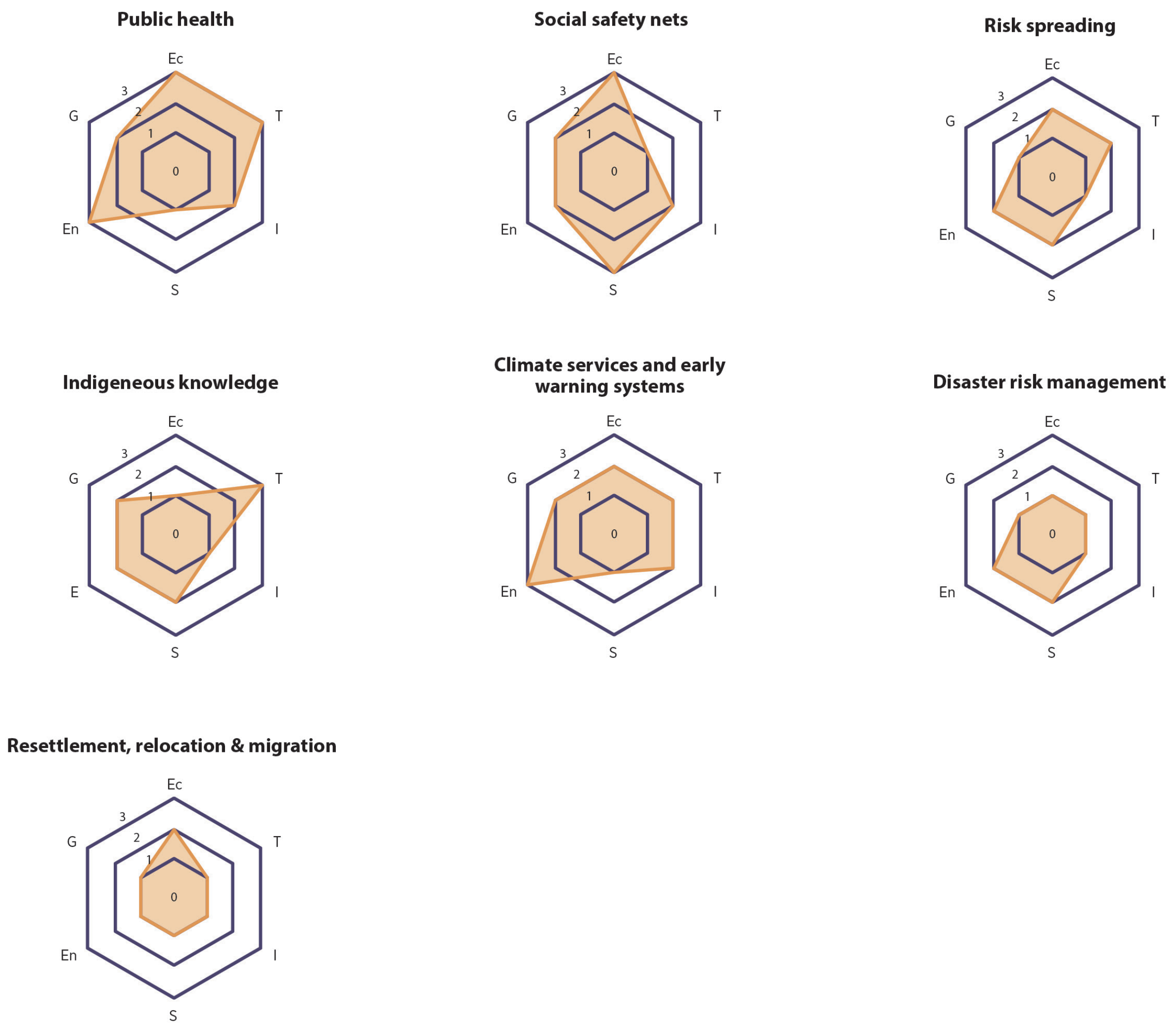
6.4.3.1 Public health systems

Public health systems include well-functioning primary healthcare centres (PHCs), capacity building for healthcare workers, disease prevention, adequate sanitation infrastructure, and policies to improve access to affordable healthcare treatment and infrastructure. These systems are crucial to reduce the vulnerability of poor communities and improve their resistance to illnesses caused by extreme temperatures and disease outbreaks (Dasgupta et al., 2016).

In India, higher public expenditure on health benefits vulnerable populations and positively impacts poverty reduction. Conversely, low public investment increases out-of-pocket health expenses, pushing people further into poverty (Balarajan et al., 2011; Kasthuri, 2018; Narain, 2016; Reddy & Paul, 2020). Budgetary allocation towards public health has been low across India, with the country's public health budget being among the lowest globally (Barik & Thorat, 2015). Rapid economic growth has increased financial commitments to support the public health system, improving the relevance, quantity and quality of nursing, medical and public health education in the country (Balarajan et al., 2011). Despite these efforts, health outcomes in India remain low, with a high burden of preventable diseases and healthcare that is neither equitable nor affordable (Rajan et al., 2013).

A significant barrier to inclusive healthcare delivery is the lack of basic infrastructural facilities at PHCs, including beds, wards, toilets, drinking water, clean labour rooms, regular electricity and adequate human workforce (Narain, 2016). Although technological capacities to reduce extreme indoor heat are available (Mahadevia & Pathak, 2020), there is a need for a long-term urban housing strategy to address the impact of indoor temperatures, particularly for low-income households and residents of informal housing.

Figure 6.9: Feasibility of cross-cutting adaptation options



Ec: Economic | **T:** Technological | **I:** Institutional | **S:** Social | **En:** Environmental | **G:** Geophysical

Source: *Authors' compilation*

Adaptation barriers in public health include inadequate policy support for proactively addressing the health impacts of climate change (e.g., higher disease incidence, morbidity and mortality), lack of trained human resources and gaps in downscaled risk assessments (Dasgupta et al., 2016; Garg et al., 2009; Moors et al., 2013; Ravindra et al., 2019). State disaster management plans have enabled disaster preparedness, with select states like Karnataka and Punjab pioneering the use of technology to track specific health conditions for improved responses (Dhiman et al., 2010). Community-level initiatives actively support health provisions during disasters and disease outbreaks following flooding (Krishnan & Patnaik, 2020). Cities and states are also implementing heat action plans (e.g., Ahmedabad, Nagpur, Bhubaneswar and Telangana) with extensive public and media outreach on the health risks of extreme heat (Knowlton et al., 2014; Mahadevia & Pathak, 2020).

6.4.3.2 Social safety nets

Prominent social safety nets in India include PDS and MGNREGA. These schemes aim to reduce rural poverty, transform livelihoods and provide a safety net for the poor, and empower women and marginalised communities (Breitkreuz et al., 2017; Desai et al., 2015;). They also act as safety nets to reduce risks and improve the resilience of vulnerable populations to climatic risks

(Adam, 2015; Fischer, 2020; Godfrey-Wood & Flower, 2017; Kaur et al., 2017; Steinbach et al., 2017).

Social safety nets such as PDS and MGNREGA have been shown to reduce the poverty gap in rural areas (Khera, 2011; Verma & Shah, 2012;), though they may not always provide substantial help to the most vulnerable (Breitkreuz et al., 2017; Dreze et al., 2017). While they fulfil their role in providing economic and livelihood security, there are notable gaps in employment provided and demanded, resource allocation, asset work completion, payments, incomplete record keeping of job cards and passbooks, and coordination problems due to the separation of implementing and payment agencies (Ambasta et al., 2008; Bassi & Kumar, 2010).

There is evidence of legitimate state intervention, especially in southern states such as Tamil Nadu (Dreze & Khera, 2013; 2015). In Andhra Pradesh, state governments have opened themselves to social audits of MGNREGA, demonstrating political will towards transparency and accountability (Basu & Das, 2015). MGNREGA focuses on empowering vulnerable sections of Indian society, including small and marginal farmers, Scheduled Castes and Scheduled Tribes (SC and ST), Other Backward Classes (OBCs), people below the poverty line, and women (Carswell & Neve 2013). Establishing crèches for women workers, abolishing contractors, effectively implementing transparency, and establishing a schedule of rates more favourable to women will significantly enhance women's participation in MGNREGA (Dreze & Khera, 2013).

The ecological feasibility of social safety nets such as MGNREGA is high. Most activities under MGNREGA have ecological co-benefits, such as rainwater harvesting structures, drought-proofing rainfed agriculture, and developing small-scale, natural resource–focused infrastructure (Adam, 2015; Fischer, 2020; Verma & Shah, 2012). These activities contribute to reducing GHG emissions through plantation development, afforestation, horticulture, land development, construction of wells renovation of ponds (Carswell & Neve, 2013).

6.4.3.3 Risk spreading and sharing

Risk spreading and sharing includes government and private sector insurance mechanisms to buffer against climatic risks, as well as autonomous adaptation strategies to manage and prevent climate impacts, such as seed saving and sharing by farmers or rotational grazing by pastoralists (Centre for Budget and Governance Accountability (CBGA), 2017; Singh et al., 2018b). It also includes practices like group leasing of land and sharecropping, where landowners and small farmers form arrangements for resource sharing (Deshingkar et al., 2003).

India's National Adaptation Fund (NAF) for agriculture, managed by the National Bank for Agriculture and Rural Development (NABARD), aims to protect vulnerable populations against climate change events. This fund could extend protection to vulnerable populations and enhance their ability to adopt sustainable practices (Singh, 2017). However, most risk-sharing schemes in the country operate on a small scale, and there is no standard procedure for monitoring their performance (Singh, 2017). Moreover, government schemes primarily benefit large-scale farmers, while small farmers and farm labourers often struggle to access these existing schemes (Deshingkar, 2012).

Risk-sharing initiatives are most prevalent in the agriculture sector. Common methods include strengthening capacity and infrastructure through better seed banks, specifically designed local tools, and innovative financial methods (Dey et al., 2019). Agricultural and pastoral societies in India practice various conservation agriculture methods, such as crop and herd diversification, intercropping, and mixed cropping, increasing their ability to manage climatic risks (Wu et al., 2014).

Grassroots agricultural initiatives have been shown to add value and generate employment (Dey et al., 2019). However, regional equality is not always achievable due to information unavailability, accessibility issues, and the varying strength of local governments (Kodirekkala, 2018). In urban areas, damages from extreme events are usually uninsured in the informal sector, and repair costs are often met through loans and savings. Few government schemes have provisions to insure property and reduce collective risks for the urban informal sector. The informal nature of settlements and employment further decreases access to risk alleviation schemes, leading residents to adopt informal techniques (Patankar & Patwardhan, 2016).

6.4.3.4 Indigenous knowledge

Indigenous knowledge includes localised traditional governance systems, methods of sustainable resource production and consumption, and risk management strategies for extreme events. Indigenous knowledge has high feasibility as indigenous communities have a better understanding of long-term local environmental conditions and changes (Inaotombi & Mahanta, 2019).

Indigenous people are often more vulnerable to climate change as their livelihoods are resource-based. However, they possess the knowledge and ability to grow high-value traditional crops and trees, which often have medicinal uses and high nutritional value, such as the Himalayan Yew (Meena et al., 2019). These communities frequently practice diverse livelihoods, being both pastoralists and cultivators.

There is increasing potential and demand for indigenous plants and cultivation techniques (Meena et al., 2019). Indigenous people have knowledge of climate change and have traditionally developed ecologically sensitive livelihoods. For example, fishers in Andhra Pradesh possess knowledge of climate change and weather patterns, and are attuned to changes in the daily characteristics of the sea (Dey & Sarkar, 2011). Traditional adaptation strategies also exist among the communities of the Upper Brahmaputra floodplains, who have learned to live with the floods (Hazarika et al., 2016). Indigenous communities in Rajasthan have traditional systems to manage drought and soil change, harvest water, and store grains and feed (Sarkar et al., 2015).

Despite high sociocultural feasibility, coordinating and managing indigenous knowledge systems can be challenging, as these communities are often located in less accessible areas, making them institutionally isolated and inadequately recognised and supported (Inaotombi & Mahanta, 2019). Indigenous communities should not be treated as 'closed systems' and can be carefully integrated into mainstream economic, social and political systems with the communities' active involvement and preferences taken into account (Swami & Parthasarathy, 2020).

As their livelihoods are largely dependent on natural resources, indigenous people tend to inhabit ecologically fragile environments such as coastal areas, mountains and floodplains. Though they have developed indigenous knowledge to adapt to changing environments, the rate of climate change is unprecedented and will require additional adaptation efforts (Wu et al., 2014).

6.4.3.5 Climate services and Early Warning Systems

Climate services provide daily and seasonal weather forecasts and longer-term climate information to inform decision-making and risk management (Singh et al., 2018a; Srinivasarao et al., 2020). India has a well-established system of climate services, including weather forecasts, agricultural advisories, two-way extension services and event-based early warnings (Venkatasubramanian et al., 2012).

Weather forecasts and agrometeorological advisories are economically feasible, offering benefits such as reduced input costs for irrigation, pesticides and fertilisers, and increased net profits for farmers (Maini & Rathore, 2011; Mittal & Hariharan, 2018; Pandey & Singh, 2019; Singh, 2011; Vashishth et al., 2013).

India has strong technical capacity to develop climate information, though mismatches in the spatial and temporal scale pose barriers to climate information uptake (Ramakrishna, 2014; Singh et al., 2018a; Venkatasubramanian et al., 2014). For example, in Tamil Nadu, spatial resolution and utility of climate forecasts were reported as key barriers, with farmers requesting higher resolution forecasts, more accurate predictions and longer lead-times (Rengalakshmi et al., 2018; Venkatasubramanian et al., 2014).

The country also has a long history of technological advances in climate services and EWS, with a strong government mandate, and is a leader in providing district-level agricultural advisories (Ramakrishna, 2014). However, institutional barriers persist, including inadequate skills for interpreting forecasts, limited human and financial resources to train end-users, and insufficient information exchange between government departments (Manjula & Rengalakshmi, 2015; Ramakrishna, 2014).

Barriers to the uptake of climate information include limited reach and delays in communication, mobile phone ownership, and geographic location (Manjula & Rengalakshmi, 2015; Singh et al., 2018a). Sociocultural acceptance of climate services is medium, constrained by issues of trust, acceptance and relevance of information (Singh et al., 2018a; Srinivasan et al., 2011; Tall et al., 2012; Venkatasubramanian et al., 2012). Access to climate information is gendered, with female farmers less likely to be aware of agro-advisories than male farmers, though efforts to make climate services inclusive have seen advances and successes (Mittal & Hariharan, 2018; Rengalakshmi et al., 2018; Venkatasubramanian et al., 2014;).

The environmental feasibility of climate services and EWS is high as they minimise risks related to climate and extreme events through early warnings and forecasts and have strong potential to build local adaptive capacities (Lobo et al., 2017; Mittal & Hariharan, 2018; Singh et al., 2018a). Seasonal forecasts aid in determining seed stocking, crop choice, crop combinations and flexible weather-based agriculture planning (Manjula a& Rengalakshmi, 2015; Mittal & Hariharan, 2018; Lobo et al., 2017).

6.4.3.6 Disaster risk management

Disaster risk management projects and reconstruction activities typically require substantial funding, which can be particularly challenging for smaller communities (Rautela et al., 2020).

India has high technical resource availability for disaster preparedness and management, with various dedicated bodies such as the National Disaster Management Authority, the Ministry of Earth Sciences, and the Indian Meteorological Department. These bodies have strong technical capacities in improving forecasting technology, disseminating early warnings, setting standard operating procedures, and using ICT- and GIS-based applications (Mehta et al., 2018; Mohanty et al., 2010; Pal et al., 2017; Pal & Shaw, 2018). However, governance challenges remain. For instance, while cyclone monitoring and warning systems have improved significantly, barriers such as state- and district-level hazard detection and monitoring, last-mile warning communication, and real-time impact-based forecasts and risk-based warnings persist (Mohapatra & Sharma, 2019). Additionally, existing legal frameworks are inadequate for handling complex interventions such as the relocation of people, and insufficient local participation of key stakeholders and vulnerable populations, as well as trust issues, often lead to resistance or poor uptake of disaster risk management initiatives (Choudhary & Neeli, 2018; Ghosh & Boyd, 2019; Goyal, 2019; Jain et al., 2021).

Disaster risk reduction has significant socio-economic co-benefits, such as improved health during heat waves (Das & Smith, 2012) and reduced exposure and vulnerability to hazard risk. However, the impacts are highly contingent on the type of intervention and its suitability and acceptability to local populations. Ecosystem-based disaster risk reduction has emerged as an effective way to manage risk while protecting and strengthening existing ecosystem services (Dhyani et al., 2018).

6.4.3.7 Migration and relocation

Moving away from risk, either through voluntary migration or planned relocation, has long been practiced as an adaptive strategy across India. While not always driven by climate change, environmental degradation and climatic variability increasingly contribute to these movements (Bhatta et al., 2015; Dallmann & Millock, 2017; Deshingkar, 2012; Jha et al., 2018; Maiti et al., 2014; Pradhan & Narayanan, 2020; Viswanathan & Kavi Kumar, 2015).

The outcomes of migration for vulnerable communities are mixed. While migration can increase income and improve asset ownership, it often reduces subjective well-being (Krishna, 2013; Mitra, 2010; Maharjan et al., 2020; ; Singh & Basu, 2019). Planned relocation measures also yield mixed economic impacts, with resettlement typically associated with unequal livelihood outcomes (Jain et al., 2021; Michael et al., 2018). Although migration and relocation can reduce risk exposure and diversify livelihoods (Deshingkar, 2012), migrants frequently face challenges such as insecure tenure, unaffordable rents, precarious livelihoods, increased conflict in destination areas, heightened risk exposure, and loss of social networks and political capital (Abbas & Verma, 2014; Jain et al., 2017b; Michael et al., 2018; Singh & Basu, 2019).

Institutional feasibility of migration is low, with officials often unwilling to accept documentation from migrants, sometimes due to discrimination or in order to obtain bribes (Abbas & Verma, 2014). Additionally, internal migration is not legally recognised in India, and migrant workers typically lack the ability to make political demands for entitlements or to seek reforms (Bhagat, 2017; Chu & Michael, 2019; Michael et al., 2018). While national and state disaster management authorities are mandated to ensure resettlement as a last resort, significant governance challenges remain (Jain & Bazaz, 2020).

The sociocultural feasibility of migration and relocation is mixed. In some cases, migration negatively impacts children's education (Afifi et al., 2016; Murali & Afifi, 2014), while in others, it can improve opportunities to earn and hence educate children (Singh & Basu, 2019). Migration can have varied intergenerational consequences depending on the type of movement and the livelihoods pursued. For example, inadequate access to education for children of migrants can perpetuate intergenerational poverty, hindering skill-building and education necessary for improved life quality, health and stable livelihoods (Abbas & Verma, 2014; Afifi et al., 2016).

Political will to recognise the importance of migration and public acceptability, particularly in destination areas, remains a critical barrier. There is strong evidence that migrants often remain politically, socially and economically disenfranchised at their destinations (Krishna et al., 2014; Kundu & Ray Saraswati, 2012; Michael et al., 2018). The acceptability of disaster-related relocation varies and depends on the type of relocation and the process undertaken. Evidence shows that phased recovery with public consultation has greater acceptability (Jain et al., 2021; Joshi & Nishimura, 2016).

Migration can also erode ecosystem services (Singh et al., 2018b), but the implications for ecological resilience are less clear. Increased use of agrochemicals can pollute soil and water systems, and migration can lead to intensified agriculture through capital investment on larger farms, adversely impacting soil and water conservation (Deshingkar, 2012).

6.5 Conclusion

India's ambition to be an advanced economy by 2047 hinges on its capacity to grow while generating jobs, ensuring climate protection, and safeguarding social and economic security of its citizens. To effectively confront the climate change challenge, the country must implement adaptation and mitigation actions that are feasible within our socio-economic contexts and geographical realities, and aligned to our development goals.

Adopting the CRD framework, this chapter offers a suite of such feasible adaptation and mitigation options that can be implemented across scale to address the climate change challenge in India. The options assessed, initially drawn from the IPCC's Fifth Assessment Report (AR5) and Special Reports, were strategically selected based on India's targets and national communication to UNFCC (see methodology in Annexure A). Our six-dimensional framework assessments reveal several climate adaptation and mitigation options with moderate-to-high feasibility across all key evaluated system: energy, land, oceans and ecosystems, urban and infrastructure, industry, and a cross-cutting category.

For instance, in energy systems, solar PV and wind energy emerge as highly viable mitigation options, scoring high-to-medium feasibility across all six assessed parameters. Solar PV has high feasibility across economic, social, technological and environmental parameters and medium feasibility for institutional and geophysical parameters. Existing policies have significantly advanced solar power development, and there is substantial potential to expand both grid connected and off-grid solar power solutions in the country, such as solar parks in low-carbon industrial clusters, expanding rooftop solar programme, developing reliable grid infrastructure for solar.

In land, oceans and ecosystems, adaptation options like conservation agriculture, agricultural diversification, grazing land management, agroforestry and water resource management have high-to-medium overall feasibility. Many of these have been supported by existing government initiatives like NMSA, NICRA, zero-budget farming and the National Agroforestry Policy. However, these options also face challenges like that of low adoption due to lack of technical know-how, inadequate extension services, low awareness and lack of equipment, among others.

Adaptation options like water resource management also offer multiple co-benefits like higher incomes, disaster risk reduction and livelihood diversification. However, its adoption is hindered by institutional barriers such as inadequate capacity to fully leverage watershed programmes (Dhawan, 2017) and ineffective community participation (Gray & Srinidhi, 2013). Mitigation options like reducing food wastage and ecosystem restoration for land, oceans and ecosystems transition also offer robust adaptation pathways and yield co-benefits for mitigation and Sustainable Development Goals (SDGs), but face governance and public acceptance challenges that must be addressed to unlock their full potential.

Green infrastructure is among the most feasible adaptation options in the urban and infrastructure systems. Integrating green and blue infrastructure including green roofs, bioswales, urban agriculture, urban parks into ongoing urban development and planning can promote multiple co-benefits with development and mitigation actions. Nevertheless, challenges such as inadequate financing and institutional capacity hinder progress. Low- and net-zero-energy buildings, electric mobility and public transport similarly offer high-to-moderate feasible mitigation options in urban systems but require strong institutional and policy support.

In the industrial sector, improving energy efficiency emerges as a moderate to highly feasible mitigation option. Public health systems and social safety nets among the cross-cutting adaptation options exhibit high economic feasibility but can be limited by institutional leakages and issues of unequal access. In contrast, adaptation strategies related to resettlement, relocation and migration exhibit low feasibility, primarily due to socio-institutional barriers, particularly in destination areas.

Overall, the chapter offers actionable insights into adaptation and mitigation options across key systems, assessing each against six parameters to identify those with multi-dimensional feasibility and potential for quick wins. These insights can be applied to local, regional and national contexts in India to inform broad policy lessons, support evidence-based interventions and shape a climate action trajectory towards a sustainable future. However, it is important to acknowledge that while many adaptation and mitigation strategies are feasible, significant knowledge gaps remain, particularly in the social, institutional and geophysical dimensions. To fully harness the potential of these options, targeted research and policy attention are needed.

7.

Climate change Mitigation, Adaptation, and Sustainable Development: Synergies and Trade-offs

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7. Climate change Mitigation, Adaptation, and Sustainable Development: Synergies and Trade-offs

- The integration of climate action into sustainable development is increasingly critical for India as the impacts of climate change escalate, threatening global development goals and reversing progress in improving living conditions.

- The Climate Resilient Development (CRD) framework as proposed by the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) and the 2030 Agenda for Sustainable Development, both based on principles of equity and inclusion, are closely aligned and offer numerous opportunities for synergies and co-benefits.

- To attain the 1.5°C goal, India will have to leverage synergies between mitigation and adaptation and its co-benefits with the SDGs while minimising trade-offs. Trade-offs can have distributional consequences and potentially exacerbate existing inequalities, vulnerabilities and regional disparities.

- Assessment of synergies and trade-offs (S&Ts) between existing and proposed adaptation and mitigation options, along with the 17 SDGs across key systems: urban and infrastructure, land, oceans and ecosystems, and energy; and the cross-cutting category shows multiple synergies between climate actions and the 17 SDGs. This analysis offers actionable insights for implementing the right mix of interventions to achieve CRD.

- The adaptation options demonstrate greater potential synergies with the SDGs than the mitigation options, particularly within land, oceans and ecosystems transitions, which exhibit maximum synergies and minimal trade-offs. Notably, 12 adaptation options in land, oceans and ecosystems align strongly with SDG 8 (decent work and economic growth) and SDG 12 (responsible consumption and production).

- Among the mitigation options, energy systems, particularly solar energy, show the most positive linkages with the SDGs, including significant synergies with SDG 7 (affordable and clean energy) and SDG 13 (climate action), while also fostering economic development through the creation of green jobs.

- Overall, the S&T assessment highlights substantial opportunities to leverage climate action and SDG synergies to achieve the 1.5°C target and the 2030 Agenda. This chapter suggests that ongoing climate initiatives can be reformulated for enhanced climate benefits while addressing trade-offs.

7.1 Introduction

As the impacts of climate change become increasingly severe, integrating climate action into sustainable development is more crucial than ever. Following the Paris Agreement and the IPCC's Fifth and Sixth Assessment Reports (AR5 and AR6), there is growing international consensus that climate action must be integrated with sustainable development (IPCC, 2022b).

Climate change threatens development goals and can reverse decades of progress in the improvement of living conditions worldwide.

Recognising this, the Climate Resilient Development (CRD) framework (see Chapter 3 and Chapter 6), introduced by the IPCC, presents a new development paradigm based on equity and inclusion, integrating climate action—both mitigation and adaptation—with the sustainable development and biodiversity conservation agenda. The 2030 Agenda for Sustainable Development, which is rooted in the principles of equity and inclusion, offers 17 internationally accepted development goals and 169 targets that promise to 'leave no one, no place and no ecosystem behind' (Revi & Ghoge, 2024). This agenda is closely tied to climate action, as many mitigation and adaptation actions align with the Sustainable Development Goals (SDGs). Evidence suggests that there are more potential synergies than trade-offs between climate action and sustainable development (IPCC, 2023). However, literature also suggests that some trade-offs are inevitable when striving to meet the SDGs (IPCC, 2022b).

To achieve the Paris Agreement's goal of limiting global temperature rise to 1.5°C or well below 2°C, it is essential to leverage the synergies between adaptation and mitigation, and its co-benefits with the SDGs while minimising trade-offs. The IPCC AR6 cycle outlines global solution space for climate action that also identifies these synergies and trade-offs (S&Ts). However, it is vital to transfer this scientific and technical knowledge from the global scale to the local scale so that national, regional and municipal governments, businesses, and communities can effectively implement these solutions (Revi & Ghoge, 2024). This requires identifying clear priorities for both climate action and sustainable development, along with mechanisms to achieve complementary goals (IPCC 2022b; Revi & Ghoge, 2024; Stern & Stiglitz, 2023). This approach is particularly relevant for India, where trade-offs can exacerbate existing economic and social inequities, increase vulnerabilities, and accelerate regional disparities.

To enable climate-resilient growth in India, assessing the S&Ts between climate adaptation and mitigation actions (both existing and proposed) in relation with the SDGs becomes crucial. Building on the feasibility assessment of adaptation and mitigation options across systems in Chapter 6, this chapter evaluates the S&Ts of climate action with sustainable development.

There are multiple synergies between adaptation, mitigation and the SDGs across systems, though some initiatives may also have potential negative impacts. For example, increasing access to clean energy sources reduces emissions and offers health co-benefits (SDG 3), particularly for women and children (IPCC, 2023). Accessible and affordable public transport can help reduce emissions, improve air quality, boost health, enhance employment opportunities and promote equity, thereby meeting adaptation–mitigation targets as well as many of the goals (e.g., SDG 4 on quality education, SDG 5 on gender equality, and SDG 8 on decent work and economic growth). Conversely, initiatives, such as afforestation, that enable carbon sequestration may also negatively affect socio-economic and environmental factors, impacting biodiversity, food and water security, local livelihoods, and the rights of indigenous peoples (IPCC, 2023).

In this chapter, the assessment of S&Ts with the 17 SDGs is examined across key systems, with the extent of S&Ts with specific SDGs identified as 'strong' or 'weak' based on literature relevant to India. Section 7.2 summarises the key S&Ts focused on adaptation actions across land, oceans and ecosystems, urban and infrastructure, and a cross-cutting category that spans all systems. Section 7.3 assesses S&Ts with mitigation actions across energy, land, oceans and ecosystems, and urban and infrastructure. This is followed by a brief conclusion in section 7.4.

7.2 Synergies and Trade-offs of Adaptation Actions with Mitigation Actions and Sustainable Development Goals

Sustainable development is generally aligned with climate change adaptation as it enhances adaptive capacity by tackling poverty, addressing socio-economic inequalities, promoting livelihood security, and improving inclusion and

Figure 7.1: Adaptation, mitigation and SDG synergies and trade-offs under land and ecosystem transitions

Adaptation–Mitigation Synergies Carbon sequestration potential is significant for adaptation options like improved cropland management, agroforestry, biodiversity management and ICZM. Adaptation options increase and restore soil organic content and soil microbes while reducing soil carbon loss and conserving carbon stock. Conservation agriculture and improved cropland management can lead to a substantial reduction in the energy input, leading to reduced secondary emissions.	**SDG Synergies** Improved cropland management and biodiversity management have synergies with 16 SDGs, followed by sustainable aquaculture (15 SDGs), water use efficiency (14 SDGs), ICZM (13 SDGs) and coastal defence (13 SDGs). Most options have strong synergies with SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production) and SDG 13 (climate action). Improvements in agriculture, livestock and aquaculture practices, biodiversity conservation, coastal zone management, and coastal defence can help achieve SDG 1 (no poverty) and SDG 2 (zero hunger) by alleviating poverty and enhancing food as well as nutritional security. Conservation agriculture, improved cropland management and efficient livestock also have strong synergy with SDG 3 (good health and well-being). Ecosystem restoration has synergies with all the 17 SDGs, out of which 10 are shown to be strong synergies. Sustainable intensification of agriculture has synergies with 13 SDGs. Reduced food wastage, efficient food production and sustainable intensification of agriculture have strong synergies with SDG 1, SDG 2, SDG 12 and SDG 13.
Adaptation–Mitigation Trade-offs Improved cropland management, ICZM and integrated soil and nutrient management have mitigation trade-offs, possibly leading to increased carbon emissions based on the type of intervention.	**SDG Trade-offs** ICZM exhibits weak trade-offs with a maximum of three SDGs (SDG 3, SDG 5 on gender equality and SDG 10 on reduced inequalities), followed by water use efficiency with two SDGs (SDG 5, and SDG 11 on sustainable cities and communities).

Note: ICZM = Integrated Coastal Zone Management
Source: *Authors' assessment*

institutions (IPCC, 2022b). Climate change adaptation aims to reduce risks and vulnerability and improve resilience of people to climate change. As such, climate adaptation actions have several synergies with SDGs including reducing poverty, hunger, gender and economic inequalities; improving access to clean water and health; and accelerating the creation of sustainable cities and communities. At the same time, trade-offs also exist, especially when adaptation strategies prioritise single development objectives like food security or heat-stress risk reduction or favour expensive solutions that have implications for budget allocations and equity (IPCC 2022b).

7.2.1 Land and ecosystem transitions

Figure 7.1 summarises the S&Ts between adaptation–mitigation and adaptation actions with the SDGs under land, oceans and ecosystems. As shown in the figure, land , oceans and ecosystems transitions have significant synergies between adaptation and mitigation actions as well as a majority of the SDGs. Most of the adaptation options have co-benefits with mitigation by removing, reducing or displacing the emissions of atmospheric carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O; Rao et al, 2019). This includes adaptation options like conservation agriculture, improved cropland management and agroforestry, among others. For example, studies have shown that zero tillage, one of the key methods of conservation agriculture, increases soil organic carbon (SOC), thereby reducing greenhouse gas (GHG) emissions. Similarly, crop residue management reduces the burning of crop residue, reducing the emission of N_2O and CH_4 into the atmosphere (Aryal et al, 2019). At the same time, certain interventions within improved cropland management, Integrated Coastal Zone Management (ICZM), and integrated soil and nutrient management can lead to mitigation trade-offs, increasing carbon emissions.

All the adaptation options demonstrate significant synergies with SDG 8 (decent work and economic growth; see Figure 7.2) as they can enhance the productivity of farms, fish ponds, and other terrestrial and aquatic systems, resulting in increased net returns and profits. For instance, improved cropland management practices such as laser land levelling can generate 270–330 person-days of employment annually per unit (Jat et al., 2014a), while agroforestry can provide 450 person-days per hectare (ha)/year, contributing up to 4,000 million person-days/year (Chavan et al., 2015). Options like biodiversity and coastal zone management also boost potential for eco-tourism, thereby revitalising local economies (Asian Development Bank [ADB], 2017; Mallick & Chakraborty, 2018a Pitchaikani, 2020; Roy & Datta, 2018) and offering alternative livelihood and investment opportunities.

Many options, such as improved grazing land management, ICZM and biodiversity conservation, enhance resilience against droughts and floods (Bargout, 2014; Krishnamurthy et al., 2014; Mukherji et al., 2016). Conservation agriculture, crop diversification and improved cropland management provide socio-ecological resilience to vulnerable farming communities, contributing to the development of climate-resilient agriculture systems (Bharucha et al., 2020; Birthal & Hazrana, 2019; Food and Agriculture Organization [FAO], 2017; Sapkota et al., 2015). Integrated crop-livestock systems, such as efficient livestock practices, are recognised as optimal strategies for climate adaptation, improving soil health, water retention and resource efficiency (Erenstein & Thorpe, 2010; Kumar et al., 2015).

Overall, nine out of the 12 adaptation options show strong synergies with SDG 12 (responsible consumption and production) through enhanced ecosystem services, sustainable food production, low-emission alternatives, water and energy conservation, increased resource efficiency, and combating land degradation. Five adaptation options under land, oceans and ecosystems transitions align strongly with SDG 6 (clean water and sanitation). Practices such as improved cropland management and biodiversity management can enhance water security, even in drought-prone regions (Aryal et al., 2015; Gill, 2014; Mallick & Chakraborty, 2018a; National Mission for Green India [GIM] & Ministry of Environment, Forest and Climate Change [MOEFCC], 2016). Many of these practices improve water use efficiency by increasing productivity with reduced irrigation. Targeted strategies like water use efficiency and water resource management contribute to SDG 6 by employing improved irrigation practices, rainwater harvesting, water markets and watershed management, ensuring efficient, reliable and equitable access to water (Manjunatha et al., 2011; Srinivasan et al., 2010). Sustainable aquaculture enhances

Figure 7.2: Synergies of adaptation options with SDGs under land and ecosystem transitions

System	↓ Adaptation Options SDGs →	1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	10 REDUCED INEQUALITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND	17 PARTNERSHIPS FOR THE GOALS
		Synergy/tradeoffs with SDGs											
Land and Ecosystem Transition	Conservation agriculture	*	***	*			**	**		**	***		
	Agricultural diversification	**					***	*	**	**	**		
	Improved cropland management	***	***	*	***	***	***	***	***	***	***	**	**
	Improved grazing land management	***	**			*	***	**	*	***	***	***	*
	Integrated soil management	***	***			**	***	***	***	***	***	***	
	Water use efficiency and water resource management		*		**	***	***	**	***	***	***	*	
	Efficient livestock	***	***		**		***	*	**	*	***		
	Agroforestry	***	***			*	***	**	***	***	***	***	
	Biodiversity management, conservation	***	***	*	**	***	***	**	***	***	***	***	**
	Integrated coastal zone management	***	***	*		**	***	**	***	***	***	***	***
	Coastal defence and hardening	***	*			**	***	***	**	**	***	**	***
	Sustainable aquaculture	***	***	**		**	***	**	***	***		*	*

Legend:

- *** High evidence (5 or more papers)
- ** Medium evidence (3–4 papers)
- * Limited evidence (2 papers)
- Strong synergy of the adaptation option with the SDG
- Weak synergy of the adaptation option with the SDG
- Weak trade-off between the adaptation option and the SDG
- No positive or negative impact

Note: The images in this chapter represent two major aspects for each adaptation and mitigation option: (a) the extent of synergy/trade-off with different SDGs and (b) the availability of evidence supporting this relationship (represented by the number of asterisks). The darker the colour, the stronger the relationship between the options and the respective SDGs. The higher the number of asterisks, the stronger the evidence supporting this relationship.
Source: *Authors' assessment*

waterbody productivity by reusing wastewater, reducing pollution and minimising the use of harmful chemicals (Chakrabarty et al., 2009; Edwards, 2008; FAO/Network of AquaCulture Centres in Asia Pacific[NACA], 2012). Coastal zone management and defence practices also contribute to SDG 6 by mitigating saltwater intrusion (Krishnamurthy et al., 2014; Namboothri et al., 2008).

Multiple adaptation options demonstrate strong synergy with SDG 1 (no poverty) and SDG 2 (zero hunger) by generating profits and nutritional benefits for marginalised populations. Efficient livestock practices, for instance, contribute to reducing rural poverty (Hegde, 2019) and improving food security (Ranade & Mishra, 2015). Three options—biodiversity management, agroforestry and improved grazing land management—align with SDG 14 (life below water) and SDG 15 (life on land). Biodiversity management enhances terrestrial and aquatic ecosystems by significantly increasing ecosystem resilience. For instance, watershed management involving local communities can multiply ecosystem services from restored forests and wetlands by three to eight times (Mallick & Chakraborty, 2018a). Agroforestry supports threatened wildlife by safeguarding habitats through microclimate regulation, protecting water sources, preventing soil erosion and providing fodder (Chavan et al., 2015; Roy & Tewari, 2012). Options such as improved cropland and integrated soil management also contribute to SDG 15 by reducing land degradation through enhanced soil microbial biomass (Das et al., 2017; Patra et al., 2020).

Ten out of the 12 adaptation options under land, oceans and ecosystems transitions show synergy with SDG 10 (reduced inequalities), while five also show synergy with SDG 5 (gender equality). Most adaptation options contribute to reducing inequalities by benefitting vulnerable populations. Agroforestry, conservation agriculture and agricultural diversification benefit small-scale and impoverished farmers, breaking the cycle of poverty and food insecurity (Basu, 2014; Birthal et al., 2015; Roy & Tewari, 2012). While biodiversity management and coastal defence interventions can benefit vulnerable communities, evidence suggests that these options may deepen poverty among marginalised groups due to unequal resource distribution and access restrictions (Faizi & Ravichandran, 2016). Options such as improved cropland management and sustainable aquaculture can promote gender equity and inclusivity (FAO, 2018; National Fisheries Development Board [NFDB], 2018), though certain technologies require gender-sensitive approaches to enhance equality (Bhatta et al., 2017).

Options like conservation agriculture, improved cropland management and efficient livestock practices also align strongly with SDG 3 (good health and well-being). These options mitigate serious health impacts associated with conventional agriculture and chemical use while improving overall health outcomes (Agarwal & Pandey, 2017; Bharucha et al., 2020; Hegde, 2019), including enhanced nutrition and other public health benefits. However, certain practices within three adaptation options—soil management practices, ICZM and increased water use efficiency—may negatively impact SDG 10 (reduced inequalities). For example, certain ICZM practices might exclude local and marginalised communities through restrictive and non-participatory implementations, particularly affecting women and economically disadvantaged groups (Badola et al., 2012; Datta, 2017; Ghosh, 2015; Krishnamurthy et al., 2014). Further, some practices under options like coastal defence, ICZM and biodiversity conservation can have untoward consequences such as introducing invasive species and negatively impacting fragile aquatic ecosystems, thereby affecting SDG 15 (Bunting et al., 2014; Chowdhury & Maiti, 2016; Jebakumar et al., 2019; Mukherjee et al., 2015; Roy & Datta, 2018).

Practices like efficient livestock management may also pose conflicts across multiple SDGs, such as SDG 15 (life on land), SDG 12 (responsible consumption and production) and SDG 16 (peace, justice and strong institutions), due to environmental concerns of resource scarcity and degradation of grazing lands (Blummel et al., 2009; Deshingkar et al., 2008; Hegde, 2019) alongside institutional challenges like limited market access and policy support (Birthal, 2008; Birthal & Negi, 2012). Water resource management practices have also led to conflicts between upstream and downstream communities (Surinaidu et al., 2013) and unequal resource access (Balasubramaniam et al., 2014), highlighting trade-offs with SDG 11 (sustainable cities and communities).

7.2.2 Urban and infrastructure systems transitions

Figure 7.3: Adaptation, mitigation and SDG synergies and trade-offs under urban and infrastructure systems transitions

Adaptation–Mitigation Synergies All adaptation options under urban and infrastructure systems transitions have strong mitigation co-benefits.	**SDG Synergies** Green infrastructure and ecosystem services show strong synergies with SDG 11 (sustainable cities and communities) and SDG 15 (life on land) as they reduce disaster risk, enhance livelihood capacities, improve quality of life, restore ecosystems and enable biodiversity conservation. Sustainable land use and urban planning has synergy with 10 SDGs. Low-energy buildings have strong synergies with most SDGs, especially SDG 3 (good health and well-being). Electric vehicles, hybrids, and non-motorised transport have synergies with ten SDGs.
Adaptation–Mitigation Trade-offs NA	**SDG Trade-offs** Sustainable water management has a strong trade-off with SDG 3 and weak trade-offs with as many as five SDGs (SDG 1 on no poverty, SDG 2 on zero hunger, SDG 9 on industry, innovation and infrastructure, SDG 14 on life below water, and SDG 15). The building codes and standards option has a weak trade-off with five SDGs (SDG 4 on quality education, SDG 6 on clean water and sanitation, SDG 11, SDG 12 on responsible consumption and production, and SDG 15), while sustainable land use and urban planning have weak trade-offs with four SDGs (SDG 7 on affordable and clean energy, SDG 10 on reduced inequalities, SDG 14, and SDG 16 on peace, justice and strong institutions). Public transport has trade-offs with SDG 5 (gender equality). Although public transport improves mobility and contributes to overall emissions reduction, women continue to face threats of sexual harassment at a high frequency.

Source: Authors' assessment

Figure 7.3 summarises the S&Ts between adaptation–mitigation actions and the SDGs under urban and infrastructure systems. All the adaptation options under urban systems have strong mitigation co-benefits. For example, green infrastructure and ecosystem services like urban parks, green roofs and conservation of wetlands can help sequester carbon and reduce the impact of urban heat islands and carbon emissions. They also have significant synergies with the SDGs, as discussed in Figure 7.4.

Figure 7.4: Synergies and trade-offs of adaptation options with SDGs under urban and infrastructure systems transitions

Adaptation Options ↓ **SDGs** →	1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	4 QUALITY EDUCATION	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
Sustainable land-use & urban planning	*	*	*		*	**		*	**
Sustainable water management	***	***	***	**	**	**			**
Green infrastructure & ecosystem services	*	*	*			*		**	*
Building codes & standards			**	**		**	***	*	**

Adaptation Options ↓ **SDGs** →	10 REDUCED INEQUALITIES	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	14 LIFE BELOW WATER	15 LIFE ON LAND	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	17 PARTNERSHIPS FOR THE GOALS	Urban and Infrastructure System Transition
Sustainable land-use & urban planning	**	***		***					
Sustainable water management	**	**							
Green infrastructure & ecosystem services	*	**		**		**		**	
Building codes & standards				*		*			

Legend:

***	High evidence (5 or more papers)
**	Medium evidence (3–4 papers)
*	Limited evidence (2 papers)

Strong synergy of the adaptation option with the SDG
Weak synergy of the adaptation option with the SDG

Strong trade-off between the adaptation option and the SDG
Weak trade-off between the adaptation option and the SDG
No positive or negative impact

Source: *Authors' assessment*

Urban green infrastructure and ecosystem services exhibit strong synergy with SDG 11 (sustainable cities and communities) through reduced disaster risk, enhanced livelihood capacities and improved quality of life (Adegun, 2017; Singh et al., 2013). Sustainable land use, urban planning, and urban water management practices also demonstrate synergy with SDG 11 by helping cities adapt to hazards (Chu, 2016; Revi, 2008), improving public health (Chu, 2016), controlling air pollution (Chandigarh Administration, 2018), and enabling equitable water supply and management (NITI Aayog, 2017). However, prevailing land use, urban planning and water management practices in cities have resulted in vulnerable infrastructure, increased hazard risks, reduced resilience and heightened pollution (Bhat et al., 2013; Chandel et al., 2016; Nagendra & Ostrom, 2014), thus impacting synergy with SDG 11 negatively.

Green infrastructure and ecosystem services also show strong synergy with SDG 15 (life on land) by increasing tree cover, restoring ecosystems and conserving biodiversity (Dhanya et al., 2014; Gopalakrishnan et al., 2011; Rishi & Khuntia, 2012). They can promote poverty alleviation through enhanced agricultural and fishery outputs, exhibiting some synergy with SDG 1 (no poverty; Kumar et al., 2011a; Sharma et al., 2007). Sustainable land use, urban planning, green infrastructure, and ecosystem services also impact SDG 2 (zero hunger) as they generally improve food and nutritional security (DeFries et al., 2016), though they may expose vulnerable populations to market shocks (Behera et al., 2016) and restrict their ability to meet food requirements (Sandhu & Sandhu, 2014). These options offer synergy with SDG 3 (good health and well-being) by promoting better health, increased human well-being, improved water quality, enhanced quality of life, stronger social relations, freedom of choice and improved liveability (Das & Behera, 2019; Khan et al., 2011; Sharma et al., 2007; Surat Climate Change Trust, 2017).

Building codes and standards have synergies with SDG 1, SDG 3, SDG 7 (affordable and clean energy), and SDG 13 (climate action) as they increase savings in the building and power sectors, reduce local air pollution, improve ventilation, enhance energy-use efficiency, and mitigate potential hazards (Bardhan & Debnath, 2016; Kumar & Pushplata, 2013; Somvanshi & Avikal, 2019; Yu et al., 2017). For example, passive building cooling can improve working conditions and productivity and provide health benefits (Sharma & Rajput, 2017), contributing to SDG 3 and SDG 8 (decent work and economic growth). However, evidence suggests that although sustainable building technologies are included in building by-laws, compliance in cities is often lacking (Ramaswami et al., 2017) and the high capital costs associated with green buildings affect SDG 8 (Abraham & Gundimeda, 2017).

Urban water management practices exhibit synergies with SDG 6 (clean water and sanitation) as they ensure affordable and equitable water supply to all citizens (NITI Aayog, 2017) and foster social inclusion (DISE, 2012). However, some interventions like sewage treatment plants in apartments could lead to unequal access to clean water and sanitation (Evans et al., 2009). Sustainable urban water management practices enhance education and empower women (Bharat et al., 2020; Patel, 2018). For instance, water, sanitation and hygiene (WASH) practices in schools can improve menstrual hygiene among girls and reduce school dropout rates (DISE, 2012), aligning with SDG 4 (quality education) and SDG 5 (gender equality). Proper building design can enhance health benefits and energy savings for middle- and low-income groups in metropolitan cities (Bardhan & Debnath, 2016), thus contributing to SDG 10 (reduced inequalities). Sustainable water management and green infrastructure also contribute to SDG 10 by ensuring equitable water supply (NITI Aayog, 2017). However, some practices under these options fail to prioritise the needs of the local population, leading to unequal access and distribution of resources (Kumar, 2011).

Sustainable land use, urban planning, green infrastructure and ecosystem services have synergies with SDG 8 by enhancing employment opportunities and productivity (Jose & Padmanabhan, 2015; Tiwari et al., 2016), supporting small-scale commercial activities (Gopalakrishnan et al., 2011), and promoting local economic development (Adegun, 2017). These options also align with SDG 9 (industry, innovation and infrastructure) and SDG 13 by promoting sustainable water resource utilisation (Dhyani et al., 2018; Rockefeller Foundation, 2019), increasing resilience and reducing climate-related risks (Chu et al., 2016; Cook & Chu, 2018; Singh et al., 2013; Tauhid & Zawani, 2018). However, challenges such as urban expansion and difficulties in community relocation hinder these synergies (Anguelovski et al., 2016; Chandel et al., 2016). Additionally, these options contribute to SDG 17 (partnerships for the goals) as Indian metro cities collaborate to achieve urban sustainability (Sharma & Singh, 2016), and international funding and cooperation enable green infrastructure projects (Tauhid & Zawani, 2018), despite occasional stakeholder conflicts (Mell, 2017).

7.2.3 Cross-cutting adaptation options

Figure 7.5: Synergies and trade-offs of cross-cutting adaptation options with mitigation and SDGs

Adaptation–Mitigation Synergies	**SDG Synergies**
Most options have some mitigation synergies. Social safety nets like MGNREGA can sequester carbon. Options like disaster risk management and climate services can also have mitigation co-benefits.	Most options have synergies with SDG 3 (good health and well-being), SDG 11 (sustainable cities and communities) and SDG 13 (climate action). Social safety nets have strong synergy with SDG 1 (no poverty), SDG 2 (zero hunger), SDG 5 (gender equality), SDG 8 (decent work and economic growth), SDG 10 (reduced inequalities), SDG 13 and SDG 16 (peace, justice and strong institutions) as tools like MGNREGA and PDS help in poverty reduction, food security, rural employment and gender equity. Climate services and early warning systems have strong synergy with SDG 9 (industry, innovation and infrastructure), SDG 11 and SDG 17 (partnership for the goals) as they have positive impacts on the resilience of industrial/housing infrastructure, reduce exposure to disasters and encourage public–private partnerships.
Adaptation–Mitigation Trade-offs	**SDG Trade-offs**
NA	Disaster risk management, risk spreading and sharing as well as resettlements, and relocation and migration each have weak trade-offs with three SDGs. Most options have weak trade-offs with SDG 5 and SDG 10.

Note: MGNREGA = Mahatma Gandhi National Rural Employment Guarantee Act; PDS = Public Distribution System
Source: *Authors' assessment*

Figure 7.5 summarises the S&Ts between adaptation–mitigation actions and with the SDGs in the cross-cutting category that runs across systems. Seven cross-cutting adaptation options—public health, social safety nets, risk spreading and sharing, indigenous knowledge, climate services and early warning systems, disaster risk management, and resettlement, relocation and migration—are considered in this assessment, in continuation of the feasibility assessment in Chapter 6. Most of these options have some synergies with mitigation. For example, social safety nets like the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), which guarantees fixed days of employment, can help to sequester carbon through tree plantation, forest restoration work, grassland development and land development activities like land levelling, stone bunding and earth bunding. These activities can also help India meet its Nationally Determined Contribution (NDC) target of creating 2.5–3 billion tonnes of carbon sink by 2030.

Figure 7.6: SDGs and cross-cutting adaptation S&Ts

Adaptation Options ↓ / SDGs →	1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	4 QUALITY EDUCATION	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH
Disaster risk management	*	**	**	**	**	**	*	*
Risk spreading and sharing	*	**			*	*		*
Climate services, including EWS	***	**			**		*	
Indigenous knowledge	**	*	*	*		*		
Public Health Systems	**				**			**
Social safety nets (e.g. MGNREGA, PDS)	***	**			**	**		***
Resettlement, relocation and migration	***	**			**	**		**

Adaptation Options ↓ / SDGs →	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	10 REDUCED INEQUALITIES	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	17 PARTNERSHIPS FOR THE GOALS
Disaster risk management	**	***	**		**		*	
Risk spreading and sharing		**	*					
Climate services, including EWS	**	**	**		***	*	**	**
Indigenous knowledge				*	**			
Public Health Systems	**	***	**		**		***	*
Social safety nets (e.g. MGNREGA, PDS)	**	**	***	**	*		***	
Resettlement, relocation and migration		***	***		**			*

Legend:

***	High evidence (5 or more papers)
**	Medium evidence (3–4 papers)
*	Limited evidence (2 papers)

Strong synergy of the adaptation option with the SDG
Weak synergy of the adaptation option with the SDG
Weak trade-off between the adaptation option and the SDG
No positive or negative impact

Note: EWS = Early warning system; MGNREGA = Mahatma Gandhi National Rural Employment Guarantee Act; PDS = Public Distribution System

Source: Authors' assessment

Among the cross-cutting adaptation options, climate services and social safety nets show strong synergies with SDG 1 (no poverty), while social safety nets also align closely with SDG 2 (zero hunger). Climate services contribute to poverty alleviation by boosting crop yields and agricultural incomes, whereas social safety nets, including effective implementation of tools like the Public Distribution System (PDS), play a crucial role in reducing poverty and enhancing food security. Estimates indicate that the poverty gap index for rural poverty is reduced by 18–22 per cent nationwide with the help of PDS programmes (Dreze & Khera, 2013), ensuring food security for the rural poor (Basu & Das, 2014; Khera, 2011).

Climate services indirectly contribute to improved food availability, nutritional security and increased crop yields, thereby reducing hunger and contributing to SDG 2 (Attri, 2020; Bal & Chandran, 2021; Ramakrishna, 2014). Options like risk spreading and sharing and indigenous knowledge offer synergies with SDG 1 and SDG 2 by alleviating poverty, cutting costs, enhancing productivity and income, and promoting balanced nutrition (Dey et al., 2019;Pradhan et al., 2018; Priyadarshini & Abhilash, 2019).

Low investment in public health and weak health infrastructure can exacerbate poverty (Balarajan et al., 2011; Kasthuri, 2018; Reddy et al., 2011), indicating weak synergy between public health systems and SDG 1. Indigenous communities, being more vulnerable to climate change, face challenges due to increasing detachment from land and productivity, particularly in economically disadvantaged regions (Datta et al., 2015). Evidence on migration as an adaptation option for poverty alleviation is mixed (Abbas & Verma, 2014; Choithani, 2017; Jain et al., 2017a; Singh, 2019; Singh & Basu, 2019). Migration can enhance food security through increased purchasing power, although this is contingent upon the type and destination of migration (Choithani, 2017; 2020).

Most cross-cutting options show synergy with SDG 3 (good health and well-being) through policy guidelines for hospital safety, public health awareness campaigns and timely warnings. Disaster risk management can mitigate disease outbreaks following disasters (Krishnan & Patnaik, 2020), although some disasters can disrupt the healthcare system (Rautela et al., 2020). Social safety nets like MGNREGA also improve health outcomes by enhancing socio-economic conditions in rural households (Aggarwal et al., 2012; Dev & Dev, 2011; Khera & Nayak, 2009). Resettlement, relocation and migration also enhance material well-being, although this is contingent upon migration type, destination and livelihoods (Jain et al., 2017b; Jha et al., 2018; Michael et al., 2018; Mitra, 2010; Singh & Basu, 2019). Disaster risk management practices ensure the safety of school children and bolster school resilience, enabling them to access education (National Disaster Management Authority [NDMA], 2009; 2016).

Indigenous knowledge, migration and social safety nets contribute to SDG 4 (quality education) through improved child education (Dev & Dev, 2011; Dey & Sarkar, 2011; Priyadarshini & Abhilash, 2019), particularly for the next generation of permanent migrants (Krishna et al., 2014). Social safety nets strongly support SDG 5 (gender equality) and SDG 10 (reduced inequalities). For instance, rural welfare programmes like MGNREGA empower women by providing employment opportunities, better wages and safer working conditions (Azam, 2012; Khera & Nayak, 2009; Pellissery & Jalan, 2011).

Options like indigenous knowledge strongly align with SDG 6 (clean water and sanitation) by promoting better water resource management through traditional practices, especially in vulnerable areas (Priyadarshini & Abhilash, 2019; Sarkar et al., 2015). Risk spreading and sharing and social safety nets enhance access to clean water and sanitation through sustainable agricultural practices (Bassi & Kumar, 2010; Das & Smith, 2012; Pradhan et al., 2018). However, the intangibility of water as a public good poses challenges for insurance and cost assessment of damages (Patankar & Patwardhan, 2016).

SDG 8 (decent work and economic growth) strongly aligns with social safety net adaptations like MGNREGA (Adam, 2015; Azam, 2012; Basu, 2014; Khera & Nayak, 2009). Disaster risk management and risk-sharing practices also support vulnerable populations through livelihood-centred approaches and insurance schemes (Pradhan et al., 2018). Additionally, public health systems contribute to SDG 8 by protecting the working population from risks like heat stress (Venugopal et al., 2015) and fostering sustainable healthcare systems (Balarajan et al., 2011).

Risk spreading and sharing, and indigenous knowledge promote SDG 12 (responsible consumption and production) through sustainable agricultural and pastoral practices (Kodirekkala, 2018; Wu et al., 2014). Social safety nets like MGNREGA contribute to SDG 12 by restoring and enhancing natural capital assets such as ecosystems and forests for biomass production and carbon sequestration, alongside civic work like canal and pond clearing (Adam, 2015; Basu, 2014; Carswell & De Neve, 2014).

Climate services and early warning systems strongly align with SDG 11 (sustainable cities and communities) by reducing disaster exposure (Andimuthu et al., 2019; Mohanty et al., 2020; Singh et al., 2018a). Other options such as disaster risk management, public health systems, risk sharing and social safety nets contribute to SDG 11 by enhancing urban and community resilience (Adam, 2015; Carswell & De Neve, 2014; Revi, 2008), and improving disaster adaptation capacities (Dhyani & Thummarukuddy, 2016; Knowlton et al., 2014; Krishnan & Patnaik, 2020; Nambiar, 2015).

Resettlement and migration can increase income and asset ownership but often lower the quality of life for migrating populations, thus impacting SDG 10 (Abbas & Verma, 2014; Chu & Michael, 2019; Cronin & Guthrie, 2011; Jain et al., 2017b; Michael et al., 2018; Mitra, 2010;Singh & Basu, 2019). Migration may also increase gendered work burdens, especially for the women left behind, thereby showing trade-offs with SDG 5 (Chindarkar, 2012; Bhagat, 2017; Jain et al., 2017b; Singh & Basu, 2019).

7.3 Synergies and Trade-offs of Mitigation Actions with Adaptation Options and Sustainable Development Goals

Mitigation aimed at reducing GHG emissions, by avoiding, removing or sequestering, is central to addressing climate risks and pursuing CRD. By limiting emissions and accelerating decarbonisation, mitigation actions alter development trajectories, which can affect the existing economic structure, markets, income distribution and consumption (IPCC, 2022b). This can also have impacts on achieving the SDGs including access to clean energy, food security, poverty reduction and income equality.

Mitigation actions aligned with limiting warming to 1.5° C could make it easier to achieve the SDGs, even though there are likely to be some trade-offs in the process. CRD can be achieved by enabling mitigation synergies with sustainable development, accounting for trade-offs and taking measures to offset them through appropriate policy interventions, which include safety nets (e.g., direct cash payments, food support and revenue recycling; IPCC, 2022b). Many mitigation actions can also have both trade-offs and synergies. Potential synergies between mitigation and sustainable development are found in renewable energy, energy efficiency, promoting public transport, Carbon Dioxide Removal (CDR) methods, among other actions.

7.3.1 Energy systems transitions

Figure 7.7: Adaptation, mitigation and SDG synergies and trade-offs under energy systems transitions

Adaptation–Mitigation Synergies	**SDG Synergies**
NA	Mitigation options such as solar PV have strong synergies with SDG 5 (gender equality), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 9 (industry, innovation and infrastructure) and SDG 13 (climate action). Efficient lighting and appliances have strong synergies with SDG 7, SDG 11 (sustainable cities and communities) and SDG 13. Wind energy and smart grids also have a higher proportion of positive externalities on multiple SDGs. SDG 7, SDG 8, SDG 9 and SDG 13 have more synergies with the options under this system transition. A climate-compatible energy transition has socio-economic implications since renewable energy provides employment opportunities and scope for economic growth. Some mitigation options have synergies with SDG 16 (peace, justice and strong institutions) and SDG 17 (partnership for the goals). Cross-boundary energy trade optimises energy transitions between the countries involved and strengthens partnerships. Options like EVs can improve air quality, with reduced disease risk and improved health, thereby contributing to SDG 3 (good health and well-being). EVs can generate 1.2 lakh jobs in powertrain, battery and charger manufacturing, thus enabling SDG 8 (CEEW 2019a; Shakti Sustainable Energy Foundation 2020a).
Adaptation–Mitigation Trade-offs	**SDG Trade-offs**
NA	Hydropower exhibits maximum trade-offs against the SDGs, with as many as three strong trade-offs and six weak trade-offs. Wind energy and hydropower have strong trade-offs with both SDG 14 and SDG 15, as they impact life both on land and below water. Energy systems transition options have the highest number of trade-offs with SDG 3 and SDG 6 (clean water and sanitation).

Note: CEEW = Council on Energy, Environment and Water; EV = Electric vehicle
Source: Authors' assessment

Figure 7.7 summarises the S&Ts between adaptation–mitigation actions and the SDGs under energy systems. Nine energy options are considered under energy systems transitions to assess synergies between adaptation, mitigation and the SDGs. These include wind energy, solar energy, hydropower, bioenergy, nuclear energy, energy-efficient lighting and appliances, smart grids, electricity storage, and carbon capture and storage (CCS) in the power sector.

Figure 7.8: SDG and mitigation S&Ts under energy system transitions

Mitigation Options ↓ / SDGs →	1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	4 QUALITY EDUCATION	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
Wind energy (onshore and offshore)	*		*				**	**	**
Solar PV	***	*	***	**	**	**	***	***	***
Bioenergy	***	**	***		**	**	***	*	
Hydropower	***	*			*	**	**	**	
Electricity storage			*				**		**
Power sector CCS							***		*
Smart grids							***		*
Efficient lighting, appliances	**					*	**	*	**
Nuclear			*				*	**	*

Mitigation Options ↓ / SDGs →	10 REDUCED INEQUALITIES	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	14 LIFE BELOW WATER	15 LIFE ON LAND	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	17 PARTNERSHIPS FOR THE GOALS	
Wind energy (onshore and offshore)				***	**	**			Energy System Transition
Solar PV			**	***		**			
Bioenergy				**					
Hydropower				**	**	***		***	
Electricity storage			**	**					
Power sector CCS				***				**	
Smart grids				*					
Efficient lighting, appliances		*	*	***					
Nuclear			**	**		*			

Legend:

***	High evidence (5 or more papers)
**	Medium evidence (3–4 papers)
*	Limited evidence (2 papers)

Strong synergy of the adaptation option with the SDG
Weak synergy of the adaptation option with the SDG

Strong trade-off between the adaptation option and the SDG
Weak trade-off between the adaptation option and the SDG
No positive or negative impact

Note: CCS = Carbon capture and storage

Source: *Authors' assessment*

There is insufficient evidence in the Indian context to comment on the possible synergies or trade-offs between energy systems transition options and SDGs related to gender (SDG 4), inequalities (SDG 10), and biodiversity (SDG 14 and SDG 15). There is also a lack of studies on externalities from smart grids, nuclear energy, CCS and electricity storage. Despite government support and international partnerships, CCS deployment remains in its nascent stages in India. Thus, research on the development–mitigation nexus related to CCS is underexplored. Research on nuclear energy also predominantly focuses on technological aspects.

Solar energy and energy efficiency improvements have positive impacts on related SDGs. Wind energy and smart grids also show predominantly positive externalities on the SDGs. SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation and infrastructure) exhibit the highest synergy with options under this system. Some of the synergies with SDGs are discussed in greater detail below.

7.3.1.1 Affordable and clean energy (SDG 7)

Renewable energy, particularly solar and wind, has become economically competitive, with their levelized cost of electricity (LCOE) now equal to or lower than that of coal (Gadre et al., 2020; Shrimali et al., 2015). India's levelized auction tariffs for wind and solar energy are among the world's lowest, despite relatively higher borrowing costs and the absence of hidden subsidies. A significant reduction in India's future power sector–related CO_2 emissions could result from the ancillary benefit of reducing renewable energy costs (Lu et al., 2020).

Off-grid solar energy access in remote or inaccessible areas provides clean energy to the bottom of the pyramid (BoP) communities (Joshi et al., 2019). Climate modelling and forecasting studies emphasise the crucial role of solar and wind energy in increasing the share of renewables in India's total energy mix (Mittal et al., 2018; Shukla et al., 2015; Vishwanathan et al., 2018; Zhou et al., 2020). In a 1.5°C scenario energy mix by 2050, renewables like solar photovoltaics (PV) and hydropower are projected to significantly increase their share compared to a 2°C scenario (Mittal et al., 2018).

Bioenergy also offers a viable alternative to coal. Biogas technologies, for example, have the potential to conserve an estimated 79 metric tonne (MT) of fuelwood annually, resulting in the avoidance of 16 MT of carbon emissions, assuming 40 per cent of fuelwood needs are currently met by unsustainable sources (Ravindranath & Balachandra, 2009). The total carbon abatement potential of biomass power, including combustion and gasification, based on technical potential is estimated at 89 million tonnes of carbon (MTC), with a 45 per cent capacity factor (Ravindranath & Balachandra, 2009).

Several demand-side interventions, such as improved energy efficiency (International Energy Agency [IEA], 2020) and smart grids (Jha et al., 2014) contribute to emission reduction efforts. Enhanced energy efficiency is associated with a reduction in marginal abatement costs (Chaturvedi & Shukla, 2014). India's initiatives to improve energy efficiency have collectively saved an additional 15 per cent of annual energy demand and avoided 300 MT of CO_2 emissions from 2000 to 2018, according to IEA analysis (2020).

Experimental results indicate that power consumption can be reduced by 40–55 per cent. Further energy savings of up to 60–65 per cent can be achieved through individual lighting device control, dimming control technology, and voltage optimisation (Gopal et al., 2018). The potential energy savings from improved room air conditioner (AC) efficiency in India, using the best available technology, are projected to exceed 118 terawatt hours (TWh) by 2030, with potential peak demand savings estimated at 60 gigawatt (GW). This is equivalent to avoiding the need for 120 new 500 megawatt (MW) coal-fired power plants (Phadke et al., 2019).

7.3.1.2 Decent work and economic growth (SDG 8)

Energy transition has socio-economic implications as renewable energy creates employment opportunities and fosters economic growth. Renewable energy technologies are typically more labour-intensive than conventional ones (Council on Energy, Environment and Water [CEEW], 2019a). Distributed renewables like small-scale hydro, rooftop solar and biomass generate significant employment per MW of installed capacity. Biomass employs 16 persons for constructing and running a one-megawatt plant. Small-scale hydro and rooftop solar employ 14 persons and 25 persons, respectively, for the same capacity (CEEW, 2019a). Ground-mounted solar projects create approximately 3.5 job-years per MW (National Resources Defense Council [NRDC], 2017). Solar energy and biomass are expected to drive substantial employment, with projections up to 1.1 million and 2 million employees, respectively, by 2050 (NRDC, 2017).

The rising sales of off-grid solar solutions can translate into increased job opportunities, expanding energy access and stimulating economic activity in previously isolated communities. To meet India's targets for solar and wind energy, over 0.3 million workers are anticipated to be employed in these sectors between 2018 and 2023, with a significant proportion in rooftop solar (NRDC, 2017). Apart from direct employment, some energy systems transition options enhance labour productivity. For example, studying the adoption of energy-efficient LED lighting in garment factories around Bengaluru, Adhvaryu et al., (2018) found that LED lighting increases labour productivity on hot days. The average factory in the study saved about US$ 2,880 in power consumption and earned about US$ 7,500 in productivity gains.

7.3.1.3 Industry, innovation, and infrastructure (SDG 9)

Renewable energy interventions can alleviate the financial burden of power subsidies on states and redirect resources towards the capital costs of renewable energy deployment (Swain, 2020). The deployment of solar energy serves as a catalyst for micro, small and medium enterprises (MSMEs), creating multiple opportunities in infrastructure, power and energy (KPMG, 2015). Ancillary activities related to renewable energy deployment also offer infrastructure development prospects and subsequent industrial opportunities. For instance, the Make in India initiative supports electric vehicles (EVs), aiming to attract global companies to manufacture solar PV, lithium-ion batteries, solar charging infrastructure and other advanced technologies in India. To boost foreign direct investment, the government conducts competitive tenders for large-scale manufacturing facilities for EVs, charging stations, solar PV cells and lithium-ion batteries, and offers financial incentives for adopting EVs.

Prominent research and development (R&D) centres, such as the National Institute of Solar Energy, National Institute of Bio-Energy and National Institute of Wind Energy, were established under various technological initiatives for renewable energy in India (Kumar et al., 2019). Low tariff rates for wind and solar energy also foster an environment conducive to industrial growth in these sectors. Transparent bidding processes further facilitate progress. The wind energy sector has developed a robust ecosystem to support project execution capabilities and local manufacturing. State-of-the-art technologies for wind turbine production are now available, with major global players having established their presence in India. India exports wind turbines and components to USA, Europe, Australia, Brazil and other Asian countries. Domestic production accounts for 70–80 per cent of the market, driven by strong local manufacturing companies (Kumar & Majid, 2020).

Continuous efforts in clean energy have spurred rigorous R&D across various sectors. For example, the National Thermal Power Corporation (NTPC) and Bharat Heavy Electricals Limited (BHEL) are collaborating on numerous experimental initiatives to enhance these technologies. BHEL conducted oxyfuel testing at the Fuel Evaluation Test Facility (FETF) in 2010. India's largest gas and energy supplier, Oil and Natural Gas Corporation (ONGC), is exploring CO_2 injection for enhanced oil recovery (EOR) at the Ankleshwar petroleum field (Shukla et al., 2020). Research into new battery chemistries and hybrids is an active field in both basic and applied research (de Sisternes et al., 2019). Moreover, hydrogen and its derivatives are gaining attention, particularly renewable-generated hydrogen, to produce synthetic fuels for construction, transport and industrial applications. There are also feedback loops between technological innovation in various energy systems transition options. Lazkano et al., (2017) found a positive effect of electricity storage on renewables innovation, as storing electricity is crucial for mitigating intermittency in renewable electricity generation. Increased knowledge about internal storage is associated with greater innovation in both renewable and conventional technologies.

7.3.1.4 Peace, justice, and strong institutions, and partnerships for the goals (SDG 16 and 17)

Certain options have synergies with SDG 16 and SDG 17 through cross-boundary energy trade, optimising energy transitions and fostering partnerships. In South Asia, the Bangladesh, Bhutan, India, Nepal (BBIN) sub-region stands out as the first to demonstrate cooperation in cross-border energy trade (Dhakal et al., 2021; Haran, 2018). The Chukha hydropower project in Bhutan, for instance, exemplifies successful cooperation between countries, with Bhutan receiving a significant investment of US$ 404 million from India, comprising 60 per cent as a grant and 40 per cent as a loan at 5 per cent interest. Such South–South financial flows are expected to mutually benefit hydropower production in the region (Timilsina, 2018; Vaidya et al., 2021).

7.3.1.5 Other synergies

The renewable energy sector also addresses poverty (SDG 1) by creating employment, increasing income and improving living standards, thereby reducing energy poverty. Buragohain (2012) found that implementing solar PV through the Remote Village Electrification Programme (RVEP) improved overall living standards and children's education, while decreasing reliance on traditional energy sources, ultimately helping households move out of poverty in the long term. Energy efficiency measures and expanded energy access can free up resources (i.e., financial resources and time savings) that can then be redirected towards other productive uses (e.g., education and employment opportunities), especially benefiting women and children in poor rural areas (Pueyo & Maestre, 2019).

Renewables also benefit health by reducing air pollution since they are emissions-free. Increased adoption of solar and wind energy leads to lower emissions of GHGs and other harmful pollutants such as SO_2, various nitrogen oxides and by-products of fossil fuels, which contribute to environmental degradation and health issues (Chaurasiya et al., 2019).

7.3.2 Land, oceans and ecosystems transitions

Four mitigation options are reviewed under land and ecosystems transitions including reduced food wastage and efficient food production, dietary shifts, sustainable intensification of agriculture, and ecosystem restoration. The literature review found no evidence linking dietary shifts and reduced food wastage in India to several SDGs, including SDG 4 (quality education), SDG 5 (gender equality), SDG 6 (clean water and sanitation), SDG 9 (industry, innovation and infrastructure), SDG 14 (life below water), SDG 15 (life on land), SDG 16 (peace, justice and strong institutions) and SDG 17 (partnership for the goals), highlighting a significant knowledge gap for these adaptation strategies. The shift towards a vegan and organic diet and its implications have been extensively discussed globally but remain underexplored in the Indian context.

Four of the five mitigation actions reviewed align well with two goals: SDG 12 for responsible consumption and production, and SDG 13 for climate action. Reduced food wastage and efficient food production contribute to efficient resource management (Ray & Ghose, 2014), lower energy consumption (Premalatha et al., 2011), reduced disease burden, diminished environmental footprint (Aleksandrowicz et al., 2019) and decreased GHG emissions (Agrawal & Nag, 2013). Dietary shifts can also promote a healthy and sustainable lifestyle, reduce environmental impact, lower GHG emissions and improve climate mitigation outcomes (Pathak et al., 2010; Rao et al., 2018; Sadhukhan et al., 2020; Sharma et al., 2020). For instance, a shift towards coarse cereals like millets and leafy vegetables could potentially reduce India's agricultural GHG emissions by 25 per cent (Rao et al., 2018). However, such shifts need to consider nutritional implications since recommendations often involve reduced consumption of milk and eggs, which are associated with higher emissions (Vetter et al., 2017).

Ecosystem restoration also contributes to SDG 12 and SDG 13 by restoring vegetation (Adam, 2015; Foundation for Ecological Security [FES], 2020), enhancing resilience against climate-induced disasters (Bawa et al., 2021; Laulikitnont, 2014), promoting ecological rehabilitation, improving soil quality and increasing carbon sequestration (Awasthi et al., 2017; Brahma et al., 2018; Edrisi et al., 2018). For example, in a revegetated mine, total sequestered carbon increased by 712 per cent over 19 years, demonstrating an annual carbon sequestration potential of 3.64 t C ha−1 yr−1 (Tripathi et al., 2014). Mangrove restoration through replanting in the Sundarbans increased organic carbon

Figure 7.9: SDG and mitigation S&Ts under energy system transitions

Mitigation Options ↓ / SDGs →	1 No Poverty	2 Zero Hunger	3 Good Health and Well-Being	4 Quality Education	5 Gender Equality	6 Clean Water and Sanitation	7 Affordable and Clean Energy	8 Decent Work and Economic Growth
Land-use & urban planning		*	**	*		*	*	**
Electric vehicles, hybrids			**				**	**
Public transport	*		**	**	**		*	*
Non-motorised transport	*		*	*	*		*	**
Aviation & shipping			*			*	**	
Low/zero-energy buildings			**	*		**	***	**

Mitigation Options ↓ / SDGs →	9 Industry, Innovation and Infrastructure	10 Reduced Inequalities	11 Sustainable Cities and Communities	12 Responsible Consumption and Production	13 Climate Action	15 Life on Land	17 Partnerships for the Goals	
Land-use & urban planning	*	**	***		*	**		Urban & Infrastructure System Transition
Electric vehicles, hybrids	**	**	**	**	*	*	*	
Public transport		*	**		**			
Non-motorised transport		*	*		*	*		
Aviation & shipping	*		**	**	*			
Low/zero-energy buildings	**		*	*	**	**		

Legend:

***	High evidence (5 or more papers)
**	Medium evidence (3–4 papers)
*	Limited evidence (2 papers)

Strong synergy of the adaptation option with the SDG
Weak synergy of the adaptation option with the SDG

Strong trade-off between the adaptation option and the SDG
Weak trade-off between the adaptation option and the SDG
No positive or negative impact

Source: *Authors' assessment*

density from 54–69 t/ha to 83–132 t/ha over five years (Chowdhury et al., 2019).

Techniques under sustainable intensification of agriculture conserve water and energy (Sapkota et al., 2017), reduce the use of chemical fertilisers (Bunting et al., 2014), improve soil quality and enhance productivity (Choudhary et al., 2018a; 2018b). Sustainable intensification also aids climate change mitigation by reducing GHG emissions from agriculture through efficient energy use and increased soil carbon sequestration (Hazra & Bohra, 2020; Kumar et al., 2020a; Yadav et al., 2018). In north-west India, adopting reduced-till or full conservation agriculture-based cropping systems could potentially reduce total global warming potential by 15–30 per cent (Kumar et al., 2018b).

These mitigation options also significantly align with SDG 1 (no poverty), SDG 2 (zero hunger) and SDG 3 (good health and well-being). Ecosystem restoration supports rural livelihoods (Abhilash, 2021; Awasthi et al., 2017; Edrisi et al., 2018; Mallick & Chakraborty, 2018a), enhances food and nutritional security through increased farm and fish productivity (Bawa et al., 2021; Das, 2017; Edrisi et al., 2018), and potentially builds resilience against zoonotic diseases and future epidemics (Bawa et al., 2021; Singh et al., 2021). Reduced food wastage and efficient food production can alleviate poverty, enhance food security (Bharucha, 2018) and reduce diet-related health burdens (Aleksandrowicz et al., 2019). Sustainable intensification of agriculture can address socio-economic challenges associated with endemic poverty (Bharucha et al., 2020; Bunting et al., 2014) and improve food and nutritional security by enhancing crop productivity with fewer resources (Islam et al., 2019 in the eastern Gangetic plains; Kumar et al., 2020; Parihar et al., 2016 in north-west India; Pradhan et al., 2018; Prasad, 2016).

Sustainable intensification of agriculture, ecosystem restoration, and afforestation and reforestation show strong synergies with SDG 8 (decent work and economic growth). Ecosystem restoration can support rural livelihoods, create new jobs (Awasthi et al., 2017;Tripathi et al., 2016; Valencia, 2019), provide regional socio-economic benefits (Edrisi et al., 2018; Mallick & Chakraborty, 2018a), and promote ecological and rural tourism (Singh et al., 2021). Sustainable intensification of agriculture also enhances livelihoods based on agriculture (Bunting et al., 2014) and increases agricultural productivity and profits (Kumar et al., 2020a). For instance, the System of Rice Intensification (SRI) has increased net returns by 31 per cent and reduced input costs by 26 per cent in Tamil Nadu (Barah, 2009). Meanwhile, in West Bengal, integrating diversified aquatic biodiversity with SRI contributed an additional income of ₹30,150 to vulnerable communities (Bunting et al., 2014).

Many programmes and strategies under afforestation, such as community-based forest management, the National Afforestation Programme (NAP) and MGNREGA, provide income and livelihood opportunities to marginalised communities throughout the year (Murthy, 2013; Press Information Bureau [PIB], 2019; Ramprasad et al., 2020; Singh, 2008; Wolosin, 2017). This option also reduces the risk of crop failure, provides alternative income, offers financial incentives, supports livestock, provides fuelwood and contributes to food production (Murthy, 2013; Sekar, 2015; Tripathi, 2015). For instance, GIM aims to improve ecosystem services on 10 million ha of land across India, potentially increasing forest-based livelihood opportunities and offering additional income for around 3 million forest-dependent households (Sharma & Chaudhry, 2013). The Clean Development Mechanism (CDM) also supports reforestation and afforestation activities, yielding substantial economic returns for farmers (Gera, 2012, in Andhra Pradesh; Tripathi, 2015, in Himachal Pradesh). This option, as evidenced, also has strong synergy with SDG 1.

Overall, afforestation and reforestation could contribute to an 11 per cent increase in the carbon stocks of Indian forests from 2006 to 2030 (Geelani et al., 2018; Ravindranath et al., 2008). Afforestation with poplar plantations could also help increase carbon sequestration potential (Gera, 2012) while building resilience to climate hazards like droughts, flash floods and landslides (Roy, 2020).

Limited evidence also suggests that urban afforestation programmes can yield multiple benefits such as reduced GHG emissions, better air quality and direct cooling of the microclimate (Imam & Banerjee, 2016), demonstrating strong synergy with SDG 11 (sustainable cities and communities). These options also exhibit synergy with SDG 9 and SDG 17, as programmes like Tamil Nadu Afforestation Programme, NAP, and those supported by

Figure 7.10: SDGs and mitigation S&Ts under urban and infrastructure system transitions

Mitigation Options ↓ / SDGs →	1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	4 QUALITY EDUCATION	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
Reduced food wastage & efficient food production	*	**	*				*	*	
Dietary shifts		**	**						
Sustainable intensification of agriculture	*	**				***	**	***	*
Ecosystems restoration	**	**	*	*		***	**	***	**
Afforestation & reforestation	***	**			*		*	***	***
Soil carbon sequestration & biochar	*	***	**			**	*	*	*

Mitigation Options ↓ / SDGs →	10 REDUCED INEQUALITIES	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	14 LIFE BELOW WATER	15 LIFE ON LAND	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	17 PARTNERSHIPS FOR THE GOALS	
Reduced food wastage & efficient food production			***	*					Land and Ecosystem Transition
Dietary shifts	*		***	***					
Sustainable intensification of agriculture			***	***		**			
Ecosystems restoration	***		***	***	**	***	**	***	
Afforestation & reforestation	***			***		***	***	**	
Soil carbon sequestration & biochar			***	***		*	**		

Legend:

***	High evidence (5 or more papers)
**	Medium evidence (3–4 papers)
*	Limited evidence (2 papers)

Strong synergy of the adaptation option with the SDG
Weak synergy of the adaptation option with the SDG

Strong trade-off between the adaptation option and the SDG
Weak trade-off between the adaptation option and the SDG
No positive or negative impact

Source: *Authors' assessment*

Japan Bank for International Cooperation (JBIC), Swedish International Development Cooperation Agency (SIDA), and various state forest departments encourage the transfer and adoption of improved technologies (PIB, 2019; Sekar, 2015; Shashidharan, 2012).

Afforestation and reforestation also support a wide range of rural and wood-based industries (Kaul, 2010; Murthy, 2013) and have enabled numerous multilateral, national and international partnerships and investment opportunities for Indian governments and institutions (Sekar, 2015; Sharma & Chaudhry, 2013). Additionally, they have established several local- and regional-level institutions like joint forest management and forest development agencies (Lok Sabha Secretariat, 2015; PIB, 2019; Sharma & Chaudhry, 2013), underlining synergies with SDG 16 and SDG 17. At the same time, while some evidence suggests increased food productivity (Murthy, 2013), studies also highlight reduced food security for marginalised communities due to exclusionary and monoculture afforestation practices (Roy, 2020; Valencia, 2019), exhibiting weak trade-off with SDG 2.

Ecosystem restoration also exhibits synergy with SDG 4 and SDG 5 by promoting equal employment opportunities for women and enhancing education opportunities for children (Abhilash, 2021). These options also align strongly with SDG 6, as ecosystem restoration rejuvenates traditional waterbodies (Adam, 2015), facilitates water recycling (Edrisi et al., 2018), restores degraded wetlands and streams (Krishnamurthy et al., 2014; Kumari et al., 2020; Mondal and Patel, 2018), promotes groundwater recharge (Mallick & Chakraborty, 2018a), and enriches aquatic and terrestrial biodiversity, thereby supporting SDG 14 and SDG 15 through the restoration of degraded habitats (Adam, 2015; Awasthi et al., 2017; Mondal & Patel, 2018; Nawab & Hussain, 2012). However, lack of safeguards can lead to unscientific restoration practices such as the use of fast-growing commercial species that can adversely affect native forests (Busch & Mukherjee, 2017).

Sustainable intensification of agriculture also demonstrates synergy with SDG 6 and SDG 7 by reducing groundwater depletion (Jat et al., 2020), enhancing water and energy use efficiency (Barah, 2009; Bharucha et al., 2020; Pretty & Bharucha, 2014), promoting biodiversity (Bharucha et al., 2020; Bunting et al., 2014), and conserving natural resources and ecosystem services (Choudhary et al., 2018a; Hazra & Bohra, 2020).

Given current agricultural and food pricing scenarios, promoting dietary shifts for health and environmental benefits could be unaffordable for more than 50 per cent of India's population, which earns less than PPP US$ 2 per day (Gupta & Bharati, 2019), demonstrating a trade-off with SDG 10 (reduced inequalities).

7.3.3 Urban and infrastructure systems transitions

Low-energy buildings have the strongest synergies with SDG 3 (good health and well-being) as they often incorporate passive cooling, which has been shown to improve the overall health of occupants in India (Kumar et al., 2018). These buildings also align with SDG 7 (affordable and clean energy) by reducing energy consumption by over 30 per cent in new residential buildings and by 40 per cent in new commercial buildings. Additionally, they support SDG 9 (industry, innovation and infrastructure; Kumar et al., 2018).

Aviation and shipping have strong synergy with SDG 13 (climate action), as many cities in India have taken effective climate action measures to improve fuel efficiency and renew fleets. Currently, three airports—Mumbai, Delhi and Bengaluru—are operating under the Airport Carbon Accreditation Scheme (Maurya, 2013).

EVs have significant synergy with SDG 8 (decent work). A projected 30 per cent increase in new vehicle sales by 2030 is expected to generate 120,000 jobs in the EV industry and related sectors, such as EV battery, charger and powertrain manufacturing (Soman et al., 2020). This initiative also aligns strongly with SDG 11 (sustainable cities and communities). Major cities in India, including Bengaluru and Pune as well as some cities in Kerala, have taken steps to promote EVs and support infrastructure like charging stations (Majumdar et al., 2015).

7.4 Conclusion

The assessment of S&Ts between adaptation–mitigation actions and SDGs in India using the IPCC systems transitions framework provides actionable insights to identify and implement the right mix of interventions and enable the transition to CRD pathways. The analysis shows that both adaptation and mitigation options have multiple synergies with SDGs across systems, although many interventions can have mixed impacts and some can lead to trade-offs.

Overall, the adaptation options show greater potential synergies with the SDGs than the mitigation options. For instance, adaptation options under land, oceans and ecosystems transitions exhibit maximum synergies with SDGs and minimal trade-offs. All the 12 adaptation options under land, oceans and ecosystems have strong synergy with SDG 8 (decent work and economic growth), while nine of the 12 options have strong synergies with SDG 12 (responsible consumption and production). Nearly 11 of the actions also synergise with SDG 13 (climate action), SDG 1 (no poverty) and SDG 2 (zero hunger). This indicates significant potential to accelerate adaptation options, like improved cropland management, improved grazing land management, biodiversity management and conservation, and conservation agriculture, that reduce vulnerability to climate extremes and improve resilience among farming families. Many of these interventions that are practised in India and included within missions and policies need to be accelerated and implemented across a wider ambit.

Similarly, the assessment of four adaptation options under urban and infrastructure systems show strong synergy with SDG 11 (sustainable cities and communities). For instance, urban green infrastructure and ecosystem services have significant potential to achieve both climate gains and help meet SDGs (synergies with nine of the 17 SDGs) in Indian cities as these interventions can reduce disaster risks, improve resilience and enhance quality of life in urban areas. However, some of these options also show mixed impacts. For instance, sustainable urban water management practices have the potential to contribute to SDG 10 (reduced inequalities) by promoting equitable access, but some of these practices also lead to unequal access by failing to prioritise the needs of the local population.

The assessment also shows that majority of the adaptation interventions (six out of the seven considered) in the cross-cutting category have significant synergies with SDG 1, SDG 2, SDG 3 (good health and well-being), SDG 11 and SDG 13. Adaptation options like social safety nets (e.g., MNREGA and PDS) align with 12 of the 17 SDGs. Social safety nets can improve food security, reduce poverty, provide decent work, improve health outcomes, reduce inequalities and improve gender equity.

Among the mitigation options, those under energy systems transitions, followed by land, oceans and ecosystems transitions, and then urban and infrastructure systems transitions, have the most positive linkages with SDGs. For instance, solar energy has synergies with 12 SDGs and no negative impacts. It has significant positive linkages with SDG 7 (affordable and clean energy), SDG 8, SDG 9 (industry, innovation and infrastructure) and SDG 13. All the mitigation options under energy systems, barring hydropower, have strong synergies with climate action. Solar PV, wind and hydropower also show significant potential for creating green jobs and opening multiple low-carbon pathways in the manufacturing sector to produce aligned low-carbon technologies and infrastructure. These renewable energy options contribute to economic development in the country through both the service sector by creating new green jobs and the manufacturing sector through the production of new low-carbon technology and infrastructure-aligned products.

The mitigation options under land, oceans and ecosystems transitions, such as ecosystem restoration (which has synergies with all the SDGs), and afforestation and reforestation, show positive synergies with SDG 1, SDG 8, SDG 9 and SDG 13 and a weak trade-off with only SDG 2. Under urban and infrastructure systems, mitigation options like low-energy buildings, promoting EVs and public transport can reduce emissions, improve energy efficiency and have positive linkages with decent work, innovation and building sustainable cities. With 50 per cent of India poised to be urban by 2047, mitigation options under this system can be key to a climate-resilient urban transition.

Overall, the S&Ts assessment shows significant scope to leverage climate action and SDG synergies to meet the goal of 1.5°C and Agenda 2030. Many of the ongoing climate adaptation and mitigation options can help achieve various SDGs, including those related to reducing poverty and hunger, decent work, access to clean water and sanitation, climate action, affordable energy and innovation, among others. At the same time, various development actions and policies have synergies with climate action and can be reformulated and tweaked for better climate benefits. For instance, policies linked to improving access to environmental services, such as Atal Mission for Rejuvenation and Urban Transformation (AMRUT) and Swachh Bharat Mission (SBM), and those linked to housing such as Pradhan Mantri Awas Yojana (PMAY), have synergies with climate action. AMRUT, aiming for water-secure cities and towns, has a component for restoration of ecosystems and creation of urban green spaces, which can be widened for greater benefits. PMAY, which envisages affordable housing for all, can be made more climate resilient with additional top-up funding to make way for climate-resilient building materials. Overall, it is possible to implement both adaptation and mitigation actions together across systems considering their synergies as well as trade-offs with sustainable development (IPCC, 2023).

8.

Enabling 1.5°C in India

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8. Enabling 1.5°C in India

- The implementation of 1.5°C-compatible adaptation and mitigation options relies upon a supportive financial, institutional, technological and behavioural environment.
- We examine six conditions to enable the four system transitions: enhancing multi-level governance; improving institutional capacities; strengthening policy instruments; climate finance; enabling technological innovation; and behavioural and lifestyle change.
- While progress has been made in technology and innovation, multi-level governance, policy instruments, and institutional capacities, more attention must be paid to climate finance—what the finance need is, where sectoral gaps exist and leveraging different sources of funding.
- Gaps also remain on understanding how to incentivise lifestyle and behavioural change for mitigation and adaptation. Further research and development (R&D) is required on developing national and sub-national data repositories on all aspects of climate action and national monitoring exercises in progress.

8.1 Introduction

The successful implementation of 1.5°C-compatible adaptation and mitigation options relies on a supportive financial, institutional, technological and behavioural environment. This ecosystem is shaped by specific enabling conditions that enhance the feasibility of adaptation and mitigation actions, accelerate systems transitions, and ultimately shift developmental pathways towards Climate Resilient Development (CRD; Intergovernmental Panel on Climate Change [IPCC], 2023). It is essential to have the right enabling conditions in place, including policies, frameworks, engagement strategies and investments, for transformative action (Summary for Urban Policymakers [SUP], 2023).

Building on discussions of the feasibility of mitigation and adaptation actions in Chapter 6, and synergies and trade-offs in Chapter 7, this report concludes with an analysis of the enabling conditions that can guide India's 1.5°C climate trajectory. Using the IPCC framework, this chapter assesses six enabling conditions that can facilitate the four key system transitions essential for CRD. These conditions include enhancing multi-level governance, improving institutional capacities, strengthening policy instruments, facilitating climate finance, promoting technological innovation, and fostering behavioural and lifestyle changes. The chapter examines India's current policy direction and presents evidence related to these six enabling conditions across the key systems transitions.

Further, the chapter highlights fourteen case studies that illustrate adaptation and mitigation actions across the country (Table 8.1). These examples, spanning various regions and sectors, demonstrate how incremental and transformative measures can support India's transition to 1.5°C pathways. The success of these case studies often relies on a combination of enabling conditions. For instance, the success of India's National Solar Mission (see Case Study 3) is based on three enabling conditions: multi-level governance, policy instruments and finance.

The chapter is organised as follows. Section 8.2 looks at multi-level governance and its role in successful adaptation and mitigation in land, oceans and ecosystems transition, supported by two case studies. Similarly, section 8.3 examines institutional capacity building and its role in climate mitigation initiatives in energy and urban systems, while section 8.4 examines how policy instruments drive effective climate action through evidence shown

Table 8.1: Illustrative case studies demonstrate how system transitions towards 1.5°C can be enabled

System Transition	Illustrative Case Study	Adaptation/ Mitigation/ Both	Enabling Conditions					
			Multi-level Governance	Institutional Capacity	Policy Instruments	Finance	Technological Innovation	Behavioural and Lifestyle Change
Energy	National Solar Mission	Mitigation	✓		✓	✓		
	Electric vehicles	Mitigation			✓	✓	✓	✓
	PAT scheme	Mitigation		✓	✓		✓	
	Rent a Roof policy	Mitigation		✓				
Land, oceans and ecosystems	Zero Budget Natural Farming	Both	✓		✓	✓		
	CAMPA and GIM	Mitigation			✓	✓		
	Integrated soil management	Both			✓	✓	✓	
	Integrated Coastal Zone Management	Adaptation						
	Improved irrigation efficiency	Adaptation	✓		✓	✓	✓	✓
Urban and Infrastructure	Building codes and standards	Adaptation			✓	✓		
Cross-cutting Options	Heat action planning in Ahmedabad, Gujarat	Adaptation		✓	✓		✓	✓
	MGNREGA	Adaptation	✓	✓	✓	✓		✓
	Early warning systems in Odisha	Adaptation		✓	✓	✓	✓	
	National Agrometeorological Advisory Services	Adaptation	✓	✓		✓	✓	

Note: CAMPA = Compensatory Afforestation Fund Management and Planning Authority; GIM = National Mission for Green India; MGNREGA = Mahatma Gandhi National Rural Employment Guarantee Act; PAT = Perform, Achieve and Trade. Different cases showcase adaptation and mitigation implementation across scales (national, state and local) and from different states in India.

Source: *Authors' compilation*

across land, oceans and ecosystems, energy, urban and infrastructure systems and the cross-cutting category. Section 8.5 highlights the pivotal role of climate finance in climate transformative action and section 8.6 emphasises the importance of technological innovation. Finally, section 8.7 addresses the importance of behavioural change in achieving climate goals, followed by a brief conclusion in section 8.8.

8.2 Enhancing Multi-level Governance

Enabling multi-level governance across different scales holds significant potential for facilitating India's transition towards a 1.5°C-consistent pathway. Governance mechanisms that span various levels—local, municipal, regional and national—and engage with diverse stakeholders can effectively support robust strategies for climate adaptation and mitigation while also promoting sustainable development. Multi-level governance can foster inclusive, transparent and equitable decision-making, enhance access to finance and technology, and strengthen monitoring and evaluation processes (IPCC, 2023). It can help build consensus among different stakeholders and diverse interest groups, improve coordination, and help address context-specific vulnerabilities and inequities through well-designed policies, legal frameworks, participatory processes and interventions.

In India's federal system States have the primary responsibility for governing many sectors that impact and are impacted by climate change. The State Action Plans on Climate Change (SAPCCs) that are meant to contextually outline the implementation plan for climate action in accordance with the national framework i.e. the National Action Plan on Climate Change (NAPCC) can be considered a strong overarching step towards enhancing multilevel governance.

8.2.1 Enhancing multi-level governance in land, oceans and ecosystems transitions

In the context of land, oceans and ecosystems transitions, the adoption of Zero Budget Natural Farming (ZBNF) in Andhra Pradesh serves as a notable example of multi-level governance via a policy-driven shift towards sustainable agriculture at both national and state levels, thereby incentivising adaptation (see Case Study 1). A critical factor contributing to the successful scaling of ZBNF in Andhra Pradesh was the layered approach to implementation, allowing for a build-up of momentum and expertise over time (Bharucha et al., 2020). Practically, it involves engaging multiple institutions at various tiers—from local gram panchayats to state-level departments—alongside a supportive network of peers, practitioners and agronomists. This network is designed to facilitate a knowledge-based transition from resource-intensive farming practices to ZBNF (Bharucha et al., 2020). In addition, ZBNF's success can be traced to two other enabling conditions: adequate financial support and strengthening of policy instruments.

ZBNF initiatives have been replicated in other regions of India as well. For example, in Himachal Pradesh, the Prakritik Kheti Khushal Kisan Scheme (PKKKS), launched in 2018, provides financial support to promote ZBNF among farmers. In Punjab, conservation agriculture techniques such as laser land levelling in rice fields, planting on raised beds and zero tillage for wheat have gained traction (Sidhu et al., 2010). Similarly, there has been a gradual shift towards sustainable agriculture in the Indo-Gangetic Plains. However, wider acceptance of ZBNF in this region has been hindered by the initial costs associated with machinery such as zero-tillage equipment (Sapkota et al., 2015).

Multi-level governance is also evident in Case Study 2, which examines mangrove management under Integrated Coastal Zone Management (ICZM), where state forest departments partner with communities and non-governmental organisations (NGOs) for joint mangrove management and protection.

Box 8.1: Case Study 1 - Zero Budget Natural Farming

Zero Budget Natural Farming (ZBNF) refers to a suite of agricultural practices aimed at minimising farm costs by reducing non-synthetic inputs and embracing natural methods. It is a policy-driven initiative in Andhra Pradesh and Karnataka, expanding into the Indo-Gangetic belt and the eastern states of India (Bharucha et al., 2020). Sustainable agriculture is a priority under national mandates like the National Mission for Sustainable Agriculture (NMSA), supported by institutions such as the National Initiative on Climate Resilient Agriculture (NICRA), with ZBNF becoming pivotal in achieving goals of climate-resilient and economically viable farming (Khadse & Rosset, 2019). ZBNF can meet both climate adaptation and mitigation goals as it enhances farm biodiversity, improves soil health, increases soil carbon sequestration and reduces small farmers' vulnerability by increasing incomes. Along with this, ZBNF helps meet several of the SDGs as it promotes decent livelihoods and food self-sufficiency, increases farm incomes, and promotes gender equality.

Policy and governance: In Andhra Pradesh, ZBNF is a state policy with a goal of transforming 6 million farms to zero-budget farms by 2027. The roll-out is managed by Rythu Sadhikara Samstha (RySS), a public sector body under the Department of Agriculture, collaborating closely with farmers through extensive extension and support networks (Bharucha et al., 2020). RySS was set up by the Andhra Pradesh government to train farmers and promote farmer-to-farmer learning. ZBNF's rapid expansion in the state can be attributed to programme's network of fellows that train farmers and its linkages with women's self-help groups (SHGs). It illustrates a successful state-led model, promoting female leadership and collective learning at the local level (Khadse & Rosset, 2019).

Institutional capacity: Andhra Pradesh leveraged its experience with group approaches, particularly through the widespread women's SHG movement, integrating ZBNF as an initiative for food and livelihood autonomy (Khadse & Rosset, 2019). SHGs mobilise farmers to adopt ZBNF, help prepare their plans, monitor progress and also offer financial credit during their transition phase.

Finance: The sustained implementation of the scheme is supported by substantial government funding. Approximately ₹100 crore comes from private philanthropy organisations like the Azim Premji Foundation for technical assistance (Bharucha et al., 2020). The government has also taken a loan of about 90 million euros or Rs 711 crore (2020-21 rates) from the German KfW bank out of the Rs 1, 015 crore to be spent on the scheme from 2020-2025 (Das et al., 2024; The New Indian Express, 2020). Besides this the scheme was allocated Rs 305 crore by the state government from 2016-17 to 2020-21.

Some other examples of multi-level governance mechanisms aiding the implementation of effective measure in land, oceans and ecosystems measures come from improved grazing land management and reduced grassland conversion to cropland. Administrative measures have emphasised building community capacities to develop and maintain pastures, and to create and manage fodder buffer stocks (Satapathy et

Box 8.2: Case Study 2 - Mangrove management under Integrated Coastal Zone Management

Integrated Coastal Zone Management (ICZM) encompasses mangrove management as well as soft coastal defence strategies such as bioshields, which offer cost-effective defences with enhanced ecological benefits. Joint mangrove management is particularly prominent in Tamil Nadu, Odisha, West Bengal and Gujarat (Dasgupta & Shaw 2013).

Enhancing institutional capacity: Forest departments partner with communities and non-governmental organisations (NGOs) for joint forest/mangrove management (Datta 2017; Roy & Datta 2018). State governments have made institutional arrangements to support mangrove-dependent communities. Further, various organisations, such as the MS Swaminathan Research Foundation (MSSRF), World Wide Fund for Nature (WWF), Wildlife Protection Society of India (WPSI) and Mangroves for the Future (MFF), are working to promote biodiversity and create awareness to aid mangrove-dependent communities economically (Dasgupta & Shaw 2013). State initiatives to enable ICZM include the Gujarat Coastal Zone Management Authority that oversees coastal management with local support (Agoramoorthy et al., 2014) and the Maharashtra Mangrove Cell that implemented GIZ's 'Sustainable Management of Coastal and Marine Protected Areas', which led to the Thane Flamingo Sanctuary (Kathiresan, 2018).

Finance: The Government of India initiated an ICZM project at both national and state levels, with financial assistance of US$ 222 million from the World Bank to implement a comprehensive coastal management approach (World Bank, 2017). Additionally, the government has made significant financial contributions to mangrove protection. Currently, 38 mangrove areas in the country are under active management action plans, receiving 100 per cent financial support from the Ministry of Environment, Forest and Climate Change (MoEFCC; Kathiresan, 2010; 2018).

Scalability and regional differentiation: Bioshield plantations on private and village lands face land use challenges, contrasting with plantations in government land that are less susceptible to anthropogenic change (Mukherjee et al., 2008; 2015). Shoreline variations near coastal protection structures depend mostly on the morphology of the coast. Seawalls along dynamically stable beaches and accreting beaches do not cause any significant morphological modifications, while along eroding beaches they are affected by toe scouring and slumping, leading to the disappearance of frontal beaches (Thankappan et al., 2018).

al., 2011). Programmes such as Joint Forest Management (JFM) promote multi-purpose management, aiming to balance tree products and herbaceous fodder through techniques like pruning, pollarding, lopping and grazing/browse rotations to ensure desired regeneration of trees and ground-cover vegetation (Roy & Singh, 2008).

In Rajasthan, the Maru Gochar Yojana (Desert Pasture Lands Development Plan), launched during 2003–04 by the central government, allocated funds directly to village panchayats to rehabilitate community lands through silvopastoral models such as '*orans*' (sacred groves) and '*gauchars*' (village grazing lands). The plan integrated traditional knowledge with scientific practice, demonstrating effective land management (Chaudhry et al., 2011). Similarly, the Partnership for Land Use Science (Forest-PLUS), a collaborative initiative between USAID India and the Ministry of Environment, Forest and Climate Change (MoEFCC), aims to promote sustainable forest management. It has developed and piloted simple yet effective grazing management techniques to enhance ecological resilience (USAID, 2017).

8.3 Improving Institutional Capacities

Building institutional capacities is crucial to achieve 1.5°C-consistent development pathways for India. Strengthening the capabilities of various institutions, from national-level bodies to local community-based organisations, will create a robust framework for climate change adaptation and mitigation. This section provides examples from energy, land, oceans and ecosystems, urban and infrastructure, and the cross-cutting category to illustrate how enhanced capacities have enabled positive climate action.

8.3.1 Institutions for energy system transitions

Improved institutional capacities have significantly facilitated transitions in energy systems, particularly in solar energy. Two notable examples are the National Solar Mission (Case Study 3) and the Rent a Roof policy (Case Study 4).

Box 8.3: Case Study 3 - National Solar Mission

The Jawaharlal Nehru National Solar Mission (JNNSM), established by the Government of India in 2010, is one of the eight missions under the National Action Plan on Climate Change. It aims to promote solar power in India, ensuring energy security while fostering sustainable and energy-efficient growth. The mission's broad objectives include: (a) establishing 20,000 megawatt (MW) of solar power by 2022; (b) expanding the supply of grid-connected solar power to 20 gigawatt (GW) by 2022; (c) advancing off-grid solar power applications to over 2 GW; (d) increasing solar-powered home lighting systems in rural areas to 20 million; (e) expanding solar thermal collectors to 20 million sq. m by 2022; and (f) creating favourable conditions for increasing solar manufacturing and consumption capability.

Stakeholder capacity building: The solar energy sector involves various actors, including business enterprises (solar firms), policy institutions, regulatory authorities (Ministry of New and Renewable Energy), research institutions (National Institute of Solar Energy), financial institutions, industry associations (Solar Energy Society of India) and NGOs. Under JNNSM, significant research and development is undertaken through the participation of these diverse actors. The R&D programme evaluates emerging technologies and identifies policy and market conditions conducive to a thriving solar industry. Workshops and training programmes disseminate and promote knowledge on solar energy. For instance, the Ministry of New and Renewable Energy has introduced a fellowship for solar science (Akoijam & Krishnan, 2017).

The solar rooftop project, conducted in collaboration with the Solar Energy Corporation of India, involves large-scale grid-connected solar rooftops. This scheme engages the residential sector, with financial assistance provided by the Central Finance Assistance and incentives for distribution companies based on the grid capacity installed. The active participation of various actors, including policymakers, the financial industry and commercial solar producers, is crucial for the success of these schemes. Regular feedback from stakeholders can significantly enhance the effectiveness of the scheme (Shrimali & Rohra, 2012). Thus, despite significant progress under the National Solar Mission, further policies are needed to commercialise solar technology, strengthen market conditions and improve access to finance.

Box 8.4: Case Study 4 - Rent a Roof

The Rent a Roof business policy, part of the Grid Connected Solar Rooftop Programme, allows developers to lease rooftop spaces to capture solar power for feeding into the grid. Anchored by the Ministry of New and Renewable Energy, this policy is crucial for generating renewable energy, offering developers a lease amount in exchange for using rooftop spaces.

The policy extends the earlier net metering system. Previously, consumers were billed for the electricity consumed, in addition to what was generated by their rooftop panels, and they bore the responsibility for maintaining the structures. Under Rent a Roof, developers take on the installation, operation and maintenance of the panels. By providing financial incentives to homeowners while placing the responsibility of maintenance on developers, the policy aims to attract more households.

In Karnataka, the Soura Gruha Yojane by the Bangalore Electricity Supply Company (BESCOM), part of the Grid Connected Rooftop Solar Programme, aligns with the Karnataka Electricity Regulatory Commission's (KERC) 2019 order recognising third-party investments in Solar Roof Top Photovoltaic (SRTPV). Developers can now install, own and operate solar panels on rooftops on the payment of a monthly rent to households. Under this arrangement: (a) third-party investments with domestic and low-tension consumers follow net metering; (b) third-party investments with non-residential and low-tension consumers follow a gross metering system; (c) domestic consumers do not pay a cross-subsidy surcharge and can obtain energy from the third party without additional costs.

Gujarat has also successfully incentivised solar installations, resulting in 50,915 subsidised residential rooftop solar plants as of March 2020, the highest number of such installations in any state. In a new initiative, residential consumers can sell surplus power at ₹2.25 per unit after adjusting their consumption. Recognising the importance of domestic consumers in advancing solar energy, Gujarat has introduced projects where owners are entitled to either rent or a share in the developer's profits.

8.3.2 Institutions for land, oceans and ecosystems transitions

Widespread participation, flexibility and integration of stakeholders, along with prioritising community-based measures over institutional ones, are crucial for sustained adaptation. Building the capacity of institutional functionaries through training and ensuring widespread dissemination of both scientific and local/indigenous knowledge by forming and strengthening networks are essential. These efforts, coupled with flexibility, integration and equity, are integral to enhancing institutional capacities. We can see these attributes in many of the initiatives under the land, oceans and ecosystems transitions that are discussed below.

Agricultural diversification is facilitated through effective institutional practices and enhanced capacity building. For example, in Himachal Pradesh, technical know-how from institutions has been transferred to rural communities through a network of regional research stations and government departments of agriculture and horticulture, accelerating crop diversification (Sharma, 2011).

Efforts to build institutional capacity have significantly advanced cropland management. For example, India has established the Kisan Sanchar Samuha, which provides weather information and farm-specific solutions to farmers via mobile phones, enhancing market connectivity (Aryal et al., 2020a). The National Initiative on Climate Resilient

Agriculture (NICRA), launched by the Indian Council of Agricultural Research (ICAR) in 2011, aims to enhance the resilience of agriculture to climate change through strategic research and technology demonstration.

Several institutions provide professional training and capacity building for forest management. The Indira Gandhi National Forest Academy and the Directorate of Forest Education organise training for Indian Forest Service (IFS)officers, state forest service officers and forest range officers (Krishnan et al., 2012). Other institutions like the Wildlife Institute of India, Indian Plywood Industries Research and Training Institute, and Indian Institute of Forest Management conduct training and research to equip personnel with requisite skills.

Efforts in building institutional capacity for ICZM have led to the setting up of the National Centre for Sustainable Coastal Management (NCSCM), which promotes sustainable management of coastal and marine areas and advises on policy and scientific matters (NCSCM, 2020). Apart from this, the various coastal zone management authorities regulate and enforce matters concerning the Coastal Regulation Zone (CRZ) Notification of 2011, improving integration across government levels, sectors, and public and private interests (Portman et al., 2012). State governments and NGOs have also made institutional arrangements to support mangrove-dependent communities.

Sustainable aquaculture is enabled through effective institutions and partnerships. Government and non-government organisations actively conduct trainings and promote certain species (Apine et al., 2019). The ICAR Central Marine Fisheries Research Institute initiated mariculture activities in the 1980s, leading to small-scale commercial practices by the 1990s (National Fisheries Development Board, 2018).

8.3.3 Institutions for urban and infrastructure system transitions

Building institutional capacity for urban and infrastructure system transitions is especially important, given the multiplicity of actors, institutions and mandates in urban areas. Decentralising climate action from national and state to city level require robust institutional frameworks and setups. City level climate action plans are decentralised, contextual and strategic frameworks that could provide guidance for climate action for cities. The Mumbai Climate Action Plan (MCAP) prepared by the Brihanmumbai Municipal Corporation in 2022 serves as a good example. The MCAP, framed as a policy document, provides strategic guidance for sector-specific mitigation and adaptation apart from identifying the climate risks and vulnerabilities that the city faces. The MCAP has also institutionalised the setting up of a 'Climate Cell' that coordinates the implementation and monitoring of all climate change related activities in the city, ensuring interdepartmental coordination for climate action.

Case Study 5, through the example of heat action planning, provides a notable example of how multiple enabling conditions—institutional capacity building, technological innovation, and increasing policy recognition of changing climate risks—can shape proactive risk management. The Ahmedabad Heat Action Plan (HAP) has set a precedent for other cities in managing extreme heat. Key lessons from this plan include recognising heatwaves as significant and increasing health risks, mapping high-risk communities, establishing public cooling centres, and issuing heatwave alerts through various media channels (Guleria, 2018). In 2020, the central government collaborated with 23 states and over 100 cities and districts to develop and implement HAPs across India (Natural Resources Defense Council [NRDC], 2020). This widespread initiative marks a significant step towards a coordinated national response to extreme heat.

At the state level, the Odisha State Disaster Management Authority has developed a HAP with critical components such as early warning systems, public outreach through online and telephone services, medical upgrades, and administrative measures like issuing notices for early school hours during extreme heat conditions (Guleria, 2018). Similarly, Andhra Pradesh has emphasised dissemination of information about heatwave risks. An awareness campaign advises citizens to avoid peak heat times (11 a.m. to 5 p.m.) and urges extra precautions for pregnant women. Several districts also undertake the distribution of oral rehydration solution (ORS) and provision of drinking water in public places (NRDC, 2020). Telangana's Heatwave Action Plan includes adaptation strategies similar to those of the Ahmedabad Municipal Corporation. Additionally, it incorporates mitigation

Box 8.5: Case Study 5: Heat action planning in Ahmedabad

Heatwaves, qualified as maximum temperatures of at least 40°C in the plains and at least 30 °C in hilly areas, are common across India and account for approximately 20 per cent of deaths resulting from extreme weather events (Mahapatra et al., 2018). Due to global warming, extreme heat events are expected to become more frequent and severe (Jacobs et al., 2019). India's average temperature has risen by ~0.7°C from 1901 to 2018 and is projected to increase by ~4.4°C by 2100 (Krishnan & Patnaik, 2020).

Adapting to increasing heat exposure is critical for risk reduction. Heat Action Plans (HAPs) are comprehensive strategies that include early warning systems and preparedness plans (Natural Resources Defense Council [NRDC], 2019). Ahmedabad's experience in May 2010, when temperatures reached 47°C and resulted in 1,344 deaths, underscored the need for such plans (NRDC, 2019). Consequently, Ahmedabad developed a HAP to mitigate extreme heat exposure.

Policy instruments: At the national level, the National Disaster Management Authority (NDMA) supports local heat action plans through the NDMA Heat Guidelines 2019 (NRDC, 2019). Additionally, the Indian Meteorological Department issues five-day heatwave warnings, updated four times a day, through the All India Weather Forecast Bulletin.

Enhancing institutional capacity: The Ahmedabad HAP strengthened institutional capacity by converging various government departments, building partnerships and recommending the appointment of a central authority within the AMC to coordinate across departments, including disaster management, health, transport, and civil society (AMC, 2016).

Implementation and impact : Ahemdabad HAP was piloted in 2013 and launched in 2014 through a partnership between the Ahmedabad Municipal Corporation (AMC), the Public Health Foundation of India, and international organizations (Hess et al., 2018). It has since become a model for 30 cities in India, focusing on protecting vulnerable populations from extreme heat (Jacobs, 2019). The plan includes public outreach on health risks, improved coordination between government agencies, and an early warning system to forecast heat events with longer lead times, enabling better preparedness (Knowlton et al., 2014). Evidence from Ahmedabad shows a reduction in mortality during heatwaves in the first two years after the HAP's implementation.

Technological innovation: Ahmedabad's Heat Action Plan (HAP) addresses the built environment by mapping high-risk areas, increasing access to cooling spaces, and launching a citywide 'cool roof' program aimed at reducing indoor temperatures by 2–5°C, particularly in informal settlements (AMC, 2016). The city planned to install 15,000 cool roofs in 2020, including on government buildings and low-income housing. Local NGOs, such as the Mahila Housing SEWA Trust, also contribute to the installation efforts. The Indian Cooling Action Plan 2019, which emphasizes cool roofs as a key strategy, aligns with these local initiatives to reduce air conditioning demand nationwide.

strategies such as maintaining waterbodies in forest areas for wildlife and promoting afforestation and plantation efforts. These efforts underscore the importance of both adaptation and mitigation in combating the effects of extreme heat.

At the central level, the National Disaster Management Authority (NDMA) is leading efforts by supporting state and local HAPs through the recently updated NDMA Heat Guidelines (2019). These guidelines provide a comprehensive roadmap for states and cities to develop effective HAPs.

Another example of institutional capacity building in urban and infrastructure systems, particularly in sustainable land use and urban planning, is the Asian Cities Climate Change Resilience Network (ACCCRN) project in Surat. This project leverages existing networks of private actors to delegate responsibilities for creating and implementing local adaptation and development strategies. To strengthen stakeholder engagement, a City Advisory Committee was established, facilitating planning for socio-economic development and addressing the city's major climate challenges. Regular interdepartmental meetings and community awareness programmes were conducted to support these efforts (TARU, 2011).

8.3.4 Role of institutions in cross-cutting adaptation options

This section discusses some successful examples of how improved institutional capacities have enabled better implementation of adaptation interventions in public health, climate services and information and communication technologies (ICT).

Enhanced institutional capacity and networks have enabled the implementation of ICT programmes for disaster risk management in India. The India Disaster Resource Network is a nationwide electronic inventory of essential as well as specialist resources for disaster response, covering specialist equipment, labour resources and critical supplies.

Installing new weather stations is a straightforward investment to support data collection for index insurance scale-up and risk spreading and sharing. This is being effectively pursued in India through robust institutions. Insurance has stimulated new markets for weather data and in some cases private companies are stepping in to fill the void. In India, for example, there is active effort from the private sector to build new weather stations and sell the data to insurance providers.

Public health initiatives have also undertaken efforts to build institutional capacity and expand networks for sharing relevant knowledge. NDMA has published several standards on specific hazards. The Disaster Management Act, 2005 requires state governments to formulate State Disaster Management Plans, detailing how to prepare for, mitigate, respond to and recover from disasters.

Additionally, the NDMA has laid out guidelines for hospital safety. The India Disaster Resource Network is also helpful in building networks to share relevant knowledge and limit risks. To detect and monitor disease outbreaks systematically, the Ministry of Health and Family Welfare, with the support of the World Bank, established the Integrated Disease Surveillance Programme (IDSP) in 2004. IDSP monitors trends in the occurrence of communicable and non-communicable diseases across the country. Its plan includes integrating existing surveillance systems, strengthening public health laboratories, and training and deploying rapid response teams for timely action during potential epidemic situations. For trauma care, a national programme on Capacity Building for Developing Trauma Care Facilities in Government Hospitals on National Highways was started, with training provided by the All India Institute of Medical Sciences (AIIMS; Krishnan & Patnaik, 2018).

8.4 Strengthening Policy Instruments

There is mounting evidence that the policy framework on climate change interacts across governance levels and is influenced by various drivers at these levels. India actively engages in climate diplomacy, where international policies are more likely to gain acceptance if they align with domestic policies. Similarly, states are inclined to adopt national recommendations when these are tailored to address local issues (Atteridge et al., 2012). This section outlines the programmes and initiatives implemented as a result of conducive policy instruments, and measures for climate change adaptation and mitigation across the systems of energy, land, oceans and ecosystems, urban and infrastructure, and the cross-cutting category.

Box 8.6: Case Study 6: Perform, Achieve and Trade scheme

Policy framework: Over the years, energy efficiency policies have evolved from taking a regulatory approach to incorporating market-based measures. The Perform, Achieve and Trade (PAT) scheme is an example of a market-driven cap-and-trade policy instrument (Misra, 2019; Sarangi & Taghizadeh-Hesary, 2020). The scheme currently covers several sectors, including aluminium, cement, chlor-alkali, fertiliser, iron and steel, pulp and paper, textiles, thermal power plants, railways, refineries, distribution companies (DISCOM) and petrochemicals. ,

In its first cycle (2012–2015), the PAT scheme covered eight energy-intensive industries and achieved energy savings of 8.7 Mtoe, surpassing the target of 6.7 Mtoe, and avoiding 31 metric tons of carbon dioxide equivalent ($MtCO_2$) emissions (Bureau of Energy Efficiency [BEE], 2023a). In the second cycle (2016–2019), the scheme expanded to 11 sectors, including refineries, railways and DISCOMs, resulting in energy savings of 14.1 Mtoe and avoiding 68 $MtCO_2$ emissions (BEE, 2023a). The third cycle achieved energy savings of approximately 1.8 Mtoe. From PAT Cycle III onwards, the roll-out has been happening annually, with new designated consumers and new sectors being added in some cycles. Seven cycles have been announced so far, with estimated savings of about 26 Mtoe, which can help avoid 70 million tonnes of CO_2 emissions. The duration of each cycle is three years, with no interim targets (Chunekar & Apte, 2023).

Strengthening policy interventions: The institutional and regulatory structure of PAT is administrated by BEE, the Central Electricity Regulatory Commission (CERC) and Power System Operation Corporation (PSOC), with India Energy Exchange (IEX) and Power Exchange India Limited (PXIL) being responsible for the power exchanges (Ministry of Power, 2017). Based on energy consumption in the pilot years, energy caps are arrived at for each designated consumer (DC)/firm. If the DC limits its energy consumption to the prescribed norms, it is issued an energy savings certificate (ESCert), which can be traded at the end of a cycle (Sarangi & Taghizadeh-hesary, 2020). If a DC exceeds its target, it is penalised by the BEE. The cement and fertiliser sectors have made significant energy savings by adhering to PAT guidelines, but the policy has not been as effective in improving energy intensity in the iron and steel and pulp and paper industries (Misra 2019; Oak & Bansal 2017; 2019).

Technological innovation: By incentivising reductions in energy consumption, BEE encourages DCs to develop innovative mechanisms and efficient technologies to reduce energy intensity. Best practices have been employed across all major sectors, resulting in energy savings. For instance, technology upgrades were observed in all sectors during the first cycle. Even the thermal power plant sector, which narrowly missed its target, adopted efficient technologies such as LED lamps, variable frequency drives, washed coal, vapour absorption machines and dynamic coal balancing (Ministry of Power, 2017).

In the aluminium sector, operational practices such as switching off cooling fans when not in use, interconnecting pumps, modifying compressed air systems, and stopping driers in the service air system were implemented. In the fertiliser sector, revamp and retrofit measures were adopted, especially in ammonia production. These measures include adopting radial-axial flow converters and vapour absorption refrigeration, replacing urea strippers with bi-metallic strippers, suction cooling of carbon dioxide compressors, replacing rotating machines and turbines, using efficient catalysts, and better heat integration methods (Ministry of Power, 2017).

8.4.1 Policy instruments for energy system transitions

Under the energy and industrial systems transitions, a key policy instrument is the Perform, Achieve and Trade (PAT) scheme, launched by the Bureau of Energy Efficiency (BEE) in 2012. The PAT scheme operates under the National Mission for Enhanced Energy Efficiency (NMEEE) and incentivises energy efficiency by setting sectoral targets for industries. NMEEE is one of the eight national missions under the National Action Plan on Climate Change (NAPCC).

Under the PAT Scheme, designated consumers (DCs), which are energy-intensive entities that consume less energy than the prescribed norms, can avail themselves of Energy Saving Certificates (ESCerts). These certificates can be traded on the Indian Energy Exchange and Power Exchange India. DCs that exceed their consumption targets can purchase these ESCerts to meet their energy-saving obligations (Bhandari & Shrimali, 2017).

8.4.2 Policy instruments for land, oceans and ecosystems transitions

Several state governments in India have undertaken policies for climate change adaptation to strengthen conservation agriculture initiatives. For example, the Haryana state government provides subsidies for the purchase of Turbo Happy Seeder machines, which are essential for conservation agriculture with straw management. The economic benefits of this subsidy outweigh the costs (Aryal et al., 2016). Institutionalising conservation agriculture production systems within government ministries, departments and regional institutions is crucial for the sustainability of these technologies.

Efforts to strengthen policy instruments are visible in various initiatives aimed at improved cropland management. NAPCC, with its eight missions—especially the National Mission for Sustainable Agriculture (NMSA)—plays a critical role. Other major domestic strategies include the National Agroforestry Policy and NICRA (Amjath-Babu et al., 2019). India also has a well-developed disaster management authority (NDMA) and several resilience-building programmes, such as crop insurance schemes (Food and Agriculture Organization [FAO], 2017).

Several initiatives by the Government of India, through the respective missions, address the need for sustainable and 'climate-smart' agriculture. For instance, the NMSA seeks to transform Indian agriculture into a climate-resilient production system through suitable adaptation and mitigation measures in crops and animal husbandry.

The Paramparagat Krishi Vikas Pariyojana (Traditional Agriculture Development Programme) promotes organic farming, eco-friendly cultivation practices that reduce dependency on agro-chemicals and fertilisers, and efficient utilisation of local natural resources. Recent policy pronouncements, such as the Pradhan Mantri Krishi Sinchai Yojana (PMKSY) , emphasise the need for greater investment in irrigation. PMKSY focuses on expanding and improving the effectiveness of water use in irrigation. It includes four major sub-programmes: Accelerated Irrigation Benefits Programme; Har Khet Ko Pani; Per Drop More Crop; and Watershed Development (FAO, 2018). A significant example of a policy initiative that has driven successful adaptation is the uptake of drip and sprinkler irrigation under PMKSY and other relevant state policies, which are discussed in Case Study 7 below.

In integrated soil management, the Government of India has initiated two major schemes: the Soil Health Management (SHM) scheme and the Soil Health Card scheme. SHM, a key intervention under the NMSA, promotes sustainable soil health management, links soil fertility maps with macro- and micro-nutrient management, and encourages judicious fertiliser application and organic farming practices (Agricoop, 2017; DAC, 2020).

The agroforestry sector has also made use of effective policy instruments. The implementation of the National Agroforestry Policy 2014 recognises the tree-crop interface as an important option to support climate-smart agriculture and scale up carbon benefits with appropriate technological and market support (Sharma et al., 2015). The National Mission for a Green India (GIM) under the NAPCC aims to bring 1.5 million hectare (ha) of degraded agricultural lands and fallows under agroforestry (Murthy, 2013).

Strengthening of policy instruments is also evident in biodiversity management and conservation initiatives. The Government of India launched GIM (see Case Study 9) by

Box 8.7: Case Study 7: Improving irrigation efficiency through drip and sprinkler methods

Improving irrigation efficiency is a key adaptation strategy in the agriculture sector to buffer against rainfall changes, reduce irrigation leakages, address the growing water demand and adapt to climate change. This focus is evident in both national and state policies across India, emphasising integrated watershed management, changing irrigation practices (e.g., drip and sprinkler irrigation), and water harvesting and storage techniques.

Policy instruments: The central government has a Centrally Sponsored Scheme on micro-irrigation to improve efficiency and encourage the use of water-conserving technologies such as drips and sprinklers. The Prime Minister Krishi Sinchayee Yojana (PMKSY), launched in 2015, subsumed ongoing schemes like Micro Irrigation (More Crop Per Drop) and the Accelerated Irrigation Benefits Programme (AIBP). Drip irrigation is a highly effective option to achieve 'more crop per drop' (Narayanamoorthy et al., 2018; PMKSY, 2019). Various state initiatives have also supported this focus, such as:

1. Gujarat Green Revolution Company Ltd. (GGRC): Incorporated in 2005, GGRC acts as a special purpose vehicle (SPV) and a 'single window clearance' for micro-irrigation schemes in the state, offering a 60–85 per cent subsidy without enforcing limits on the scale of adoption.

2. Andhra Pradesh Micro Irrigation Project (APMIP): Launched in November 2003, APMIP acts as the nodal agency for all micro-irrigation subsidy programmes in the state, offering subsidy of 50 per cent or ₹2 lakh per family for medium and large farmers, whichever is less.

3. Karnataka implements micro-irrigation programmes through several line departments, with the horticulture (drip irrigation among horticulture farmers) and agriculture (sprinkler irrigation systems for row crops) departments being the main implementers. The state offers an 80 per cent subsidy on drip irrigation for 'general category' beneficiaries and a 90 per cent subsidy for Scheduled Caste (SC) and Scheduled Tribe (ST) beneficiaries.

Technological innovation: Examples of low-cost technological innovations that have improved access to micro-irrigation technologies include: (a) Madhya Pradesh, where Pepsi allowed poor farmers to experiment with drip irrigation without significant capital investments, using laterals made out of low-grade plastic straw. This approach encouraged several farmers to eventually adopt conventional drip irrigation systems. (b) Karnataka, where a wide range of low-cost micro-irrigation technologies (e.g., tape drips, Chennai drips and Euro drips), both in quality and price, are found in and around Kolar town, allowing farmers to experiment with low-cost forms of technology before eventually adopting conventional systems based on positive experiences.

Scalability and regional differentiation: In states like Maharashtra and Tamil Nadu, most micro-irrigation adopters are large farmers due to the high initial investment required for drip and sprinkler irrigation (Kumar & Palanisami, 2010; Palanisami & Raman, 2012). However, with ambitious Centrally Sponsored Schemes, states such as Andhra Pradesh, Karnataka, Odisha and Punjab have seen a majority of micro-irrigation adopters among small farmers (Palanisami & Raman, 2012). Among various states, the implementation of micro-irrigation promotion and subsidy schemes has been most successful in Andhra Pradesh and Gujarat, largely due to the creation of SPVs for micro-irrigation, such as APMIP and GGMC (Palanisami & Raman, 2012).

improving forest cover and quality (MoEFCC, 2016). Key policy, legal and regulatory provisions include the National Environment Policy 2006 and Joint Forest Management Policy 1993, which support the implementation of the Ecosystem Services Improvement Project.

ICZM instruments, such as the CRZ Notification of 1991, developed by the MoEFCC, aim to protect and improve the quality of the coastal environment (Sonak et al., 2008). The notification includes provisions to enhance transparency and stakeholder participation. District-level committees with local representatives assist ICZM authorities in implementing the coastal law, and public hearings during the preparation of ICZM projects enhance stakeholder participation in the ICZM regime (Puthucherril, 2011). The re-engineered CRZ Notification also ensures livelihood security for fishing and other local communities, encourages conservation of coastal stretches, and promotes development based on scientific principles. Meanwhile, the Island Protection Zone Notification is being implemented for the Andaman and Nicobar Islands and Lakshadweep.

Box 8.8: Case Study 8: Building codes and standards in Indian towns

The Model Building Bye-Laws (MBBL) 2016, issued by the Ministry of Housing and Urban Affairs (MoHUA), is a robust policy framework that integrates various elements of green buildings. These include provisions for rainwater harvesting, sustainability, water conservation and management, solar energy utilisation, energy efficiency (via passive solar building design), and organic waste management. This framework serves as a template for states and union territories to tailor their own by-laws according to local needs (Singh & Raghubanshi, 2020).

In Mumbai, the building by-laws mandate allocation of space for wastewater treatment and recycling plants in layouts exceeding plot size of 4,000 sq. m for single residential layouts, 2,000 sq. m for group housing, and 1,500 sq. m for other uses. The Brihanmumbai Municipal Corporation (BMC) further incentivises compliance by offering fiscal benefits in property tax, ranging from 5–15 per cent, to tenements and societies that manage their waste effectively (Government of Maharashtra, 2015). Such regulations and incentives play a crucial role in the reducing daily waste collection and water demand, thereby enhancing resilience to various climate pressures (Chappelle et al., 2019).

The implementation of green building certification in India, initiated with the establishment of the Leadership in Energy and Environmental Design (LEED) India chapter in 2001, has expanded significantly through bodies like Green Rating for Integrated Habitat Assessment (GRIHA) and Indian Green Building Council (IGBC) across different states and districts. This expansion has built local capacity to enhance climate resilience in built infrastructure. For instance, Shimla has successfully incorporated regulations on solar passive design and energy conservation in public, government and semi-government buildings, making it a pioneer among Indian hill towns (Kumar & Pushplata, 2015).

However, scalability barriers persist. While MBBL 2004 provided a blueprint for states and union territories to adapt their building by-laws, some regions like Andaman and Nicobar Islands, Punjab, Sikkim, and Tamil Nadu are yet to amend their regulations, and Tripura lacks any building by-laws altogether (Singh & Raghubanshi, 2020). Moreover, building regulations borrowed from the National Building Code (NBC) and the Delhi master plans, which do not suit the unique geographical and socio-economic contexts of Indian hill towns, continue to pose challenges (Kumar, 2016).

8.4.3 Policy instruments for urban and infrastructure systems transitions

Under urban and infrastructure systems, a range of policy instruments covering multiple sectors, including but not limited to urban planning, transport, buildings, urban water and water management, can enable a sustainable, climate-resilient transition in the system. Planning and policy instruments such as master plans, city development plans and, more recently, city-level climate action plans and heat action plans are laying the roadmap for the convergence of development and climate action. In the building sector, building codes and standards exemplify improved policy instruments for enhanced risk management (Case Study 8). In the transport sector, the National Urban Transport Policy (NUTP) 2006 and the subsequent National Urban Transport Mission 2014, issued by Ministry of Urban Development, focus on comprehensive improvements in urban transport services and infrastructure, prioritising moving people instead of vehicles.

Box 8.9: Case Study 9:Mahatma Gandhi National Rural Employment Guarantee Act

The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), 2005 is a national law, establishing the legitimate and justiciable 'right to work' for all rural households (Khera & Nayak, 2009). Funded primarily by the union government and implemented nationwide, it guarantees 100 days of unskilled manual labour to all adult members willing to work in a household (Joyita, 2013). A recent draft has proposed an additional 50 days of wage employment specifically for drought-affected or calamity-prone areas (Ministry of Rural Development [MoRD], 2019), reflecting a shift towards investing in climate-proofing villages (Adam, 2015; Fischer, 2020; Verma & Shah, 2012).

Key policy instruments with legal mandates: MGNREGA stands out for its rights-based framework, ensuring legal entitlements to wage employment (Gandhi et al., 2010). Supported by comprehensive guidelines from the Ministry of Rural Development, it mandates allowances and compensation in case of failure to provide work on demand or delays in wage payments (MoRD, 2019). To enhance accountability, the act incorporates provisions for social auditing, monitoring and grievance redressal (Raabe et al., 2010), emphasising transparency to combat corruption and ensure quality in rural works.

Institutional capacities: Implementation of MGNREGA involves central, state and local government institutions across India, including zilla panchayats at the district level, taluk panchayats at the block level and gram panchayats at the village level (Raabe et al., 2010). The scheme promotes decentralisation by empowering Panchayati Raj Institutions to plan and execute climate-resilient development projects (Joyita, 2013).

Financial structure: MGNREGA's funding is shared between the central and state governments. The expenditure covers wages for unskilled, semi-skilled and skilled labour, materials, and administrative costs (Babu, 2014). The central government disburses funds directly to districts through the National Employment Guarantee Fund, covering 75 per cent of the material and wage expenses for semi-skilled and skilled workers. The central government fully funds the wages of unskilled workers, while the state government finances the remaining 25 per cent of expenses, along with unemployment allowance payments and administrative costs of the State

8.4.4 Policy instruments for cross-cutting transitions

One of the cross-cutting options that has been enabled by strong policy instruments is the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), 2005. MNREGA is a development policy with strong adaptation and mitigation synergies (Case Study 9).

8.5 Climate Finance

Climate finance is a pivotal enabling condition in achieving CRD in India. To meet the 1.5°C target and transition to a low-carbon economy, India needs to invest 7–18 per cent of its GDP (McCollum et al., 2018; Srinivasan et al., 2023). For a detailed analysis of climate finance trends and priorities, refer to our report *Climate Finance in India* (2023), which this section is largely drawn from.

To meet its Nationally Determined Contribution (NDC) targets, India requires approximately US$ 167 billion annually from 2016 to 2030, which is about 8 per cent of its GDP_{2015}. Achieving the 2°C goal will necessitate annual energy investments of 4–16 per cent of India's GDP_{2019}, while the 1.5°C target will require 7–18 per cent over the period 2016–2050 (McCollum et al., 2018).

In 2019 and 2020, India's climate finance flows were about US$ 44 billion per year. However, this amount is insufficient to meet the 1.5°C target (Climate Policy Initiative [CPI], 2022; Srinivasan et al., 2023). Of the green finance tracked in these years, approximately 87 per cent was raised from domestic commercial finance and 83 per cent from public budget allocations. However, nearly 90 per cent of the available finance is directed towards mitigation efforts, with only about 10 per cent for adaptation.

Private climate finance is limited, mainly consisting of loans, private equity, venture capital and green bonds (Prasad & Sud, 2019; Singh, 2017). International funding from multilateral development banks (MDBs) and bilateral institutions are modest and mainly in the form of concessional loans. For example, MDB climate finance to India rose from US$ 1.9 billion in 2015 to US$ 3.7 billion in 2022 (European Investment Bank, 2023).

Adaptation funding is largely drawn from public budgets. According to India's Third National Communication to the United Nations Framework Convention on Climate Change (UNFCCC), adaptation expenditure was about 5.6 per cent of GDP (₹13.35 trillion) in 2021–2022, up from 3.7 per cent in 2015 (Government of India, 2023). The business-as-usual scenario estimates a need for ₹57 trillion by 2030, which could increase to ₹72 trillion when factoring in climate-induced damages.

While government investments in adaptive capacity for vulnerable sectors like urban areas, agriculture and water have increased, they do not fully meet adaptation needs. Public and budgetary finance for climate action is through allocations to the MoEFCC. State governments can also seek additional resources to implement their state climate action plans through the national missions under NAPCC as well as channels set up under the Climate Change Finance Unit by the central government such as the National Clean Energy and Environment Fund, the National Adaptation Fund, Compensatory Afforestation Fund Management and Planning Authority (CAMPA) and the National Disaster Response Fund (Singh, 2017).

Other resources include allocations by the Finance Commission, funds from bilateral and multilateral agencies, carbon offsetting and trading schemes (domestic and international), and green bonds (Arif, 2024; MOEF, 2023). Mitigation efforts have been supported by a strong focus on renewable energy, facilitated by budgetary increases for the Ministry of New and Renewable Energy and various market mechanisms. Regulatory frameworks like the PAT scheme and Feed-in-Tariffs have improved energy efficiency and supported investments in low-carbon generation (Srinivasan et al., 2023).

However, to ensure a just energy transition and sustainable infrastructure, greater private investment is essential. While renewable energy policies have attracted some private funding, more emphasis is needed on demand-side initiatives like green buildings and energy efficiency (Srinivasan et al., 2023). Public co-investment strategies, including loan guarantees and concessional grants, can help mitigate risks for private investors.

Building effective partnerships across India's financial system, including ministries, banks and development institutions, is crucial for a successful transition. Multilateral and regional development banks can strengthen financial commitments and boost private investment confidence. Additionally, aligning private investments with adaptation programmes will require government incentives and policy support.

Ultimately, India must shift investments from carbon-intensive sectors toward low-carbon and resilient development, prioritising energy transitions and sustainable land use to address gaps in infrastructure and ecosystem services.

8.5.1 Financing land, oceans and ecosystems transitions

Climate finance in India is typically channelled through ongoing initiatives. One notable example of financing land, oceans and ecosystems transitions through national legislature and policy is the role of CAMPA and GIM (Case Study 10). In addition, in 2014, the 14th Finance Commission added forest cover to the devolution formula that determines the amount of tax revenue distributed annually by the central government to each of the 29 states. Indian states now have a sizeable new fiscal incentive to protect and restore forests. India's tax revenue distribution reform created the world's first ecological fiscal transfers (EFTs) for forest cover and serves as a potential model for other countries (Busch & Mukherjee, 2017). The 15th Finance Commission also included forest cover in its devolution formula, assigning it a weight of 7.5 per cent to compensate states for the opportunity costs of forest protection and conservation.

Box 8.10: Case Study 10 - Compensatory Afforestation Fund Management and Planning Authority (CAMPA) and National Mission for Green India (GIM)

India's Nationally Determined Contribution (NDC) has targeted the creation of additional carbon sinks of 2.5–3 billion tonnes of CO_2 emissions by 2030 (Ministry of Environment, Forest and Climate Change of India [MoEFCC], 2023). This goal highlights afforestation as a key mitigation strategy, aligning with the long-term plan to bring 33 per cent of the country's area under forest cover. As part of the Bonn Challenge, India aims to restore 26 million ha of land by 2030 using critical policy and financial instruments like the Compensatory Afforestation Fund Management and Planning Authority (CAMPA) and National Mission for Green India (GIM; MoEFCC, 2021).

Compensatory afforestation serves as a financial lever to incentivise state governments to accelerate afforestation activities. CAMPA, established in 2016, has legislative and financial backing of ₹20,000 crore to support state governments in conserving, protecting and expanding forest resources. While 90 per cent of these funds are allocated to the states, 10 per cent is retained at the national level for monitoring and evaluation. However, as of 2017, only 26 per cent of the state funds had been disbursed, indicating significant underutilisation (Singh, 2017). Additionally, under the CAMPA Act, 2016, ₹60,070 crore has been allocated to the National Compensatory Afforestation Fund (NCAF). Out of this, ₹48,477 crore had been transferred to 31 states by the end of 2020 (MoEFCC, 2021).

GIM, with a budgetary allocation of ₹46,000 crores, is a national scheme under the National Action Plan for Climate Change (NAPCC). It aims to reduce forest degradation, restore carbon stocks in 10 million ha and strengthen institutional capacity. The mission focuses on increasing forest and green cover while enhancing the quality of existing forests (MoEFCC, 2018). By emphasising multiple ecosystem services, GIM seeks to leverage the co-benefits of greening as a carbon sequestration and emission reduction strategy. Additionally, a key objective of the mission is to increase forest-based livelihood income for households living in and around forests (MoEFCC, 2021).

Bringing India's total degraded land under restoration will cover about 28 per cent of globally degraded land area (~350 million hectares). This can potentially help the country receive more international funds to invest in biodiversity and ecosystem restoration. With this available expenditure, considering ecosystem restoration and biodiversity conservation at the centre of all policies, various restoration outcomes can support socio-economic and ecological sustainability (Singh et al., 2021b).

Several national policies with significant financial allocations support adaptation in land, oceans and ecosystems transitions. Notable national interventions include the Pradhan Mantri Fasal Bima Yojana (PMFBY), which has an allocation of ₹9,000 crore to enhance agricultural resilience to extreme events and climate change (FAO, 2018). Additionally, state schemes like Gujarat's Suryashakti Kisan Yojana (SKY) aim to boost solar power usage in agriculture. Launched in 2018, SKY's first phase involved an investment of ₹870 crore, aiming to build about 137 feeders and install solar photovoltaics with a capacity of 175 MW (Singh et al., 2019d). The central government also finances sustainable intensification of agriculture by increasing investments in efficient irrigation.

8.5.2 Financing urban and infrastructure systems transitions

Financing climate-resilient, sustainable urbanisation in India that is 1.5°C-compliant is a significant challenge. Currently, there are no comparative estimates of urban climate finance in India, though there are specific examples from different sectors. Urban climate action is seeing more funding in mitigation with a focus on sectors such as energy-efficient buildings, public and private electric transport, and urban greening (to a lesser extent), as discussed below.

- **Earmarking funds for climate action:** In Hyderabad, 10 per cent of the municipal budget is designated as a 'green budget' to support the city's greening initiatives (Singh et al., 2021a). Similarly, the Brihanmumbai Municipal Corporation (BMC) had allocated 32 per cent of its total capital expenditure budget for climate-relevant activities for FY 2024–25, alongside an additional ₹2,163 crore to implement components of the Mumbai Climate Action Plan (BMC Climate Budget Report: FY 2024–25). The Greater Cochin Development Authority's budget for FY 2024–25 aims to achieve carbon neutrality while promoting sustainable urban development. This includes investments in renewable energy infrastructure, compact urban design, enhanced public transport networks, energy-efficient building practices, and the conservation of green spaces and biodiversity (The New Indian Express, 2024).

- **Financing green buildings:** Several green building technologies are commercially available and most of them provide positive financial returns within a relatively short span of time (Maharashtra Energy Development Agency [MEDA] & Shakti Foundation, 2017). The scaling up of green buildings can be achieved by considering specific climatic zones, utilising local energy-efficient materials, and implementing various available energy-efficient technologies (Kumar et al., 2018; Shakti Foundation, 2018). Notably, 'green buildings' is one of the sectors identified by the Reserve Bank of India (RBI) for allocating proceeds from green deposits for regulated entities (RBI, 2023). Additionally, the Pradhan Mantri Awas Yojana (Housing for All [Urban] Mission) includes a sub-mission on technology that integrates green technologies and building materials into its framework along with the facilitation for preparation and adoption of geo-climatically suitable house layouts and designs. Under the latest version of the PMAY- U 2.0, innovative, sustainable, green and climate responsive special or demonstration projects are eligible for an additional Technology Innovations Grant (financial grant) in addition to the existing fund under PMAY-U 2.0. The Pradhan Mantri Awas Yojana – Gramin (PMAY – G) scheme in rural areas also provide guidance for the construction of green houses within the scheme, with an aim to promote green and sustainable housing in rural areas. The scheme grants the states and UTs to come up with their own incentive structures to promote the adoption of green technologies and construction materials.

- **Promoting electric vehicles in India**: The central government, through the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, promotes the use of electric vehicles (EVs). In its first phase (2015–2019), FAME incentivised 2.8 lakh EVs by providing subsidies worth ₹343 crore and sanctioned 465 e-buses to various states. In the second phase (2019–2024), with a budgetary allocation of ₹10,000 crore, the scheme focused on creating charging infrastructure and encouraging EV adoption through incentives.

Multiple states in India have also implemented policies to encourage the adoption of EVs through financial incentives for consumers (Shekhar et al., 2019). For instance, Andhra Pradesh has introduced a five-year plan that reimburses road taxes and registration charges for EV owners until 2024. Additionally, producers will benefit from the reimbursement of the goods and services tax (GST). The state government aims to convert all public transport buses to EVs by 2029 and is working to develop Amaravati and Tirupati as 'electric mobility cities', with further plans to promote EVs in Vijayawada and Visakhapatnam (Shekhar et al., 2019).

Table 8.2: Key enablers and barriers to urban climate finance in Indian cities

Finance Enablers	Finance Barriers
• Government schemes such as AMRUT can be leveraged for climate-oriented actions, supporting integrated master plans, public transportation focused on non-motorised mobility, sustainable water management, and green spaces (Padigala, 2014; Sami, 2016). • Revenue sources such as taxes and user charges can be allocated for adaptation expenditure, including maintenance of infrastructure and incremental actions (Cook & Chu 2018). • Multiple funding channels can help overcome barriers. For example, Surat transitioned from relying on external adaptation finance to utilising local funds, mainstreaming adaptation actions into urban development (Cook & Chu 2018). • Tamil Nadu's pooled water infrastructure funds were established through bonds from which 14 municipalities have effectively financed small water infrastructure projects (Hoque, 2012).	• Funding from state or central governments often lacks mandatory measures that promote climate co-benefits (Sethi et al., 2018). • Urban financing is predominately led by the central government, leaving city municipalities under-resourced for implementing development and climate-resilient initiatives (Khosla & Bhardwaj, 2019). • Deficits in intergovernmental adaptation resources force cities to depend on private actors for strategy and project financing to safeguard against climate change damages (Anguelovski et al., 2016). • Donor-driven urban climate action may prioritise global priorities over local needs (Khosla et al., 2017). • Financial instruments like municipal bonds tend to favour projects that generate an increase in cash flow (e.g., through user charges), often excluding adaptation investments such as storm water drains or emergency shelters for the urban poor (Cook & Chu 2018). • Cities have limited autonomy to modify existing tax structures (Cook & Chu 2018), reducing their ability to adapt and diversify revenue sources. Fragmentation of authority and decision-making further constrains effective action (Sami, 2016). • High capital costs for green buildings deter investments in such sustainable projects (Abraham & Gundimeda, 2017)

Note: AMRUT = Atal Mission for Rejuvenation and Urban Transformation

Source: *Authors' compilation*

While cities do not have clearly demarcated funding for adaptation, there are growing examples of internationally, public and privately funded project-based interventions that invest in actions, such as in flood risk mitigation and urban greening, that can have adaptation co-benefits (Singh et al., 2021a). Yet, while finance can enable urban adaptation, significant barriers remain (Table 8.2).

8.6 Enabling Technological Innovation

Technological innovation is a key enabler to achieve 1.5°C-consistent climate action. Alongside dedicated financing and human capacity building, technological innovation in emerging sectors such as biotechnology, artificial intelligence and Internet of Things (IoT) can facilitate multiple adaptation and mitigation strategies. These innovations can drive effective interventions like smart water and electricity metering, fuel-efficient vehicles, precision farming and climate-smart agriculture.

8.6.1 Land and coastal ecosystems

Technological innovation in agriculture is transforming risk management and improving irrigation efficiency, soil health and crop yields. Key practices include laser land levelling (Aryal et al., 2015b; Jat et al., 2014a), permanent raised bed planting (Sidhu et al., 2010), residue management (Sapkota et al., 2015), and zero-tillage farming (Gathala et al., 2011). These methods have been shown to enhance agricultural productivity and sustainability. For example, the System of Rice Intensification (SRI) has significantly reduced input costs and increased returns in states like Uttarakhand, Tamil Nadu and Bihar (Dass & Chandra, 2012; Diwakar et al., 2012). Research into rice varieties, genetic expression and cropping patterns, alongside effective pest and weed management, has led to greater adoption of SRI practices (Barah, 2009).

Innovation and experimentation on developing drought- and heat-tolerant crops is also being enabled at government and private agriculture research institutes across India (see Chapke & Tonapi, 2018; Dar et al., 2020; Mottaleb et al., 2017). Significant funding and capacity building efforts support the development of appropriate agricultural technologies (Roy & Singh, 2013). The ICAR Indian Grassland and Fodder Research Institute (IGFRI) has pioneered initiatives such as the 'round the year fodder production system' and 'Azolla as supplement feed for livestock' through various collaborative projects (ICAR-IGFRI, 2015; 2019).

Conservation efforts have also advanced, with Indian biologists developing conceptual tools to document biodiversity and employing digital mapping for classification of vegetation. They have utilised molecular techniques for the conservation of threatened species and examined indigenous knowledge and community management systems (Bawa et al., 2021). The Department of Biotechnology's project on threatened plants demonstrates the efficacy of ecological niche modelling (ENM) in guiding conservation surveys and addressing data gaps related to species distribution (MoEFCC, 2019).

Additionally, the National Natural Resource Management System employs remote sensing technology combined with traditional data tracking to inform policies for managing natural resources (MoEFCC, 2019). Remote sensing and geographic information systems (GIS) are instrumental in sustainable coastal management, monitoring coastal habitats, and conducting impact assessments for hazards like cyclones and rising sea levels (Kankara et al., 2014; Nayak, 2017; Roy & Datta, 2018).

Innovative coastal protection technologies are being tested to enhance resilience against extreme weather events. These include a combination of natural and built defence structures (Kudale et al., 2014; Murthy et al., 2020), along with low-cost solutions for coastal communities (Verhagen, 2019). In aquaculture, low-cost organic systems, such as using vermicompost to reduce feed and fertiliser costs, are being explored for sustainable fish production (Chakrabarty et al., 2009).

Technology also plays a critical role in addressing food production challenges (exacerbated due to climate change and environmental degradation). There is a thrust on increasing yields while reducing environmental externalities through sustainable intensification (Pingali et al., 2019).

Box 8.11: Case Study 11 - Integrated soil management

Integrated soil management (ISM) includes Soil Health Management (SHM) and Integrated Nutrient Management (INM). SHM promotes sustainable soil practices tailored to specific locations and crops, including soil fertility mapping, balanced nutrient management and organic farming (AGRICOOP, 2017). INM aims to enhance soil fertility by optimising nutrient inputs, such as replacing chemical fertilisers with vermicompost, farmyard manure and biofertilisers.

Multi-level policy instruments and institutional capacity building: To support these practices, the Government of India has launched two key initiatives: the Soil Health Management (SHM) scheme and the Soil Health Card scheme. Effective from 2014, SHM operates under the National Mission for Sustainable Agriculture (NMSA) and promotes organic farming through programmes like the Paramparagat Krishi Vikas Yojana (Traditional Farming Improvement Programme). The Soil Health Card scheme, introduced in 2015 with a budget of ₹568 crores, has reached approximately 45 million farmers in its initial two years (Indian Chamber of Food and Agriculture, 2017).

The government aims to cover all farmers nationwide, providing funding to states for issuing soil health cards. Various states are implementing these national policies. For instance, the Karnataka State Department of Agriculture has distributed over 78 lakh soil health cards in the first cycle (2015–16 and 2016–17) and 67 lakh cards in the second cycle (2018–19) (Annual Report of Agriculture Department Karnataka, 2018–19). Training programmes educate farmers on soil health maintenance and appropriate fertiliser application based on soil tests (Kannan & Ramappa, 2017). Capacity building is crucial, as research indicates that educated farmers are more likely to adopt ISM practices (Aryal et al., 2018c; Kannan & Ramappa, 2017).

Technological innovation: Technological innovations play a significant role in ISM. Practices such as zero tillage, nitrogen management and balanced nutrition management offer evidence-based improvements in soil health (Parihar et al., 2020; Pathak, 2010). Institutions like the Cereal Systems Initiative for South Asia in Bihar and the Central Soil Water Conservation and Training Institute in Ooty facilitate the adoption of these techniques. Additionally, effective soil management enhances the its water-holding capacity, helping to mitigate drought in dryland regions (Srinivasarao et al., 2013).

Finance: Financial support for ISM includes the National Project on Management of Soil Health and Fertility, implemented by the Department of Agriculture and Cooperation (DAC) during the 11th Five-Year Plan, with an outlay of ₹430 crore (AGRICOOP, 2008). The establishment of soil testing laboratories continues, often providing services to farmers at minimal or no cost (AGRICOOP, 2017). In Karnataka, soil testing is mandatory to access agricultural subsidies, promoting technology adoption (Kannan & Ramappa, 2017).

Scalability and regional differentiation: While many ISM technologies benefit small-scale farmers, challenges such as land availability and declining field sizes can hinder adoption in regions like the Indo-Gangetic Plains (Aryal et al., 2018a; DeFries et al., 2016). Practices like zero tillage, particularly beneficial in rain-fed systems, require integration with residue retention and crop rotation to maximise their effectiveness (Keil et al., 2015).

8.6.2 Urban and infrastructure systems

Technological innovation can enable adaptation and mitigation in cities through improved land use planning and management, smart energy and water systems, developing dynamic decision support systems, and reduced disaster exposure (Dhyani et al., 2018; Rockefeller Foundation, 2019). For example, Chennai, Hyderabad and Bengaluru have pilot projects on metering and measurement of water using electromagnetic meters (Shah, 2016) to minimise water loss.

Since the 2000s, there has been a global push to make cities 'smarter' through technology, driven by major companies such as IBM, CISCO and SIEMENS. This movement inspired India's 100 Smart Cities initiative (Kapur & Sequeira, 2015). Within the Smart Cities Mission (SCM), the 'Climate Smart Cities' initiative aims to foster climate-friendly solutions. Currently operational in Bhubaneswar, Kochi and Coimbatore, the Climate Smart Cities project focuses on making urban infrastructure and development more resource efficient, disaster resilient, and inclusive of both mitigation and adaptation measures (Nandan, 2018). Initiatives includes urban design initiatives, promoting green spaces, constructing green buildings and improving storm water drains (National Institute of Urban Affairs [NIUA], 2020). For example, Surat has incorporated smart LED street lighting and greening of urban pathways, yielding mitigation co-benefits (Surat Climate Change Trust, 2017).

A key feature of SCM is the Integrated Command and Control Centres (ICCCs) that facilitate continuous data analysis and the creation of dashboards for effective decision-making across various sectors such as water, streetlights, solid waste management and road development (MoHUA, 2023). Cities under SCM have also experimented with Supervisory Control and Data Acquisition (SCADA) to optimise water supply, water meters, intelligent transportation system (ITS) to improve public transportation service (MoHUA, 2023).

In Bengaluru, the Bangalore Water Supply and Sewerage Board has installed bulk meters at key locations across the city, employing geotagged meters to gather information on water usage. This metering system aims to improve water supply efficiency and can also identify illegal connections when the usage exceeds acceptable levels (NITI Aayog, 2017b).

8.6.3 Cross-cutting options

States are pioneering the use of technology to track specific health impacts of climate change, enhancing preventive response. For example, the Ahmedabad Heat and Climate Study Group has developed a HAP featuring a novel early warning system that forecasts extreme heat days with extended lead times, allowing for a broad range of public health preparedness activities to be coordinated effectively (Knowlton et al., 2014). However, nationally, government expenditure on health needs to increase from less than 2 per cent to at least 5–6 per cent of GDP in the short term (Kasthuri, 2018b). This increase would provide a much-needed infrastructure boost in rural and marginalised areas, ultimately enhancing access to healthcare services, infrastructure and personnel (Kasthuri, 2018b).

While technology is being used to improve social security programmes such as MGNREGA and the Public Distribution System (PDS), its implementation remains inadequate (Ambasta et al., 2008). In Tamil Nadu and Chhattisgarh, monitoring systems have introduced simple, user-friendly technologies with potential for scaling up (Khera, 2011).

Significant technological innovations have emerged in the space of decision-making under uncertainty, particularly through investments in Agrometeorological Advisory Services (AAS; see Case Study 13) and early warning systems (Case Study 14). However, large-scale implementation of AAS in India faces challenges. A field study in Maharashtra found that district-level weather forecasts, covering 7,000– 8,800 sq. km, often encompass multiple agroclimatic zones, leading to broad-scale forecasting and inaccurate weather predictions (Lobo et al., 2017a). Additionally, seasonal climate forecasts are often presented in probabilistic language that is difficult for users to interpret. They lack detailed location of rains, timing, lead times, duration and rainfall volumes, which are key to decision-making (Manjula & Rengalakshmi, 2015).

Private climate information service providers have made inroads into the forecasting space, thanks in part to their vast observation networks and computational facilities. Their flexibility allows them to operate without the constraints that often hinder government responses (Singh et al., 2018b)

Box 8.12: Case Study 12 - National Agrometeorological Advisory Services

India's labour-intensive and subsistence-based agriculture sector is particularly vulnerable to climatic risks (Gopalakrishnan & Subramanian, 2020). Agrometeorological Advisory Services (AAS) have contributed to high productivity and increased resilience in agriculture by encouraging farmers to adopt modern agricultural practices, weather-based irrigation and pest management, and improved the use of post-harvest technologies (Maini & Rathore, 2011).

Multi-level governance: AAS fall under the ambit of the Indian Meteorological Department (IMD), Ministry of Earth Sciences and was created after a series of pilot experiments that started in the 1980s, led by the National Centre for Medium Range Weather Forecasting (Venkatasubramanian et al., 2014). IMD issues quantitative district-level weather forecasts for up to five days, twice a week. Weather is forecasted on seven parameters: rainfall, maximum and minimum temperatures, wind speed and direction, relative humidity, and cloudiness. Weekly cumulative rainfall forecasts are also generated. This information is further transferred to the IMD's Regional Meteorological Centres and 130 AgroMet Field Units (AMFUs) representing agroclimatic zones in the country (Venkatasubramanian et al., 2012).

Improved institutional capacities: In 2008, the IMD launched a District-level Agrometeorological Advisory Service (DAAS) to provide relevant district-level weather information and management advisories across the country (Venkatasubramanian et al., 2014). DAAS has a four-tiered system to inform farmer decisions: meteorological (weather forecasting), agriculture advisories, extension (two-way communication with users) and information dissemination (through social media, mobile phones etc.; Singh et al., 2016). It sustains a multi-institutional information dissemination partnership involving multiple stakeholders such as the Indian Council of Agricultural Research (ICAR); SAUs; Krishi Vigyan Kendras (KVKs); Department of Agriculture and Cooperation; state departments of agriculture, horticulture, animal husbandry and forestry; development NGOs and media agencies (Venkatasubramanian et al., 2014; Tall et al., 2014)

Technology and innovation: Operational numerical weather forecasting services have utilised advances in atmospheric modelling capabilities. The dissemination of information is carried out at district and sub-district levels. State Composite Bulletins and National Agrometeorological Advisory Services Bulletins are also issued (Singh et al., 2018a). A pilot project in Ahmednagar district of Maharashtra has demonstrated the effective use of multimodal delivery system for disseminating agrometeorological advisories, using mobile telecommunication (SMS), announcements over the village public address system (loudspeakers); and weekly posters in prominent places and on walls/blackboards (Lobo et al., 2017b). These practices were in addition to the existing execution of training and technology support provided by agricultural professionals and use of farmer networks for communicating climate information (Lobo et al., 2017a; Rengalakshmi et al., 2018).

Box 8.13: Case Study 13 - Early warning systems

Early warning systems (EWS) are understood as the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organisations threatened by a hazard to prepare and act appropriately and in sufficient time to reduce the possibility of harm or loss (United Nations Office for Disaster Risk Reduction [UNISDR], 2012). India has developed robust EWS through dedicated public funding to build domestic technical expertise as well as creation of tiered institutional architecture to implement EWS across the country.

Institutional capacities: A key aspect of driving EWS in India is through the central institutional authority of National Disaster Management Authority (NDMA), with its legal binding under the Disaster Management Act, 2005. The act empowers constituting national and state executive committees as well as a National Institute of Disaster Management (NIDM) for capacity building, National Disaster Response Force (NDRF) for response, and the Disaster Mitigation Fund (Government of India, 2005). This conjugation can be seen from the coordination of cyclone warning where operations at the national level is done by the 'weather central' at Pune. The Cyclone Warning Division (CWD) at New Delhi is responsible for international coordination, supervision of cyclone warning activities and liaising with the central government. CWD also functions as the Regional Specialised Meteorological Centre - Tropical Cyclones (Ministry of Earth Sciences, 2021)

Technological innovation: The impact of Paradip cyclone in 1999 triggered Odisha to strengthen state EWS. Odisha is the country's first state to have adopted an early warning dissemination system through a chain of ICTs, which includes sensors, incident monitoring and decision-making subsystems. These include alert tower siren systems, digital mobile radio, mass messaging system, location-based alert system and satellite communication (Rajendran & Shyam, 2021).

Scaling, regional variations: Across India, various models for EWS have been studied. An initiative by Kolkata Municipal Corporation supported by the Asian Development Bank (ADB) presents a case of the first comprehensive city-level EWS for flood forecasting in India. The initiative is centred around communities and other stakeholders to act quickly and appropriately to reduce flood risk and includes weather forecasts; flood models for various intensities of rainfall; real-time information on key pump status, sump and canal water levels, actual rainfall, inundation levels; and a messaging system to provide warnings and real-time information to city officials and citizens (ADB, 2018). In some districts of Uttar Pradesh, a community-based early warning system has been established by the Poorvanchal Gramin Vikas Sangathan (PGVS). This initiative is considered unique because it empowers local communities through capacity building to identify and manage their own risks (Seneviratne, 2019).

8.7 Behavioural and Lifestyle Change

Addressing climate change effectively requires both individual and social change, particularly in India, where rapid population growth is accompanied by rising affluence and carbon-intensive consumption, albeit among a small segment of the population. Behavioural and lifestyle changes in key sectors can significantly reduce carbon emissions, as illustrated in Table 9.3. However, to achieve the 1.5°C target, these changes must be integrated into broader systemic transformations, supported by policy measures, financial incentives and behavioural nudges rooted in psychology.

Table 8.3: Examples of mitigation behaviour and their potential to reduce greenhouse gas emissions

		Example and Status in India	Emissions Reduction
Land and Ecosystem Transitions	Reduced Food Wastage	While there are some initiatives to reduce food wastage in India, clear links to reduction in greenhouse gas (GHG) emissions are lacking. Effective interventions should focus on bringing about behavioural change; for example, through public education on food waste (Morone et al., 2019). Alongside healthier diets, improving food production efficiency and reducing waste can minimise environmental impacts and address diet-related health issues (Aleksandrowicz et al., 2019). **Local Initiatives:** • Micro-management of restaurant waste: Initiatives like the 'public fridge' in Mumbai aim to redistribute excess food (Bharucha, 2018). • Annakshetra: This organisation collects surplus food from weddings for distribution to disadvantaged communities, thus preventing waste (Agrawal & Nag, 2013).	GHG emissions from food surplus have risen from 130 Mt CO_2eq/year to 530 Mt CO_2eq/year over the past 50 years. Projections suggest that by 2050, food surplus could increase to 850 kcal/capita/day, potentially raising emissions from food waste to 1.9–2.5 Gt CO^2eq/year (Hic et al., 2016).
	Dietary Shifts	India's dietary shift is marked by increased consumption of milk, dairy and processed foods (Green et al., 2018; Tak et al., 2019). This rising consumption of livestock products could elevate GHG emissions unless per-product emissions are mitigated (Vetter et al., 2017). While sustainable diets could enhance nutrition, they come at a 50% higher cost (Chaudhary & Krishna, 2021). • As incomes rise, rice and meat will become more common in diets. Rice-based diets contribute to higher GHG emissions and green water footprints, while wheat-based diets have larger blue water footprints. • Compared to less diverse diets, rice and meat combinations yield 31% higher GHG emissions and increased water usage (Green et al., 2018). • Research in Mumbai indicated a willingness to pay a premium for plant-based and cell-based meats, presenting an opportunity to encourage behavioural changes (Arora et al., 2020). • Incorporating edible insects into diets can provide a sustainable and nutritionally adequate food source, reflecting traditional practices in many cultures (Premalatha et al., 2011).	Transitioning to traditional, nutritious foods instead of refined cereals could reduce malnutrition-related premature deaths by 14–30%, meet nutritional needs, and lower water demand by up to 65%. It may also decrease GHG emissions by 26–34% and resource inputs by 40% (Damerau et al., 2020). Adopting healthy diets alongside improving food production efficiency and reducing waste can further mitigate environmental impact and address diet-related health issues (Aleksandrowicz et al., 2019). For example, a non-vegetarian meal with mutton emits 1.8 times more GHG than a vegetarian meal and 1.5 times more than a chicken meal; thus, shifting diets can significantly aid in GHG mitigation (Pathak et al., 2010).
	Ecosystem Restoration	The National Mission on Biodiversity and Human Well-Being aims to foster pride in India's natural heritage and engage citizens in biodiversity conservation (Bawa et al., 2021).	Ecosystem restoration can have significant mitigation benefits, for example, through mangrove restoration and blue carbon conservation (Chowdhury et al., 2019).

		Example and Status in India	Emissions Reduction
	Afforestation and Reforestation	While farmers may not prioritise tree planting for carbon sequestration, significant economic returns from carbon credits can motivate such efforts (Gera, 2012).	Carbon sequestration from poplar plantations in agroforestry currently stands at 542 metric tonnes of carbon per year, excluding wood products (Gera, 2012). The estimated carbon sequestration potential of agroforestry in India ranges from 0.25 to 19.14 Mg C/ha/year for trees and from 0.01 to 0.60 Mg C/ha/year for crops (Dhyani et al., 2016).
Urban and Infrastructure Systems	Transportation	The National Urban Transport Policy (NUTP) promotes quality and pricing strategies to shift users from private vehicles to public transport (NUTP, Ministry of Urban Development, 2006). Currently, many public transport users in India rely on non-motorised options, such as cycling and walking, for last-mile connectivity, with 35–65% of households in medium-to-large cities owning at least one bicycle (Tiwari & Jain, 2013). However, this trend is changing as vehicle emissions rise. To combat this, Andhra Pradesh has launched a five-year plan to transform Amaravati and Tirupati into 'electric mobility' cities by providing incentives like GST reimbursement and waiving registration fees (Shekhar et al., 2019).	
	Low/Zero-energy Buildings	The UJALA scheme promotes energy-efficient lighting by providing affordable LEDs, expected to save 100 billion kWh annually. The Bureau of Energy Efficiency (BEE) implemented the Energy Conservation and Building Code (ECBC), requiring 75% of new commercial buildings to be compliant and enabling 20% of existing buildings to retrofit for reduced energy consumption from 2012 to 2017. BEE's standards and labelling programme assigns star ratings to appliances, making energy performance labels mandatory for high-energy equipment and establishing minimum energy performance standards. This initiative resulted in energy savings of 121 billion units from 2011 to 2018 (MoEFCC, 2018). Additionally, awareness and education on energy-efficient buildings enhance public acceptance of these regulations (Chandel et al., 2016).	The UJALA scheme is expected to have annual estimated greenhouse gas emission reductions of 79 Mt CO^2 (MoEFCC, 2018).

Source : *Authors' compilation*

To promote sustainable and environmentally conscious behaviour, the Indian government launched Mission LiFE in 2021, aiming to make at least 80 per cent of villages and urban local bodies environmentally friendly by 2028. The mission envisions three core shifts—changes in demand, supply and policy—across seven themes: energy, water, single-use plastics, waste, e-waste, sustainable food systems and healthy lifestyles.

This section examines behavioural and lifestyle change as an enabling condition for climate adaptation and mitigation across land, oceans and ecosystems, and urban and infrastructure systems. Table 9.3 gives examples of mitigation behaviour and its potential to reduce greenhouse gas (GHG) emissions across these two systems. This is followed by a look at what shapes adaptation behaviour, with the help of a case study on what is prompting the shift to EVs (Case Study 14).

For climate change adaptation, perceptions, local values and beliefs, and perceived efficacy of interventions influence behaviour shifts towards adoption of adaptation strategies. For example, evidence shows that leveraging traditional risk management practices and knowledge systems in land restoration, forest conversation and agrarian systems is effective. However, a lack of knowledge about conservation strategies and its benefits limits adoption (Aryal et al., 2016) as does a traditional mindset regarding crop management practices (Sapkota et al., 2015).

- **Perceived efficacy enables adaptation:** In Odisha, where saline-resistant fish varieties are adopted more by local communities due to expectations of increased productivity gains in flooded areas (Satapathy et al., 2011).

- **Clear monetary benefits motivate adaptation**: For instance, higher income from forest-based livelihood activities motivate households to follow better conservation practices (Mishra, 2019).

- **Build on traditional risk management practices:** Pastoralists in Rajasthan demonstrate resilience to climate variability through established risk management strategies (Mukherji et al., 2016). Religious conservation ethics, such as sacred groves, promote sustainable practices (Das & Behera, 2019; Saniotis 2011). Additionally, strong cultural ties can foster self-regulation in resource sharing, as seen in communities where fishers choose elevated coastal areas for safety and views (Namboothri et al., 2008).

- **Education and awareness building:** Literacy is a key factor in adopting sustainable practices like minimum tillage and nutrient management (Aryal et al., 2018a). Educated farmers have a better grasp over technical knowledge, leading to improved soil management (Kannan & Ramappa, 2017). Initiatives targeting children, such as gender-sensitive disaster management puppet shows in Tamil Nadu, have also been effective in promoting awareness (UNDP, 2010).

- **Knowledge networks:** Climate knowledge risk gateways and networks, like The Honey Bee Network, facilitate the exchange of ideas and solutions across various sectors, linking both formal and informal science and scientists (Dey et al., 2013).

- **Collective action:** Programmes like Paryavaran Mitra (Friends of Nature) foster networks of young environmental leaders in schools, promoting environmental awareness and encouraging positive behaviour at the individual, school, family and community levels. Over 1,62,000 students have participated in this programme across India (MoEFCC, 2019).

In urban and infrastructure systems, the top-down nature of interventions often limits communities participation, isolating local knowledge and experience from the decision-making process for climate change actions (Archer et al., 2014). However, innovative programmes are emerging to encourage urban adaptation. For instance, Chennai's 'Shut the Tap' initiative employs behavioural economics to 'nudge' certain sections of the city to adopt water conservation practices, educating school children and households on methods and technology for conserving water and reducing waste. Similarly, Bengaluru's Zero Energy Development Housing scheme, the first residential project to earn a platinum rating by IGBC India, utilises low-energy materials and passive solar design to reduce energy consumption and green roofs to improve indoor thermal comfort. This has led to an increased community awareness on sustainable living (Garg et al., 2017a) and generated a demand for such housing (Bulkeley & Castán Broto, 2014).

Box 8.14: Case Study 14 - Enabling adoption of electric vehicles through financial incentives

Electric vehicles (EV) have multiple benefits such as reduced vehicular emissions and health co-benefits; reduced energy consumption for transportation (Fady M. A Hassouna et al., 2020); reduced congestion (NITI Aayog & Rocky Mountain Institute, 2017; Dhar et al., 2016; Global Green Growth Institute [GGGI], 2014; CSTEP & GGGI, 2016); and mitigation synergies projected to be approximately 1,155 $MtCO_2$ between 2015 and 2050 (Gupta et al., 2018).

Policy thrust: The National Electric Mobility Mission Plan 2020 (NEMMP), provides a roadmap for faster manufacturing and adoption of EVs in India. Towards this end, Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme was launched as part of NEMMP in 2015 (Ministry of Heavy Industries and Public Enterprises, 2019). The first phase of FAME (2015–2019) covered all vehicle segments where the demand incentive is availed by buyers at the point of purchase and the same is reimbursed to the manufacturers from Department of Heavy Industry (DHI) on a monthly basis (IEA, 2020b; The Energy and Resources Institute [TERI], 2019). The second phase (2019 onwards) encompassed speed, range and energy efficiency requirements in a more stringent manner where 90 per cent of the remaining lithium-ion battery driven models were excluded (IEA, 2020b). The second phase is not based on battery size, unlike the first phase, even though the idea behind both the phases is incentive allocation. It is applicable mainly for public transportation vehicles but includes privately-owned two-wheelers as well (TERI, 2019). The demand incentive was limited to vehicles with advanced batteries defined as 'motor vehicles' as per the Central Motor Vehicle Rules (CMVR) by the Ministry of Road Transport and Highways and it is also based on proportion in domestic manufacturing, installation of mileage monitoring device and compliance to CMVR standards (TERI, 2019).

Behavioural change by financial incentives: The FAME scheme promoted EVs by providing financial incentives for their purchase, charging infrastructure deployment and research and development (R&D) of EVs (Gadepalli et al., 2019). The demand incentive for buyers of EVs in the form of an upfront reduced purchase price was to enable wider adoption (Ministry of Heavy Industries and Public Enterprises, 2019). Eighty-six per cent of the budget in second phase of FAME scheme is allocated for demand incentives where purchase subsidies are provided to two-wheelers, three-wheelers, four-wheelers and buses over a period of three years (TERI, 2019).

8.8 Conclusion

Effective climate action and the transition to CRD in India depend on creating an enabling environment. This environment must include appropriate governance across levels, converging legal and regulatory frameworks, aligned policies and incentives, technological innovation, strategic cross-sectoral partnerships, and adequate finance to drive transformative change.

This chapter, informed by the CRD framework, outlined in the IPCC's AR6, highlights six enabling conditions essential for facilitating climate mitigation and adaptation across key systems in India: multi-level governance, institutional capacity building, policy instruments, adequate finance, technological innovation, and behavioural and lifestyle change.

The evidence presented illustrates how multi-level governance, effective policy instruments, technological innovations and institutional capacity have accelerated climate actions across key systems. For example, in land, oceans and ecosystems, the promotion of sustainable agriculture through conservation practices, cropland management, and soil health management has thrived in several states due to robust central institutional frameworks, such as NMSA and NICRA. Capacity building at the state and local levels, along with community engagement, has supported this progress, backed by effective policy interventions like SHM and PMKSY, as well as a multi-stakeholder governance approach and targeted technological advancements.

In the energy sector, market-driven policy instruments like the PAT scheme have resulted in significant energy savings and spurred technological innovations in energy-intensive industries. The success of the PAT scheme underscores the importance of a cohesive policy framework, continuous technological advancements and strengthened institutional capacity.

Urban and infrastructure systems have also seen progress, with many states and cities developing climate action plans and implementing initiatives like heat action plans, model building by-laws, and shifts to low-carbon transportation, including promoting EVs. However, challenges remain due to inadequate financing and limited policy and fiscal autonomy for municipal governments, hindering the scaling of these efforts.

In the cross-cutting category, technological innovations, strong policy instruments and improved institutional capacities have enhanced early warning systems and strengthened social security and livelihood security policies such as PDS and MGNREGA, which help reduce climate vulnerability among marginalised populations.

The remaining two enabling conditions, climate finance and behavioural change, require urgent attention. Although there have been investments in the renewable energy sector and electrification, followed by the transport sector (i.e., through EVs), much more is required to channel climate finance into broader adaptation and mitigation strategies crucial to meet India's 1.5°C targets. Currently, domestic funding is inadequate, emphasising the need to attract private investment to accelerate the energy transition, and build resilient infrastructure and ecosystem services for all. Building effective partnerships among all levels of government, banks and financial institutions is critical for creating a unified climate action agenda. This is essential to redirect all investments away from carbon intensive sectors towards low-carbon development and incentivise private investments into adaptation and mitigation projects.

Additionally, significant knowledge gaps persist regarding effectively promoting lifestyle and behavioural changes that align with climate goals. While India has made a beginning with Mission LiFE, concrete examples of how behavioural change can enable adaptation or mitigation at scale are still lacking.

The case studies on ZBNF, the PAT scheme, National Solar Mission and HAPs illustrate the synergy of multiple enabling conditions in making climate action more feasible. These insights can inform future policies and interventions, paving the way for systems transitions in key areas and a climate-resilient future in India.

9.

Conclusion

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Conclusion

India faces a serious challenge of addressing climate change while meeting its development goals and tackling persistent socio-economic issues such as poverty, inequality, and unemployment. This report adapts the IPCC's Climate Resilient Development (CRD) framework to the Indian context, offering evidence-based insights to achieve 1.5°C-compatible development that aligns with the country's sustainable development goals and its economic aspirations.

While conventional thinking suggests climate action can undermine growth, emerging scholarship shows that the two can be complementary. Strong climate policies that foster systemic change, innovation, and investment can create 'a sustainable growth story' (Stern and Stiglitz 2023, pp. 278–279). The IPCC's CRD framework brings together climate action (adaptation and mitigation), sustainable development, and biodiversity conservation agendas, based on complementary development interventions rather than trade-offs (Stern and Stiglitz, 2023; IPCC 2022; IPCC, 2023). While CRD articulates a global solution space and outlines feasible adaptation and mitigation options, these need to be tailored to specific national and sub-national contexts.

This report synthesises from a wide-range of secondary sources - peer reviewed literature, national and sub-national government reports, policy papers, and practice reports, to provide analysis of India's current climate trends and projections (Chapter 1), climate impacts and risks (Chapter 2), its broad macroeconomic indicators and national circumstances (Chapter 3), existing climate policy framework (Chapter 4) and mitigation pathways (Chapter 5). Together, these sections provide the necessary context to operationalise the CRD framework in India.

The findings highlight the significant climate risks India faces due to changes in climate-impact drivers (temperature and precipitation changes), which are increasing the frequency and intensity of extreme events like floods, drought, and heat waves. Key sectors such as agriculture, water, urban and infrastructure, health and terrestrial ecosystems are particularly vulnerable to these risks, which can destabilise the Indian economy and adversely impact the well-being of its people and ecosystems. These risks will worsen as temperatures rise, with each half degree increase leading to disproportionately severe impacts and losses and damages. Furthermore, the most vulnerable groups - economically weaker and socially marginalised communities – bear the brunt of these climate impacts.

Beyond climate challenges, India must address significant deficits in infrastructure and essential services, social and economic inequalities, a growing urban population and increasingly mobile rural population, and slow employment growth. These issues must be tackled to ensure resilient development and realise the goal of becoming an advanced economy. Thus, CRD in India is critical to ensuring economic and social security, creating new green jobs, promoting climate protection and resilience, particularly for country's most vulnerable populations.

To implement CRD, India must shift from siloed sectoral approaches to simultaneous, system-wide transitions in key economic systems/sectors: energy, agriculture and forestry (land, oceans and ecosystems), urban and infrastructure and industry. Transforming these sectors is crucial, as they each play a key role in the economy and are essential for reducing emission intensity and enhancing climate resilience.

India's climate policies have tried to balance development needs, such as secure livelihoods and access to universal basic services, with addressing climate risks and environmental degradation. The country has focused on climate actions that also promote development, such as clean cookstoves, resilient infrastructure, and afforestation. While the country's commitment to a low-carbon development pathway is evident through its NDCs, much more needs to be done to accelerate the transition and ensure a climate-resilient future.

An analysis of adaptation actions and policies in India shows some progress in vulnerable sectors like water, agriculture, and urban. However, challenges remain in improving risk assessments, ensuring effective sub-national implementation, securing adaptation financing, and strengthening synergies between adaptation and mitigation.

On the mitigation side, while India is on its track to meet its renewables target, a clear roadmap is still missing, to implement energy efficiency at scale and phase out coal power while ensuring alternate jobs for lost livelihoods, both necessary for deeper decarbonisation.

Within this larger context, the report uses the IPCC's CRD framework to assess 16 mitigation and 23 adaptation options (Chapter 6) at a national scale across key systems for their feasibility across six-dimensions. The options, narrowed down based on India's NDC targets and relevance to 1.5°C pathways and are assessed across key systems: energy, industrial, land, water and ecosystems, urban and infrastructure, and a cross-cutting category of options that run across systems. These first-of-its kind feasibility assessments of adaptation and mitigation actions for India offer several actionable insights on which options can provide quick wins because they have moderate to high feasibility. These assessments are also useful to identify barriers to the implementation of climate actions.

For instance, in land, oceans and ecosystems, adaptation options like conservation agriculture, agricultural diversification, grazing land management, agroforestry, and water resource management have high to medium overall feasibility. Many of these have been supported by existing government initiatives like zero budget farming, National Agroforestry Policy, NICRA. However, these options also face challenges like that of low adoption due to lack of technical know-how, inadequate extension services, low awareness, and lack of equipment, which hinders their effective scale-up.

In energy systems, solar PV and wind energy emerge as highly viable mitigation options, scoring high to medium feasibility across all six assessed dimensions. While existing policies have significantly advanced solar PV power development there is substantial potential to expand both grid-connected and off-grid solar power solutions in the country, such as solar parks in low-carbon industrial clusters, expanding rooftop solar installation, and developing reliable grid infrastructure for wide-spread solar deployment.

To remain below 1.5°C, India will have to leverage synergies between mitigation and adaptation and its co-benefits with the SDGs while minimising trade-offs. Our assessment of synergies and trade-offs (Chapter 7) between adaptation and mitigation options, and SDGs, shows multiple synergies between climate actions and the 17 SDGs. For example, 12 adaptation options in land, oceans and ecosystems align strongly with SDG 8 (decent work and economic growth) and SDG 12 (responsible consumption and production). Among the mitigation options, energy systems, particularly solar energy, show the most positive linkages with the SDGs, including significant synergies with SDG 7 (affordable and clean energy) and SDG 13 (climate action), while also fostering economic development through the creation of green jobs.

Finally, the report examines six enabling conditions (Chapter 8) that enhance the feasibility of adaptation and mitigation actions in India to accelerate systems transitions, and ultimately shift developmental pathways towards CRD. These enabling conditions include multilevel governance, building institutional capacities, strengthening policy instruments, technological advancements, adequate finance, and societal and behavioural change. Through illustrative case studies across states and sectors, the chapter demonstrates how incremental and transformative measures can support India's transition to 1.5°C pathways.

Taken together, the report's feasibility assessments, evaluation of synergies and trade-offs of adaptation and mitigation actions and the 17 SDGs, along with the analysis of enabling conditions provides a comprehensive solutions framework that can guide climate action policy in India. This framework can support interventions at national and sub-national scales to shape a 1.5°C trajectory towards a resilient and sustainable India.

Annexes

ANNEX 1

Sector	1994	2000	2007	2010	2014	2016	2019
Energy	744	1027	1374	1510	1910	2129	2374
Industry	103	89	142	172	202	226	264
Agriculture	344	356	373	390	417	408	421
LULUCF	14	-223	-177	-253	-301	-308	-485
Waste	23	53	58	65	78	75	73
Total (without LULUCF)	1214	1524	1947	2137	2607	2839	3132
Total (with LULUCF)	1229	1301	1772	1884	2306	2531	2647

Table 5.1: Sector-wise national greenhouse gas emissions (in $MtCO_2e$) for 1994–2019

Note: LULUCF = Land Use, Land-Use Change and Forestry.

Source: *MoEFCC, 2023*

ANNEX 2

Methodology: Multidimensional Feasibility Assessment

The guiding question of this assessment is: **What adaptation and mitigation options are feasible in a 1.5°C India?** Across systems transitions, we chose 23 adaptation options and 16 mitigation options. We first created a longlist of adaptation and mitigations options from the Fifth Assessment Report (AR5) and the three Special Reports of the Intergovernmental Panel on Climate Change (IPCC). Next, these options were narrowed down based on whether they are relevant for 1.5°C pathways and reported new literature. Finally, the options were strategically selected based on India's targets and commitments as evidenced in India's Second National Communication to the United Nations Framework Convention on Climate Change (UNFCCC; Government of India [GOI], 2012), the country's Intended Nationally Determined Contribution (INDC) (Union Environment Ministry, 2015), and the Biennial Update Report to the UNFCCC (Ministry of Environment, Forest and Climate Change [MoEFCC], 2015).

To conduct the feasibility assessment, we answer the following questions:

- What are the economic, sociocultural, technological, environmental, governance and physical barriers to specific adaptation options?
- Which options are feasible for multiple dimensions, thereby presenting quick wins? (see Figure 1, Figure 2)
- Which adaptation options present multiple synergies with specific Sustainable Development Goals (SDGs) and climate change mitigation? (see Chapter 8)
- What are the enabling conditions that can facilitate systems transitions to 1.5°C? (see Chapter 9)

Each adaptation and mitigation option was assessed using a six-dimensional feasibility framework (Table A1). These dimensions were then divided into 19 indicators based on the literature. For example, 'technological feasibility' had two indicators: technical resource availability (for the adaptation option) and risks mitigation potential of the option (which included stranded assets and unforeseen impacts).

Table A1: Six-dimensional feasibility assessment. The dimensions were further divided into 19 indicators

Dimension	Indicators	Questions Guiding the Adaptation Indicators
Economic	Micro-economic viability	What are the economic costs and trade-offs of the option?
	Macro-economic viability	Would the option lead to higher productivity?
	Socio-economic vulnerability reduction potential	To what extent does the option reduce inequalities?
	Employment and productivity enhancement potential	How many people can be employed or how much can a system's productivity increase under the option?
Technological	Technical resource availability	Are the technological and associated human, financial and administrative resources needed available?
	Risk mitigation potential	To what degree can the option reduce the likelihood and/or consequences of risks?
Institutional	Political acceptability	Is the option politically acceptable? Does the option reflect stakeholder perceptions about the meaning and purpose of adaptation?
	Legal and regulatory feasibility	Is the option appropriate to jurisdictional context? Is it challenging to implement the legal changes needed for the option? Are there known legal and regulatory barriers?
	Institutional capacity and administrative feasibility	Would current institutions be able to implement the option? Is the option administratively supported? Are human resources to support implementation of the adaptation option clearly identified? Are responsibilities delineated for managing implementation of the option?
	Transparency and accountability potential	Are policy goals and targets for the option explicitly articulated; monitoring and evaluation protocols set up to track implementation; and transparent reporting mechanisms in place to synthesise progress and gaps?
Environmental	Ecological capacity	Does the option enhance supporting, regulating or provisioning ecosystem services in any way?
	Adaptive capacity/ resilience building potential	Does the option enhance the ability of systems, institutions and humans to adjust to potential damage, take advantage of opportunities, or respond to consequences? Does the option contribute to resilience building (i.e., ability to cope with stressors and reorganise to maintain structures and functions, retain capacity to transform)?

Geophysical	Physical feasibility	Is the physical potential of the adaptation option a constraint?
	Land use change enhancement potential	Does the option enhance carbon stocks (e.g., through forest restoration)?
	Hazard risk reduction potential	Does the option reduce the number of people exposed to a hazard?
Social	Social co-benefits	Are there health and education benefits to be had from the option? Does the option minimise negative trade-offs with other development policy goals, or identify positive synergies with other policy goals?
	Sociocultural acceptability	Is there public resistance to the option? Does the option typically find acceptance within existing sociocultural norms, or does itutilise diverse knowledge systems including indigenous and local knowledge?
	Social and regional inclusiveness	Are different social groups and remote regions included in the option? Does the adaptation option adversely affect vulnerable groups or other areas?
	Intergenerational equity	Does the option compromise the ability of future generations to meet their own needs in any way?

Source: *de Coninck et al., 2018; Singh et al., 2020*

For each adaptation option, an assessment was conducted at an indicator level, giving scores of high, medium and low based on peer-reviewed literature. Where there was insufficient evidence, options were scored as 'low evidence' or 'no evidence', highlighting knowledge gaps. These indicator-level scores were then averaged to develop high, medium and low feasibility scores for each dimension. The full methodological approach is given in Figure A1.

Figure A1: Methodological process used to assess the feasibility of adaptation options under five systems transitions

1 Defined scope

National feasibility assessment in India covering 5 system transitions (energy; land and ecosystems; urban and infrastructure; industry; and crosscutting transitions), and 23 adaptation options

2 Developed indicators

Developed 19 indicators across six feasibility dimensions (economic, institutional, socio-cultural, environmental, and geophysical feasibility)

3 Created literature database

Conducted review of peer-reviewed and grey literature for each adaptation option (2000-2020)

4 Conducted assessment

Assessed each option at indicator level, giving scores of high, medium, low feasibility. Where evidence was sparse options were scored as having low/no evidence

5 Combined indicators

Combined indicator-level assessments by taking an arithmetic mean of the relevant underlying indicators to develop dimension-level scores for each option (NE scores were not included).

6 Checked robustness

Cross-checked dimension-level scores through expert elicitation (3-5 experts per system transition). Feasibility scores adjusted based on feedback.

7 Assessed synergies and trade-offs

Assessed positive or negative implications of adaptation option for mitigation and the SDGs.

8 Reviewed enabling conditions

For each option, five enabling conditions were reviewed (multilevel governance, finance, institutions, behavioural change, and technological).

Source: *Singh et al., 2021*

After the feasibility assessment, we also assessed the synergies and trade-offs of adaptation options with (a) mitigation; and (b) specific SDGs to assess options that present triple wins and thus should be prioritised (Step 7 in Figure A1). A final step involved examining the conditions that enable adaptation, using empirical evidence and case studies from across different states and sectors in India (Step 8 in Figure A1).

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Abbreviations

ABBREVIATIONS

AAGR	Average Annual Growth Rate
AAS	Agrometeorological Advisory Services
ACCCRN	Asian Cities Climate Change Resilience Network
ADB	Asian Development Bank
AEEE	Alliance for Energy Efficient Economy
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
ASSURE	Accelerating Sustainable and Super Efficient Real Estate
BAU	Business As Usual
BBIN	Bangladesh, Bhutan, India, Nepal
BBMP	Bruhat Bengaluru Mahanagara Palike
BCM	Billion Cubic Meters
BECCS	Bio-Energy With Carbon Capture and Storage
BEE	Bureau of Energy Efficiency
BEEP	Building Energy Efficiency Programme
BHEL	Bharat Heavy Electricals Limited
BLDC	Brushless Direct Current
BMC	Brihanmumbai Municipal Corporation
BRT	Bus Rapid Transit
BRTS	Bus Rapid Transit Systems
CA	Conservation Agriculture
CAFE	Corporate Average Fuel Economy
CAGR	Compound Annual Growth Rate
CAMPA	Compensatory Afforestation Fund Management and Planning Authority
CAMS	Carbon Accounting and Management System
CBGA	Centre for Budget and Governance Accountability
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CDM	Clean Development Mechanism
CDRI	Coalition for Disaster Resilient Infrastructure
CEA	Central Electricity Authority
CEEW	Council On Energy, Environment and Water
CERC	Central Electricity Regulatory Commission
CFL	Compact Fluorescent Lamps
CHDHN	Concurrent Hot Day Hot Night

CMIP	Climate Model Intercomparison Project
CMVR	Central Motor Vehicle Rules
CNG	Compressed Natural Gas
CORDEX	Coordinated Regional Climate Downscaling Experiment
CPI	Climate Policy Initiative
CRD	Climate Resilient Development
CRZ	Coastal Regulation Zones
CSP	Concentrated Solar Power
CSTEP	Centre for Study of Science, Technology and Policy
CWC	Central Water Commission
DACCS	Direct Air Carbon Capture and Storage
DALY	Disability-Adjusted Life Years
DFC	Dedicated Freight Corridor
DISCOM	Distribution Company
DRIP	Dam Rehabilitation and Improvement Programme
DRR	Disaster Risk Reduction
EAF	Electric Arc Furnace
ECA	Energy Conservation Act
ECBC	Energy Conservation Building Code
EEDI	Energy Efficiency Design Index
EESL	Energy Efficiency Services Limited
EFT	Ecological Fiscal Transfers
EIR	Entomological Inoculation Rate
EMDE	Emerging Markets and Developing Economies
ENM	Ecological Niche Modelling
ENSO	El Niño–Southern Oscillation
EPW	Economic and Political Weekly
EQUINOO	Equatorial Indian Ocean Monsoon Oscillation
EU	European Union
EV	Electric Vehicles
EWS	Early Warning Systems
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles
FAO	Food and Agriculture Organization
FEC	Final Energy Consumption

FES	Foundation for Ecological Security
FICCI	Federation of Indian Chambers of Commerce and Industry
FY	Financial Year
FETF	Fuel Evaluation Test Facility
GBM	Ganga–Brahmaputra–Meghna
GCM	General Circulation Model
GDP	Gross Domestic Product
GGGI	Global Green Growth Institute
GHG	Greenhouse Gas
GIM	Green India Mission
GIS	Geographic Information System
GLOF	Glacial Lake Outburst Flood
GOI	Government of India
GRIHA	Green Rating for Integrated Habitat Assessment
GST	Goods and Services Tax
GT	Gigatonnes
GTC	Gigatonnes of Carbon Dioxide Equivalent
GVA	Gross Value Added
HAP	Heat Action Plan
HCVI	Hunger and Climate Vulnerability Index
HIO	High-Impact Opportunities
HPB	High Performance Buildings
HVAC	Heating, Ventilation, and Air Conditioning
HWD	Heat Wave Duration/Days
ICAR	Indian Council of Agricultural Research
ICCC	Integrated Command and Control Centres
ICFRE	Indian Council of forestry Research and Education
ICT	Information and Communications Technology
ICZM	Integrated Coastal Zone Management
IDSP	Integrated Disease Surveillance Programme
IEA	International Energy Agency
IFS	Indian forest Service
IGBC	Indian Green Building Council

IGCC	Integrated Coal Gasification Combined Cycle
IGFRI	Indian Grassland and Fodder Research Institute
IGP	Indo-Gangetic Plains
IIHS	Indian Institute for Human Settlements
IITM	Institute of Tropical Meteorology
IMD	India Meteorological Department
INDC	Intended Nationally Determined Contribution
INM	Integrated Nutrient Management
INR	Indian National Rupees
IOT	Internet of Things
IPCC	Intergovernmental Panel On Climate Change
IPPU	Industrial Processes and Product Use
ISA	International Solar Alliance
JBIC	Japan Bank for International Cooperation
JFM	Joint forest Management
JNNURM	Jawaharlal Nehru National Urban Renewal Mission
KUSUM	Kisan Urja Suraksha Evam Utthaan Mahaabhiyan
LCOE	Levelized Cost of Electricity
LED	Light-Emitting Diodes
LEED	Leadership In Energy and Environmental Design
LPG	Liquefied Petroleum Gas
LULC	Land Use Land Cover
LULUCF	Land Use, Land-Use Change and forestry
MCAP	Mumbai Climate Action Plan
MDB	Multilateral Development Banks
MEDA	Maharashtra Energy Development Agency
MGNREGA	Mahatma Gandhi National Rural Employment Guarantee Scheme
MNRE	Ministry of New and Renewable Energy
MoAFW	Ministry of Agriculture & Farmers' Welfare
MOEFCC	Ministry of Environment, forest and Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MoSPI	Ministry of Statistics and Programme Implementation
MPASR	Multipurpose Artificial Surfing

MPEHWD	Maximum Population Exposed To Heatwave Days
MSME	Micro, Small and Medium Enterprises
MTW	Maximum Taxi Weight
NABARD	National Bank for Agriculture and Rural Development
NAEB	National Afforestation and Eco-Development Board
NAP	National Afforestation Programme
NAPCC	National Action Plan On Climate Change
NBC	National Building Code
NCRMP	National Cyclone Risk Mitigation Project
NCSCM	National Centre for Sustainable Coastal Management (
NDC	Nationally Determined Contributions
NDMA	National Disaster Management Authority
NDMP	National Disaster Management Policy
NEMMP	National Electric Mobility Mission Plan
NFDB	National Fisheries Development Board
NFSM	National Food Security Mission
NGO	Non-Governmental Organisations
NHM	National Horticulture Mission
NICRA	National Innovations In Climate Resilient Agriculture
NIO	North Indian Ocean
NIUA	National Institute of Urban Affairs
NMBHWB	National Mission On Biodiversity and Human Well-Being
NMEEE	National Mission for Enhanced Energy Efficiency
NMSA	National Mission On Sustainable Agriculture
NMSHE	National Mission On Sustaining Himalayan Ecosystem
NMSKCC	National Mission On Strategic Knowledge for Climate Change
NMT	Non-Motorised Transport
NPP	Net Primary Productivity
NRDC	National Resources Defence Council
NRHM	National Rural Health Mission
NTDPC	National Transport Development Policy Committee
NTFP	Non-Timber forest Products
NTPC	National Thermal Power Corporation

NUHM	National Urban Health Mission
NURM	National Urban Renewal Mission
NUTP	National Urban Transport Policy
NWM	National Water Mission
PAT	Perform, Achieve, Trade
PCWA	Per Capita Water Availability
PDMC	Per Drop More Crop
PDS	Public Distribution System
PGCIL	Power Grid Corporation of India Limited
PHC	Primary Healthcare Centres
PIB	Press Information Bureau
PKVY	Paramparagat Krishi Vikas Yojana
PLI	Production Linked Incentive
PM	Particulate Matter
PMAY	Pradhan Mantri Awas Yojana
PMFBY	Pradhan Mantri Fasal Bima Yojana
PMKSY	Pradhan Mantri Krishi Sinchai Yojana
PPP	Purchasing Power Parity
PV	Photovoltaic
RBI	Reserve Bank of India
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
R&D	Research and Development
RMI	Rocky Mountain Institute
RS	Remote Sensing
RSPM	Respiratory Suspended Particulate Matter
RVEP	Remote Village Electrification Programme
S&T	Synergies and Trade-offs
SAPCC	State Action Plans On Climate Change
SAU	State Agriculture Universities
SBM	Swachh Bharat Mission
SC	Scheduled Caste
SCADA	Supervisory Control and Data Acquisition

SDG	Sustainable Development Goals
SDS	Sustainable Development Scenario
SECI	Solar Energy Corporation of India
SEEMP	Ship Energy Efficiency Management Plan
SHM	Soil Health Management
SLR	Sea Level Rise
SOC	Soil Organic Carbon
SPEI	Standardized Precipitation Evapotranspiration Index
SPM	Suspended Particulate Matter
SPS	Stated Policies Scenario
SRES	Special Report On Emissions Scenario
SRI	System of Rice Intensification
SSP	Shared Socio-Economic Pathways
ST	Scheduled Tribes
SUP	Summary for Urban Policymakers
SWM	Solid Waste Management
TCO	Total Cost of Ownership
TERI	The Energy and Resources Institute
THI	Temperature-Humidity Index
UHI	Urban Heat Island
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention On Climate Change
USAID	United States Agency for International Development
VSCS	Very Severe Cyclonic Storms
WASH	Water, Sanitation and Hygiene
ZBNF	Zero Budget Natural Farming
ZT	Zero Tillage

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