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REPORT

Long-term climate compatible growth for India

Modeling low-carbon pathways and policies for India's power, industry, and transport sectors

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CONTENTS


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Foreword

We know from scientific assessments by the Intergovernmental Panel on Climate Change that to limit global warming to 1.5°C, the world's carbon dioxide emissions need to fall to net zero by the middle of the century. These assessments, however, do not comment on how the effort to achieve this global emission reduction target should be distributed between countries. This is highly pertinent for India, which is a fast-growing economy with low historical and per capita emissions but which is highly vulnerable to the impacts of climate change.

This study is grounded in the concept of carbon budgets and determines India's fair share of the global carbon budget using four budget allocation approaches. Four Indian research groups then use different energy-economy models to distribute these budgets across time and sectors to determine decadal milestones for India's key energy sectors, viz. power, industry, and transport.

Together, these four models capture a variety of interlinkages between sectors and actors in the economy and can help take a system-wide approach in planning for these sectors to grow in a climate-compatible manner.

The analysis shows that India's power sector is already decarbonizing and a least-cost approach to building new power plants and retiring old, inefficient thermal power plants could accelerate power sector decarbonization. This is crucial not only to support real emissions reductions in electrifying end-use sectors but also to free up carbon space for the industry and transport sectors, which will become the largest and fastest-growing sources of emissions in India, respectively. With limited decarbonization options currently available in both these sectors, a multidimensional approach is required, including policy support for demand reduction, R&D, and achieving cost-parity and scaling of new green technologies. A carbon tax can also be a powerful tool to ensure real emissions reduction, compensate for falling fossil fuel-based tax revenues, and finance a just transition and adaptation measures for affected people.

Decarbonizing India's rapidly growing economy requires a disruptive transformation in the way we consume, produce, plan, and develop. Pegging sectoral growth plans with these climate-compatible milestones at the national level can give long-term signals and goals for these sectors to work towards, spurring innovative new business models and technologies, redirecting finance, and planning for the transition to be just and equitable.

Aligning long-term goals with near-term action is the need of the hour, and this report aims to provide a blueprint for key sectors in India to contribute to a thriving and equitable low-carbon economy.

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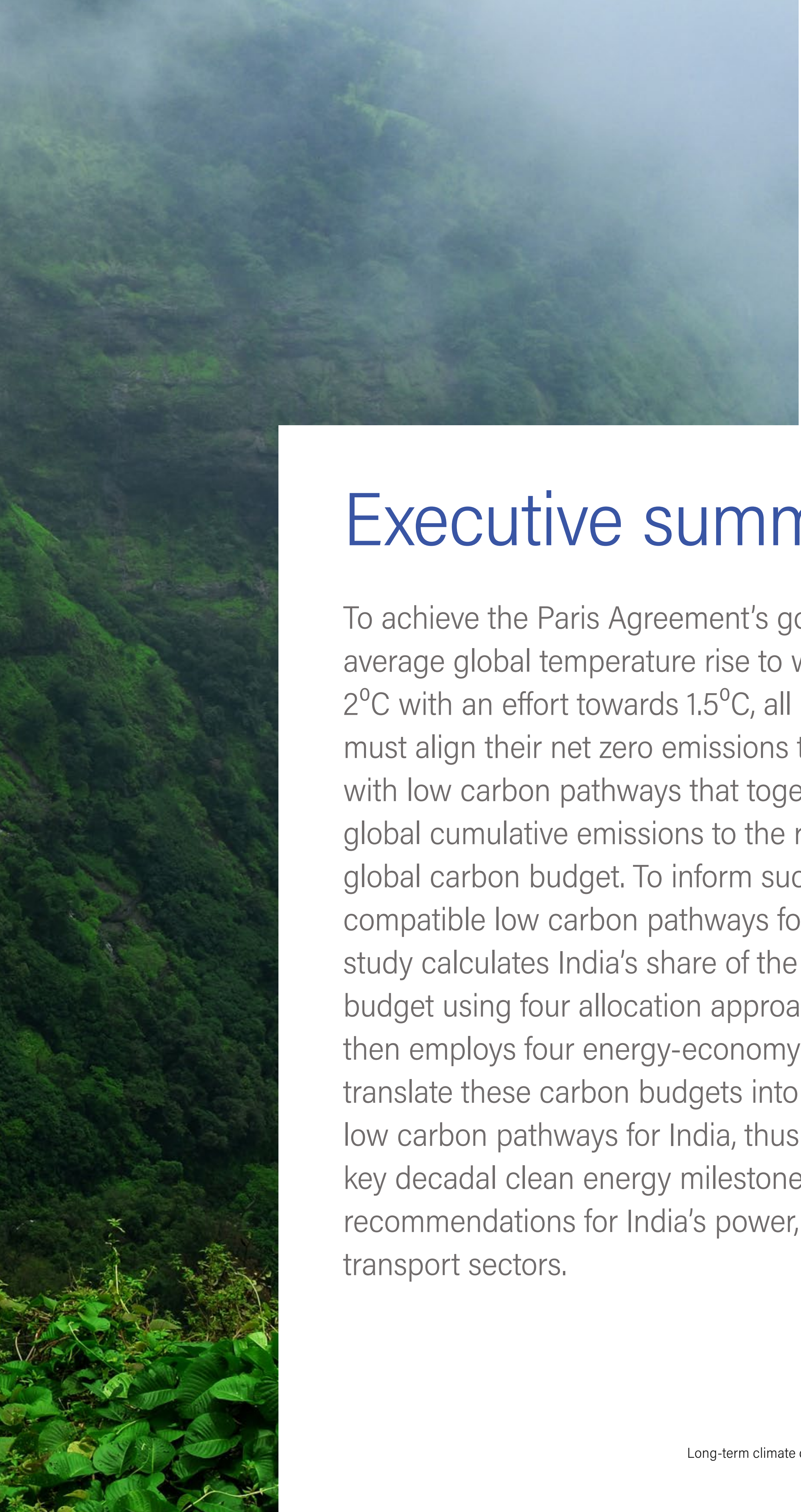
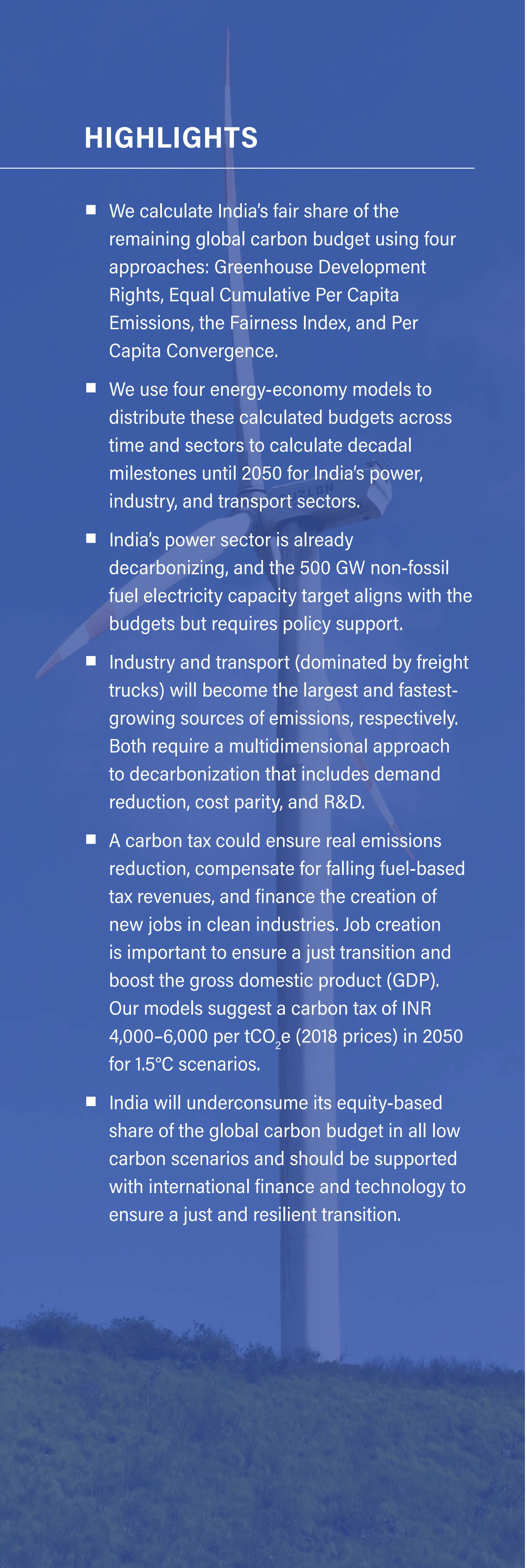


Executive summary

To achieve the Paris Agreement's goal of limiting average global temperature rise to well below 2°C with an effort towards 1.5°C, all countries must align their net zero emissions targets with low carbon pathways that together limit global cumulative emissions to the remaining global carbon budget. To inform such climate compatible low carbon pathways for India, this study calculates India's share of the global carbon budget using four allocation approaches and then employs four energy-economy models to translate these carbon budgets into long-term low carbon pathways for India, thus highlighting key decadal clean energy milestones and policy recommendations for India's power, industry, and transport sectors.



HIGHLIGHTS

- We calculate India's fair share of the remaining global carbon budget using four approaches: Greenhouse Development Rights, Equal Cumulative Per Capita Emissions, the Fairness Index, and Per Capita Convergence.
- We use four energy-economy models to distribute these calculated budgets across time and sectors to calculate decadal milestones until 2050 for India's power, industry, and transport sectors.
- India's power sector is already decarbonizing, and the 500 GW non-fossil fuel electricity capacity target aligns with the budgets but requires policy support.
- Industry and transport (dominated by freight trucks) will become the largest and fastest-growing sources of emissions, respectively. Both require a multidimensional approach to decarbonization that includes demand reduction, cost parity, and R&D.
- A carbon tax could ensure real emissions reduction, compensate for falling fuel-based tax revenues, and finance the creation of new jobs in clean industries. Job creation is important to ensure a just transition and boost the gross domestic product (GDP). Our models suggest a carbon tax of INR 4,000–6,000 per tCO$_2$e (2018 prices) in 2050 for 1.5°C scenarios.
- India will underconsume its equity-based share of the global carbon budget in all low carbon scenarios and should be supported with international finance and technology to ensure a just and resilient transition.

GLOBAL CONTEXT

Average global temperatures have risen by 1.07°C from pre-industrial times, and the impact of this rise on climate change is already starkly evident across the globe (IPCC 2022). In 2018, the Intergovernmental Panel on Climate Change (IPCC) published compelling evidence on the need to limit global warming to 1.5^{0}C (IPCC 2018). This evidence confirms the near-linear relationship between atmospheric CO$_2$ emissions and global warming, enabling this temperature target to be translated into the corresponding quantum of emissions. At a 67 percent probability of limiting the global temperature rise to 1.5°C, the world has a carbon budget of 400 GtCO$_2$ emissions left, as estimated by the IPCC's Sixth Assessment Report (IPCC 2022). At current trends, this is projected to be fully consumed between 2030 and 2035. As of February 2022, 134 countries accounting for 88 percent of the global GHG emissions (Net Zero Tracker n.d.) had committed to a net zero target to tackle this urgent challenge. However, in the absence of roadmaps/emissions trajectories underlying each country's target, the cumulative alignment of these net zero targets with the global carbon budget is unknown, as the same net zero targets can be met by discharging different quantities of cumulative carbon emissions. Similarly, net zero goals do not describe how effort is to be distributed between different countries; it is their chosen decarbonization trajectories and the cumulative emissions (their shares of the global carbon budget) that they discharge to achieve these net zero goals that determine the relative distribution of effort.

India's per capita emissions are currently less than half of the global average, but at the same time, India is the third-largest national emitter of annual GHG emissions. Moreover, rapid growth is expected in the coming decades as India's rising population, urbanization, and per capita income increase the demand for electricity, transport, housing, and goods and services. To allow space for this growth and development to occur and acknowledge both India's resulting restricted financial capability to fund the low carbon transition and its low contribution to the cumulative historical stock of emissions that has primarily led to the extant temperature rise, India has strongly favored the Common but Differentiated Responsibilities (CBDR) principle that acknowledges the different capabilities and responsibilities of individual countries in addressing climate change. To operationalize such equity principles in how climate action is pursued by different countries while simultaneously ensuring overall alignment with the global goal of limiting temperature rise to 1.5°C or well below

2°C, the global carbon budget can be distributed among countries by using allocation approaches based on different combinations of equity and other principles. This can help distribute mitigation responsibility among countries and set the carbon constraints within which they must decarbonize their economies in alignment with science.

ABOUT THIS REPORT: OBJECTIVE AND APPROACH

This report calculates India's share of the global carbon budget reported by the IPCC's AR6 (IPCC 2022) using multiple allocation approaches based on principles relevant to the Indian narrative on climate action: Responsibility, Equity, Capability/need, Sovereignty, Cost-effectiveness, and Stringency. These carbon budgets are then back-casted across their corresponding time frame by four energy-economy models hosted by four partner organizations to provide economy-wide and sectoral energy consumption and emission trajectories. These energy consumption trajectories inform key milestones in the power, transport, and industry sectors, indicating where they need to be in the short, medium, and long term to be able to grow in accordance with the budgets.

Back-casting approach

As opposed to the more common forecasting approach that projects future trajectories based on historical trends under certain assumptions, a back-casting or "future-back" approach helps assess where one needs to be in the short and medium term to achieve a desired outcome in the long term. As a result, using this approach within our study highlights the scale of transformation needed in the interim years to constrain India's cumulative emissions to the calculated budgets in the long term.

Multi-model analysis

Each model's structure is embedded in its own unique paradigm and treats the economy differently. By employing four energy-economy models to create low carbon scenarios that follow the same narrative (alignment with India's share of the global carbon budget that we calculate), together, their outputs for each milestone indicator constitute a range that is aligned with the same objective (alignment with the carbon budget) while simultaneously encompassing their very different assumptions regarding India's economic growth, development, and energy consumption. This comparison across different models that attempt to achieve the same objective allows us to explore commonalities in, and differences between, their results, which helps synthesize common insights that can inform India's long-term decarbonization strategy in a variety of alternative future scenarios. The choice of models was based on their unique frameworks and solution methods (as shown in the section titled "Overview of Models" below).

The four models and the corresponding modeling partners involved in this study are listed in Table ES-1.

TABLE ES-1 | List of partner organizations and their energy-economy models

ORGANIZATION	MODEL
WRI India	Energy Policy Simulator (EPS)
Council on Energy, Environment and Water (CEEW)	Global Change Analysis Model (GCAM)
Centre for Study of Science, Technology and Policy (CSTEP)	Sustainable Alternative Futures for India (SAFARI)
KPMG Assurance and Consulting Services LLP	Computable General Equilibrium (CGE)

This report assesses the level of effort required for India to transition from the current scenario to one that would be in alignment with the Paris Agreement vis-à-vis its fair contribution to the global carbon budget. This report provides inputs to policymakers and industries to help them determine the targets their clean energy policies should align with in the interim years 2030, 2040, and 2050 to achieve climate compatible growth in India over the long term.

CALCULATING INDIA'S SHARE OF THE GLOBAL CARBON BUDGET

As many as 29 approaches to dividing the global carbon budget among countries were found in the literature. Out of these, we shortlisted 10 approaches that were pertinent to the objective of the study, and then developed a multicriteria framework to whittle down this list. This framework assessed each allocation approach against a set of chosen principles—Responsibility, Equity, Capability/need, Sovereignty, Cost-effectiveness, and Stringency—that are important to consider in the Indian context. The top four approaches whose underlying principles exhibited the best overlap with the chosen principles were selected for this study and are listed in Table ES-2.

TABLE ES-2 | Principles underlying chosen budget allocation approaches

ALLOCATION APPROACH	UNDERLYING PRINCIPLES
Greenhouse Development Rights (GDR)	▪ Responsibility ▪ Capacity
Equal Cumulative Per Capita Emissions (ECPC)	▪ Responsibility ▪ Equality
Fairness Index (FI)	▪ Egalitarian Principle ▪ Ability to Pay Principle ▪ Efficiency Principle ▪ Desert Principle ▪ Polluter Pays Principle
Per Capita Convergence (PCC)	▪ Sovereignty ▪ Equality

These approaches were then used to calculate India's share of the global carbon budget under the temperature scenarios of 1.5°C and 2°C, each under a 50 percent and 66 percent probability of being met. The time frame of the calculated carbon budgets was 2020–2100, in line with that of the global carbon budget. The study deploys multiple allocation approaches (to distribute the global carbon budget among countries) and does not single out any particular approach as the most appropriate. The set of 16 carbon budgets calculated for India is given in Table ES-3.

Note that because global carbon budgets include only CO_2 emissions, non-CO_2 greenhouse gases [GHGs] have not been included in the calculation of India's share. The inclusion of non-CO_2 GHGs may impact the allocations to different countries.

BACK-CASTING INDIA'S CALCULATED CARBON BUDGETS WITH FOUR ENERGY-ECONOMY MODELS

Overview of the models

Each model presents its own subjective assessment of India's future, based on its unique methods, assumptions, and paradigm. We thus analyze each model's outcomes in the context of its own assumptions rather than directly comparing them. At the same time, all models develop their low carbon scenarios with the same storyline of alignment with the carbon budgets calculated for India, which allows us to combine their results for each indicator into a range.

Computable General Equilibrium (CGE) is the only full equilibrium, top-down model employed in the study and thus presents unique outcomes by capturing the impact of an induced low carbon transition in each sector on the rest

TABLE ES-3 | Carbon budgets calculated for India for 2020–2100

TEMPERATURE THRESHOLDS	1.5°C					2°C				
India's carbon budget (in $GtCO_2$)	Total global	Greenhouse Development Rights (GDR)	Equal Cumulative Per Capita Emissions (ECPC)	Fairness Index (FI)	Per Capita Convergence (PCC)	Total global	GDR	ECPC	FI	PCC
50% probability	500	672	305	239	58	1,350	677	440	354	155
66% probability	400	672	289	226	46	1,150	675	408	327	132

Notes: All figures are in gigatonnes of CO_2 ($GtCO_2$).

Source: Authors.

of the economy. Global Change Analysis Model (GCAM) (Joint Global Change Research Institute n.d.) is the only global integrated assessment model (IAM) employed in the study. As a recursive dynamic, partial equilibrium model, it computes how demand is met across all sectors individually but in the most cost-optimal manner to the economy. Sustainable Alternative Futures for India (SAFARI) (Ashok et al. 2021) is a bottom-up, systems dynamics model that estimates the energy, resource, and emissions implications of achieving developmental goals such as housing for all, health, and education, and the demands that meeting these goals will generate. The economic and energy activity in sectors not directly impacted by the achievement of development goals is driven by investment assumptions in their own macroeconomic CGE model. The Energy Policy Simulator (EPS) (Energy Policy Solutions n.d.) is a recursive dynamic, partial equilibrium, systems dynamics model that assesses "what-if" scenarios by evaluating the impact of the policy package chosen by the user on various socioeconomic and environmental outcomes such as energy, emissions, GDP, jobs, costs, and health.

Methodology

Of the 16 carbon budgets calculated for India above, each partner modeled 6 carbon budgets using the ECPC, FI, and PCC approaches, each aligned with the 1.5°C and 2°C temperature scenarios. This selection was made by choosing to model only the budgets following a 66 percent probability of meeting their corresponding temperature targets (as they represent a higher likelihood of meeting their corresponding temperature target and are the most commonly used in the literature). The two GDR budgets were also excluded because their emissions exceeded all four models' reference scenario cumulative emissions up to 2100 and were approximately 1.5 times the size of the global carbon budget, implying very high negative emissions by developed countries. The authors chose not to consider this approach given the current nascent stage of negative emissions technologies and the uncertainty around their feasibility in limiting net emissions to the carbon budget.

Next, three of the models—CGE, SAFARI, and the EPS—are set up only up to 2050, whereas carbon budgets are a 2100 concept. Therefore, to broadly assess what share of the global 2100 budget is consumed by 2050, we aggregated the cumulative emissions from 2018 to 2050 in the global net zero scenarios developed by IIASA (Huppmann et al. 2018) and published in the IPCC SR1.5 report (IPCC 2018) for each temperature scenario. We then used the four shortlisted budget allocation approaches to calculate India's share of the cumulative emissions until 2050 in these low carbon scenarios in both temperature scenarios. We found that in IIASA's global scenarios, in the 1.5^{0}C-aligned scenarios, most of the 2100 carbon budget was fully consumed by 2050, leading to global net zero emissions around the same period. Because India's budgets are a fraction of the 2100 global budget, they follow the same trajectory and most of the 1.5°C budgets are consumed by 2050, implying net zero for India by 2050. Similarly, in the 2°C scenarios, global net zero occurs from 2070 to 2085, and so more than half the 2100 budget is consumed by 2050, which therefore also applies to India. However, the sizes of these calculated 2050 "budgets" for India are larger than India's cumulative business as usual (BAU) emissions until 2050 because of the equity principles underlying the allocation approaches. Thus, we allowed for all scenarios to peak before 2050 (with the peaking year depending on the size of the budget) but reach net zero after the global net zero years.

Each model then back-casted each of the six chosen carbon budgets across 2020–50. CGE created the budget scenarios by adjusting investments toward low carbon technologies such that the resultant cumulative emissions met the timelines discussed above for each carbon budget. GCAM directly back-casted the carbon budget from 2020 to 2100 because it could be fed as an input into the model. In SAFARI, because meeting development goals drives demand, the team chose a fixed set of goals to be met in the budget scenarios and then explored different low carbon pathways of meeting them by using different policies such that the cumulative emissions from 2020 to 2050 aligned with the carbon budget. In the EPS, the team chose policy packages in such a way that the cumulative emissions aligned with the carbon budget. The policies were chosen based on their feasibility, mitigation potential, and socioeconomic co-benefits, after which they were vetted by sectoral experts.

Three models (CGE, GCAM, and SAFARI) did not include the land use, land use change and forestry (LULUCF) sector. As this sector is a significant carbon sink for India, we conducted a separate assessment to understand the potential for (cumulative) carbon sinks in five different scenarios to assess what additional leeway could become available if the budgets are too stringent and cannot be met by mitigation policies alone (Table ES-4). The following scenarios were considered:

- Scenario 1 (reference pathway based on forecasting)
- Scenario 2.1 (Nationally Determined Contribution [NDC]-compliant scenario without GHG emission/removal cap by 2100 [Highly Optimistic Scenario])
- Scenario 2.2 (NDC-pledge-compliant scenario without GHG emission/removal cap by 2100 and land expansion cap after 2030 [Highly Optimistic Scenario])
- Scenario 3.1 (NDC- and National Forest Policy [NFP][1] -pledge-compliant scenario with moderate emission cap [Moderate Scenario])
- Scenario 3.2 (NDC- and NFP-pledge-compliant scenario with conservative emission cap)

Note that because a base year for the NDC commitment has not been officially announced, 2005 has been used because it is the base year for the other NDC commitments.

RESULTS: CONSUMPTION OF THE ESTIMATED BUDGETS FROM 2020 TO 2050 ECONOMY-WIDE AND BY KEY SECTORS

Table ES-5 shows that by 2050, the 1.5°C PCC budget is overconsumed in three models; 50–75 percent of the 2°C PCC budget is consumed; 30–40 percent of the two 1.5°C (FI and ECPC) budgets is consumed (thus approximately aligning with a net zero in 2070); and 25–35 percent of the 2°C (FI and ECPC) budgets is consumed across the four models. If India underconsumes its fair share of the global carbon budget, its climate ambition should be supported by international finance and technology, not just for mitigation but also to ensure that development priorities are not lost sight of in the trade-off, that the low carbon transition does not negatively impact the livelihoods of people employed in current fossil fuel industries, and that the loss and damage from the impacts of climate change that has already occurred are fairly compensated.

TABLE ES-4 | Annualized GHG removal from LULUCF sector under five scenarios

YEAR	SCENARIO 1	SCENARIO 2.1	SCENARIO 2.2	SCENARIO 3.1	SCENARIO 3.2
2030	−329.88	−472.12 to −522.24	−467.05 to −516.93	−417.14 to −406.40	−374.90 to −364.12
2040	−332.38	−478.05 to −528.67	−465.36 to −514.96	−415.88 to −405.21	−373.81 to −363.13
2050	−334.89	−483.96 to −535.07	−463.68 to −513.00	−414.64 to −404.02	−372.77 to −362.16
2100	−347.59	−513.25 to −566.72	−455.52 to −503.48	−408.59 to −398.26	−367.72 to −357.40

Notes: GHG = greenhouse gas; LULUCF = land use, land use change and forestry. All figures are in megatonnes of carbon dioxide equivalent ($MtCO_2e$).

Source: Authors.

TABLE ES-5 | Consumption of the calculated carbon budgets up to 2050 per the four models and their distribution across sectors

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	CARBON BUDGET VALUE, 2020–2100 ($GTCO_2$)	CUMULATIVE EMISSIONS, 2020–2050 ($GTCO_2$)	SHARE OF POWER SECTOR (%)	SHARE OF INDUSTRY SECTOR (%)	SHARE OF TRANSPORT (%)
Reference		127, 116, 113, 133	40, 52, 39, 27	23, 34, 37, 51	21, 14, 22, 19
2°C ECPC	408	103, 111, 99, 104	40, 52, 34, 20	24, 34, 41, 50	20, 14, 23, 21
2°C FI	327	99, 110, 96, 101	44, 52, 35, 19	22, 34, 40, 50	20, 14, 22, 21
1.5°C ECPC	289	91, 94, 96, 84	47, 49, 36, 14	23, 35, 40, 51	18, 16, 21, 22
1.5°C FI	226	86, 91, 92, 81	44, 48, 37, 13	24, 35, 39, 51	19, 17, 22, 22
2°C PCC	132	81, 97, 92, 70	45, 49, 36, 11	25, 36, 40, 52	17, 16, 21, 22
1.5°C PCC	46	72, 39, 88, 60	39, 34, 36, 9	28, 45, 41, 52	19, 21, 21, 21

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $GtCO_2$ = gigatonnes of CO_2.

Source: Authors.

MILESTONES IN THE POWER, TRANSPORT, AND INDUSTRY SECTORS FOR CLIMATE COMPATIBLE GROWTH IN INDIA

For each sectoral indicator, the four models together provide a range of permissible outcomes that align with each of the six carbon budgets. We compare them with historical values.

Power sector

Indicator 1: Absolute installed capacity of electricity from non-fossil fuel sources (corresponding to the target announced at COP26)

At COP26 in November 2021, India announced a target of reaching 500 GW of electricity generation capacity from non-fossil fuel sources by 2030. (Lolla et al. 2021) suggest that if this target is met, India will not need additional coal-fired power capacity to meet the projected electricity demands of 2030 beyond the 36.6 GW capacity that is already under construction. As of September 2022, India had achieved 171.7 GW toward this target (CEA 2022).

According to our projections, the 500 GW target is higher than the reference scenario 2030 projections of all four models (287, 432, 427, and 475 GW by CGE, GCAM, SAFARI, and the EPS, respectively). This indicates that current policies need to be enhanced to achieve this target.

Further, to stay compliant with five out of six of the calculated carbon budgets (1.5°C PCC is an outlier), the required cumulative installed capacity in 2030 from non-fossil fuel sources is approximately 420–590 GW across the models, as seen in table ES-6. *India's 500 GW target is thus compatible with almost all the carbon budgets calculated for India.*

Note that biomass does not play an important role in any of the models' scenarios, and nuclear energy plays an important role only in CGE, where it is included to provide the base load.

TABLE ES-6 | Power sector: Cumulative installed capacity from non-fossil fuels

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	SEPTEMBER 2022 HISTORICAL VALUE (GW)[a]	2030 MILESTONE (GW)	2040 MILESTONE (GW)	2050 MILESTONE (GW)
Reference	172	287, 432, 427, 475	394, 887, 828, 1020	551, 1231, 1351, 1598
2°C ECPC		587, 447, 440, 440	804, 969, 1204, 865	957, 1663, 2166, 1560
2°C FI		591, 447, 454, 444	1039, 969, 1259, 915	1244, 1825, 2233, 1757
1.5°C ECPC		591, 543, 430, 463	1150, 1513, 956, 1126	1680, 2741, 1738, 1847
1.5°C FI		591, 543, 425, 466	1290, 1609, 966, 1182	2499, 3046, 1897, 1955
2°C PCC		599, 447, 419, 498	1322, 969, 691, 1297	2570, 3526, 1466, 1929
1.5°C PCC		770, 1536, 420, 775	1718, 4746, 857, 1641	2984, 6831, 2061, 2194

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GW = gigawatt; MSW = municipal solid waste. Non-fossil fuels include solar, wind, hydro, nuclear, biomass, Municipal Solid Waste (MSW), and geothermal.

Sources: Authors; a. CEA 2022.

Indicator 2: Share of installed capacity of electricity from non-fossil fuel sources (NDC target) and the corresponding share of electricity generation from non-fossil fuel sources

Further, India's enhanced NDC submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in August 2022 conditionally committed to achieving 50 percent of the installed capacity of electricity from non-fossil fuel sources (Government of India 2022). In September 2022, 42 percent of this target was achieved (CEA 2022). According to GCAM, SAFARI, and the EPS, which project the power sector technology mix in the reference scenario on a least cost basis, this target is significantly exceeded at 62–65 percent. Further, the four models together recommend that the share of the non-fossil fuel capacity be in the range 59–72 percent to align with all carbon budgets except 1.5°C PCC (which is very stringent and therefore an outlier), indicating the scope for enhanced ambition (Table ES-7).

The lower capacity utilization factor (CUF) of renewables compared with thermal power plants leads to a difference between their shares of installed electricity capacity and generation. Table ES-8 gives a snapshot of the electricity generation that results from the abovementioned capacity shares according to the four models.

TABLE ES-7 | Power sector: Share of non-fossil fuel energy in total installed capacity

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	SEPTEMBER 2022 VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	42	45, 65, 62, 63	43, 73, 73, 70	45, 75, 77, 75
2°C ECPC		64, 65, 63, 64	65, 75, 82, 72	67, 81, 89, 84
2°C FI		63, 65, 64, 64	69, 75, 83, 73	71, 84, 90, 85
1.5°C ECPC		61, 69, 63, 68	70, 85, 79, 82	77, 94, 88, 91
1.5°C FI		59, 69, 62, 69	73, 87, 80, 83	92, 94, 89, 91
2°C PCC		60, 65, 62, 72	72, 75, 75, 88	92, 99, 87, 92
1.5°C PCC		70, 95, 62, 82	85, 100, 78, 90	95, 100, 90, 93

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Sources: Authors; a. CEA 2022.

TABLE ES-8 | Power sector: Share of non-fossil fuel energy in total electricity generation

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	24.62	25, 35, 43, 39	26, 45, 56, 55	29, 48, 59, 68
2°C ECPC		42, 35, 43, 50	45, 45, 70, 70	51, 57, 81, 89
2°C FI		42, 35, 44, 50	51, 45, 71, 71	57, 60, 82, 91
1.5°C ECPC		41, 38, 43, 54	53, 61, 65, 83	66, 81, 79, 96
1.5°C FI		41, 38, 43, 55	59, 63, 66, 84	87, 87, 80, 96
2°C PCC		44, 35, 44, 59	60, 45, 57, 93	88, 95, 76, 96
1.5°C PCC		55, 86, 43, 76	76, 100, 62, 94	93, 100, 85, 97

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Sources: Authors; a. CEA 2020b.

Industry sector

Indicator 3: Percentage share of electricity in the industry sector's fuel mix

Up to now, India has primarily focused on energy efficiency in the industry sector, followed by a certain level of material efficiency. However, our analysis shows that at current trends, the industry sector will replace the power sector as the largest source of annual emissions in India by 2050, driven by the rising demand for energy-intensive materials such as cement and steel that is generated by rapid urbanization, the meeting of development goals as seen in SAFARI, and the domestic manufacturing of renewables captured by CGE. To decouple the growth of the industry sector from emissions, a technology switch from fossil fuels to electricity to meet the heat and energy needs of industrial subsectors would play an important role. Currently, electricity constitutes 14.45 percent of the industry sector's fuel energy mix (MoSPI 2022) and is estimated to reach a maximum of 32 percent by 2050 in the reference scenario per GCAM due to the falling costs of electricity and reduced technological barriers (the other models follow historical trends and thus do not change much over time). To stay compatible with our calculated carbon budgets, this share needs to be much higher, as shown in Table ES-9. Moreover, electrification alone will not suffice; to mitigate the remaining emissions, other low carbon fuels such as green hydrogen, green ammonia and sustainably produced biomass and waste will be needed, as well as technological innovation in carbon capture, utilization, and storage (CCUS) and other solutions to neutralize/reduce CO_2 process emissions such as those from the calcination process in the cement sector. Table ES-9 gives the share of the industry fuel mix that must come from electricity over time to stay compatible with the calculated budgets.

TABLE ES-9 | Industry sector: Percentage of electricity in fuel mix

■ CGE ■ GCAM ■ SAFARI ■ EPS

SCENARIO	2019 HISTORICAL VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	14.45	23, 28, 22, 14	20, 31, 22, 14	17, 32, 22, 15
2°C ECPC		30, 29, 21, 14	31, 32, 22, 17	30, 36, 22, 24
2°C FI		32, 29, 21, 14	38, 32, 23, 18	43, 38, 24, 27
1.5°C ECPC		33, 34, 22, 14	43, 41, 23, 22	52, 47, 24, 31
1.5°C FI		33, 34, 22, 14	46, 42, 25, 23	60, 49, 27, 34
2°C PCC		33, 29, 22, 14	48, 32, 25, 25	64, 64, 27, 38
1.5°C PCC		33, 54, 21, 22	48, 92, 25, 30	66, 95, 27, 41

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Sources: Authors; a. (MoSPI 2022).

Transport sector

Indicator 4: Percentage of electric vehicles in total annual vehicle sales

Although currently less than 1 percent of total vehicle sales is from electric vehicles (EVs [BEE n.d. a]), the aggravating impacts of air pollution, India's dependence on expensive oil imports, and the business case for developing India as a hub for EV battery manufacturing (Saran 2021) have together led to a growing emphasis on incentivizing both the demand for EVs locally as well as their local manufacturing under the "Make in India" scheme. Although no EV target has been specified in a policy yet, announcements have been made to achieve a 30 percent share of the total vehicle fleet for EVs by 2030 (R. Shah 2018), 100 percent share of 2-wheeler sales for EVs by 2026 (a vehicle segment that dominated 76 percent of the total fleet in 2017 [Carpenter 2019]), and 100 percent electrification of railways by 2023, of which 65 percent was achieved by 2020 (Ministry of Railways 2021). The FAME II scheme provides demand incentives to achieve the first two targets among other segments, and the April–September 2022 period saw a 404 percent uptake in electric 2-wheelers and a 268 percent growth in electric 4-wheelers over the same period in the previous year (Bharadwaj 2022). GCAM and the EPS show that almost 100 percent electrification of 2-wheelers, 3-wheelers, and the railways is possible by 2050 (these segments currently account for more than 80 percent of India's vehicle sales [IBEF 2022]), followed by the electrification of 4-wheeler LDVs (light duty vehicles, i.e., cars) with some policy and R&D effort to bring down costs and reduce the technological hurdles associated with, for example, batteries. Table ES-10 shows the share of sales that will have to come from EVs in each vehicle mode segment for compatibility with India's temperature goals. These ranges constitute outcomes from GCAM and the EPS, because the other two models do not report this variable.

TABLE ES-10 | Transport sector: Percentage of electric vehicles in total vehicle sales

🟥 GCAM 🟪 EPS

SCENARIO	2-WHEELERS			3-WHEELERS			4-WHEELERS			BUSES			TRUCKS		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	52, 18	80, 36	91, 38	26, 13	85, 28	93, 30	30, 17	58, 31	73, 33	4, 9	40, 20	58, 23	0, 1	0, 3	1, 4
2°C ECPC	52, 27	80, 53	92, 80	27, 27	84, 53	94, 80	30, 17	58, 33	74, 51	4, 10	40, 19	59, 25	0, 1	0, 3	1, 5
2°C FI	52, 30	80, 60	92, 90	27, 30	84, 60	95, 90	30, 16	58, 31	74, 52	4, 10	40, 19	60, 30	0, 2	0, 6	1, 10
1.5°C ECPC	53, 40	82, 80	92, 100	31, 40	90, 80	95, 100	30, 18	59, 43	74, 71	5, 10	43, 24	60, 40	0, 3	0, 9	1, 15
1.5°C FI	53, 40	82, 80	92, 100	31, 40	90, 80	96, 100	30, 18	59, 43	74, 71	5, 10	43, 27	62, 45	0, 3	0, 9	1, 15
2°C PCC	52, 40	80, 80	95, 100	27, 40	84, 80	98, 100	30, 22	58, 62	75, 82	4, 24	40, 48	69, 60	0, 5	0, 15	3, 20
1.5°C PCC	67, 50	99, 100	100, 100	74, 50	100, 100	100, 100	33, 50	74, 100	85, 100	8, 38	96, 75	98, 75	0, 12	100, 25	100, 25

Notes: Models: EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. EV = electric vehicle.

Source: Authors.

Indicator 5: Percentage share of electricity in the transport sector's fuel mix

Currently, more than 97 percent of the energy used by India's transport sector comes from fossil fuels, predominantly oil (MoSPI 2022). A transformational shift from fossil fuels to electricity will be needed for alignment with the calculated budgets. However, GCAM and the EPS find that although the 2-wheeler, 3-wheeler, and 4-wheeler segments can be fully electrified by 2050, this has little impact on the overall shift to electricity because the largest share of transport emissions beyond 2030 is contributed by freight trucks, which is the hardest segment to electrify and cannot be fully electrified by 2050. Supporting these segments will need additional focus with policies that encourage a mode shift to freight rail and the uptake of alternative fuels such as gas, biofuels, and green hydrogen for road freight. In SAFARI, electrification levels are low because it meets the emissions constraint using demand reduction interventions such as incentivizing a mode shift from private to public vehicles, fuel efficiency (already mandated by the Corporate Average Fuel Efficiency [CAFE] standards), and better urban planning, which have a very strong impact on emissions reduction. Table ES-11 gives the share of electricity in the transport sector's fuel mix across all the scenarios per the four models.

Primary energy consumption

The primary energy consumption fuel mix is an important indicator for gauging the level of real decarbonization across an economy. This is because robust efforts toward electrification or alternative fuels (such as hydrogen or biomass) in end-use sectors (such as transport, industry, and buildings) would contribute to economy-wide decar-

TABLE ES-11 | Transport sector: Percentage of electricity in fuel mix

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	2.8	2, 3, 3, 3	2, 6, 3, 5	2, 7, 3, 6
2°C ECPC		2, 3, 4, 3	2, 6, 5, 6	3, 7, 8, 10
2°C FI		3, 3, 4, 3	4, 6, 5, 7	4, 7, 9, 13
1.5°C ECPC		4, 3, 3, 4	7, 6, 5, 9	7, 8, 8, 19
1.5°C FI		5, 3, 4, 4	8, 6, 6, 10	8, 8, 8, 20
2°C PCC		6, 3, 4, 5	10, 6, 7, 15	12, 9, 10, 31
1.5°C PCC		6, 4, 3, 7	11, 46, 8, 24	14, 80, 14, 44

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Sources: Authors; a. MoSPI 2022.

bonization only if they are sourced from parallel decarbonizing supply-side sectors (such as electricity from renewable energy [RE], green hydrogen, and so on) without simply displacing emissions from the former to the latter. Moreover, top-down models such as the CGE capture the "substitution effect" in the economy; that is, as the demand for coal falls in the faster-decarbonizing power sector, its price falls, and so it gets picked up by the industry sector due to its lower cost. Thus, although coal consumption may fall in the power sector, the primary energy mix would still capture the continued presence of that coal in the economy through its increased consumption in industry. The next two indicators give the shares of renewables and coal needed in India's primary energy mix for alignment with India's calculated carbon budgets.

Indicator 6: Share of renewables (solar, wind, and geothermal) in primary energy consumption

Table ES-12 shows that in 2019, 9.4 percent of India's energy consumption came from non-fossil fuel sources (IEA 2021). This share must rise to about 14–45 percent in 2030 (not considering 1.5°C PCC) and even higher thereafter to be climate compatible.

TABLE ES-12 | Primary energy consumption: Share of non-fossil fuel sources

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	9.4	22, 16, 17, 29	25, 18, 20, 35	31, 18, 22, 39
2°C ECPC		43, 15, 14, 32	44, 16, 25, 42	49, 19, 34, 60
2°C FI		43, 15, 18, 32	52, 16, 28, 44	56, 21, 38, 65
1.5°C ECPC		44, 14, 14, 35	55, 20, 24, 55	64, 30, 33, 73
1.5°C FI		44, 14, 18, 35	61, 22, 27, 56	79, 34, 37, 75
2°C PCC		45, 15, 15, 38	62, 16, 22, 64	80, 48, 32, 80
1.5°C PCC		53, 44, 14, 50	70, 85, 25, 71	83, 95, 41, 85

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Sources: Authors; a. IEA 2021.

Indicator 7: Share of coal in primary energy consumption

Conversely, the share of coal in India's primary energy mix stood at 44.5 percent in 2019 (and the share of coal, oil, and solid biomass together accounts for more than 80 percent of the total primary energy consumption [IEA 2021]), and massive efforts will be required to reduce this share over time. Table ES-13 shows the level of coal in India's primary energy mix that aligns with the calculated carbon budgets.

TABLE ES-13 | Primary energy consumption: Share of coal

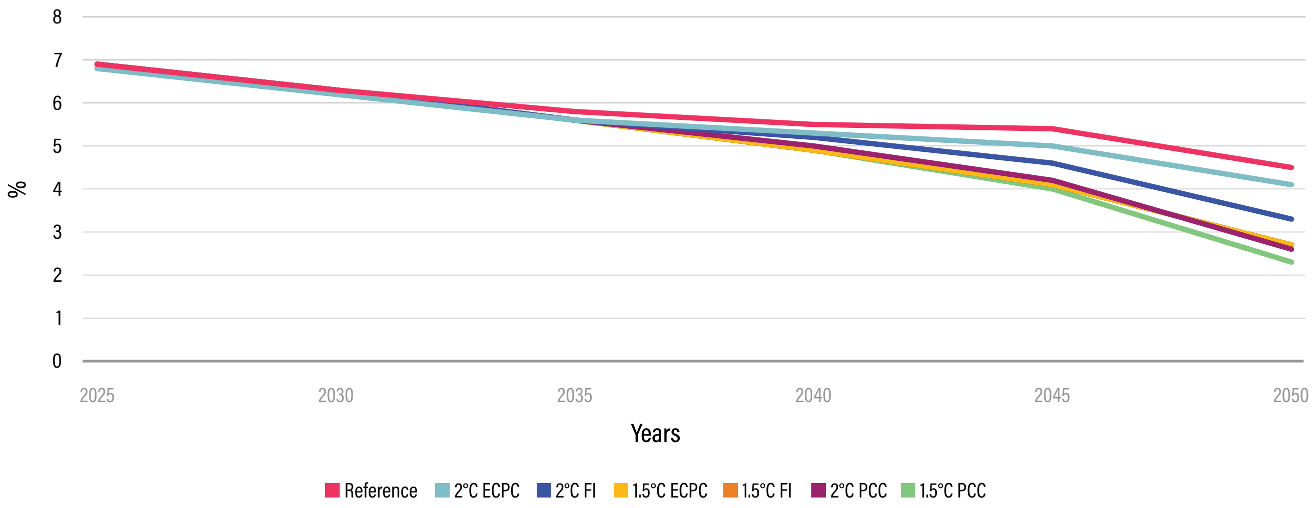
🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	44.5	43, 47, 51, 38	38, 44, 47, 32	33, 43, 46, 28
2°C ECPC		29, 48, 53, 36	27, 45, 39, 25	23, 39, 33, 13
2°C FI		29, 48, 52, 35	23, 45, 36, 24	19, 36, 28, 11
1.5°C ECPC		29, 49, 51, 33	22, 37, 41, 16	15, 23, 33, 6
1.5°C FI		29, 49, 50, 33	19, 35, 38, 14	7, 18, 28, 5
2°C PCC		27, 48, 51, 31	19, 45, 41, 9	6, 9, 29, 4
1.5°C PCC		23, 17, 53, 19	13, 0, 40, 6	5, 0, 25, 3

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Sources: Authors; a. IEA 2021.

FIGURE ES-1 | CGE: Five-year GDP growth rate (%)



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

Source: Authors.

SOCIOECONOMIC INDICATORS AND CARBON PRICE

GDP, jobs, income inequality, and health

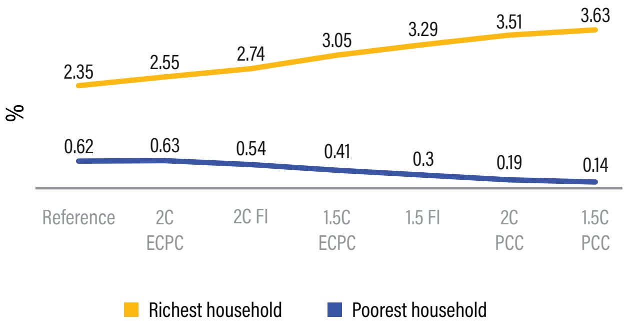
CGE

Our analysis of the impact of the low carbon scenarios on GDP using the CGE, SAFARI, and EPS models shows the following.

According to CGE, a shift away from fossil fuels negatively impacts the GDP (Figure ES-1). This is because of several factors in the model:

- Fossil fuel industries are labor intensive, whereas low carbon industries are capital intensive. Thus, a shift from the former to the latter negatively impacts jobs in current fossil fuel industries, reducing the private income of workers.
- Direct impacts on jobs also affect indirect jobs (those created in the supply chain of the industries of the directly impacted jobs) and induced jobs (those created as a result of the economic activity from direct and indirect jobs), leading to an overall decrease in private income, which then exacerbates income inequality (Figure ES-2) and dampens economic activity across the economy, as seen in the GDP.

FIGURE ES-2 | CGE: Income inequality across scenarios



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

- CGE treats investments in renewables as sourced from disinvestments in fossil fuel industries rather than as additional new investments. Thus, there is a low net increase in total investments, as a result of which they do not compensate for the fall in income when the GDP is calculated.

This highlights the need for a just transition to ensure that workers in fossil fuel industries are reskilled and re-employed in new jobs to prevent higher income inequality, lower private income, and impacts on the overall GDP.

SAFARI

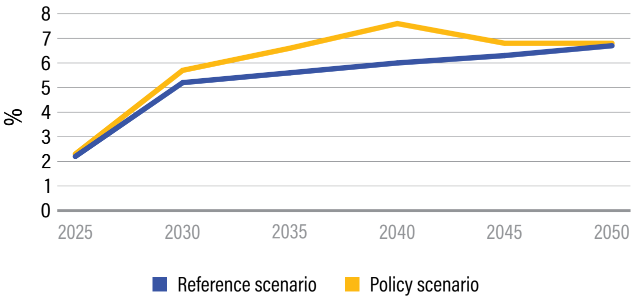
On the other hand, SAFARI shows that the achievement of the development goals in the policy scenarios (which are not met in the reference scenario) leads to the mobilization of additional investments up to 2050, notably in construction, which causes GDP growth to increase up to 2050 (Figure ES-3).

EPS

Although the EPS exhibits similar negative impacts on employment and thus on income and the GDP as in CGE, the imposition of a carbon tax not only alleviates these negative impacts but also raises the GDP to levels higher than in the reference scenario (Figure ES-4). This occurs because the carbon tax compensates for falling government revenues from the oil excise duty, which the government then re-spends in the economy, creating new direct, indirect, and induced jobs, and contributing to the GDP. The investments in low carbon technologies such as green hydrogen and EVs also contribute to new job creation and the GDP.

On the other hand, the EPS shows that a shift away from fossil fuels to green energy/technologies (i.e., the chosen clean energy policy package) leads to a net fall in expenditure across the economy relative to the reference levels (Figure ES-5), after accounting for new investments in new technologies and increased expense on electricity.

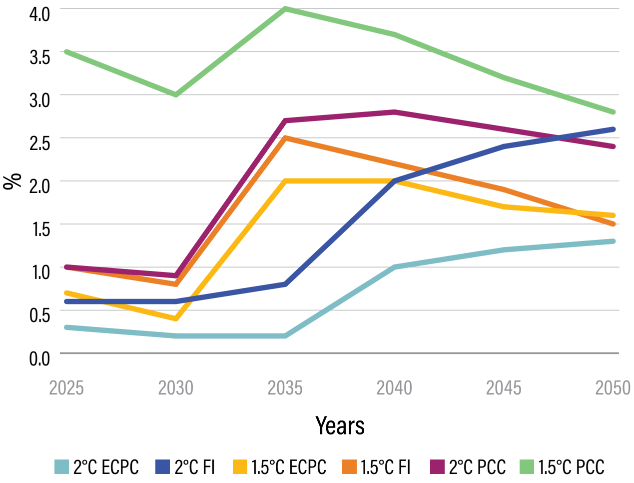
FIGURE ES-3 | SAFARI: Five-year GDP growth rate (%)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. GDP = gross domestic product.

Source: Authors.

FIGURE ES-4 | EPS: Change in GDP relative to reference scenario (%)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

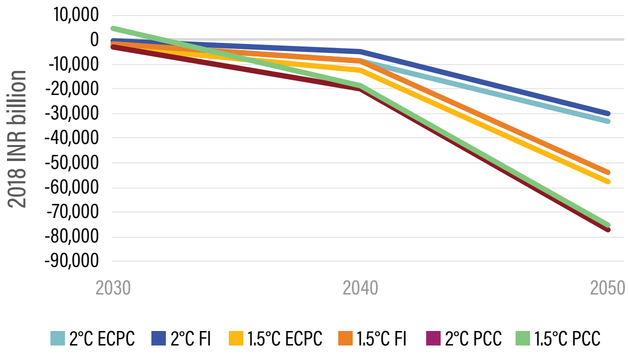
These are primarily savings from lower fossil fuel expenses in the electricity, industry, and transport sectors. These savings are primarily in the private sector, both by individuals who, for example, would significantly reduce their private expenditure on fuel as they shift to EVs (net of the electricity purchased for EVs), as well as by private companies.

Although a part of these savings in the private sector may be re-spent in the economy (either through higher domestic private expenditure or increased investments by the companies), we observe in the EPS that the maximum re-spending in the economy occurs through the public sector, which is the most effective way of inducing a positive multiplier effect across the economy. Thus, for these aforementioned savings to positively impact the whole economy, a part of these savings would have to be recycled from the private sector to the government, where they can then be pumped back into the economy through higher public expenditure.

We find that, in the EPS, a carbon tax in the power and industry sectors not only recycles private savings to the government, but also incentivizes operations away from fossil fuels and compensates for the significant dent in Indian coffers due to a fall in revenues from the excise duty on oil products, which currently constitutes 25 percent of government revenues. Another policy lever in the EPS then allows for these carbon tax revenues to be utilized for public spending (instead of competing sources of government expenses), which leads to a rise in the GDP (see Figure ES-4) and jobs (see Figure ES-6).

Although new public spending occurs statically in the EPS where public investment is already occurring, we recommend that sources of revenue be reinvested in job-creating low carbon technologies such as RE; in R&D on technologies currently in a nascent stage of development, such as green hydrogen and biofuels; and on compensation for the distributional impacts of the low carbon transition on vulnerable sections of society such as small businesses and laborers (thus offsetting the negative impacts seen in CGE).

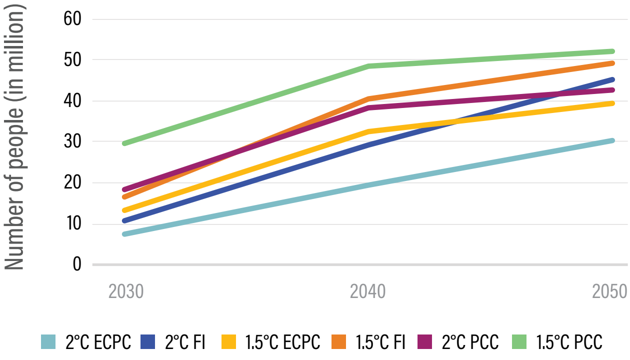
FIGURE ES-5 | EPS: Cost to the economy from the policy package (2018 INR billion) relative to BAU



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. BAU = business as usual.

Source: Authors.

FIGURE ES-6 | EPS: Change in jobs relative to reference scenario (millions)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

The EPS also shows that a green transition would lead to significant health benefits (in monetary terms [Figure ES-7]). Although the EPS does not disaggregate these impacts across the different sections of society, vulnerable sections of society who are the worst exposed to air pollution and adverse work conditions in the mining and fossil fuel sector, and so on, may gain higher marginal benefits because their ability to work would increase, and their private expenditure on healthcare would reduce.

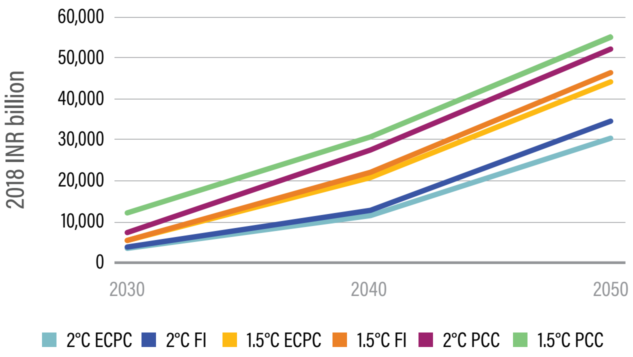
Carbon price

The above discussion highlights the importance of the carbon tax as a crucial policy instrument for ensuring positive economic impacts from the low carbon transition. Among our four models, GCAM and the EPS include a carbon price within the model framework, although in very different ways. In GCAM, the carbon constraint is achieved in each time step at the least cost to the economy. The cost of mitigation in each sector is determined by the various technology costs; therefore, to meet the overall carbon constraint, the model endogenously calculates the minimum economy-wide carbon price that would be required to make green technologies adequately price competitive with fossil-fuel-based technologies. Table ES-14 summarizes the changing carbon price in each low carbon scenario over time, interpreted as the carbon price required to meet the desired emissions target at the least cost to the economy in the GCAM framework.

POLICY RECOMMENDATIONS

The sectors and actors of the economy are interlinked, and so a systemic approach to decarbonization is necessary to identify and manage its trade-offs and maximize its impact. For this, a comprehensive strategy comprising cross-cutting policies and actions is needed. Interlinkages and dependencies between sectors in the economy

FIGURE ES-7 | EPS: Monetized health benefits (2018 INR billion)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Health benefits refer to avoided deaths and climate benefits from the chosen policy package in monetary terms with respect to the reference scenario.

Source: Authors.

TABLE ES-14 | Carbon price estimated by GCAM for 2018 (INR/tCO_2)

SCENARIO	2025	2030	2035	2040	2045	2050
2°C ECPC						2,806
2°C FI						3,538
1.5°C ECPC				4,330	5,195	5,935
1.5°C FI				4,737	5,795	6,877
2°C PCC					5,831	9,766
1.5°C PCC		8809	26,574	50,005	60,643	72,562

Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. tCO_2 = tonnes of CO_2.

Source: Authors.

decrease the impact of narrowly focused strategies without maximizing the mitigation and development potential of the policy. For example, an economy-wide—rather than sectoral—incentive away from fossil fuels, such as a carbon tax, can prevent unintended consequences such as the substitution effect, where the falling consumption of a fuel due to regulation or market forces in one sector (such as power) reduces its price, making another sector (that is not regulated, such as industry) pick it up instead owing to its reduced cost. Similarly, electrification in end-use sectors will only lead to real emissions reduction in the economy if the power sector is simultaneously decarbonized.

Policies that counterbalance socioeconomic trade-offs must be part of the mix. A well-designed and well-implemented carbon tax could play an important role in this. We find a carbon tax to be a crucial and highly effective policy to offset the fall in government tax revenues from fossil fuels (oil excise duty in the Indian context) due to decarbonization; shift a part of the cost savings from the falling expenditure on fossil fuels in the private sector to the public sector; and boost jobs and GDP to levels higher than in the reference scenario by using the carbon tax to finance public spending. We recommend that carbon tax revenues be reinvested in job-creating low carbon technologies such as RE; R&D on nascent technologies; and compensation for the distributional impacts of the low carbon transition on vulnerable sections of society such as small businesses and laborers.

The GCAM model uniquely provides the minimum carbon price required across the economy to meet the desired emissions constraint in that time step, whereas the value of the carbon tax in the EPS is determined subjectively by the user, chosen according to its ability to sufficiently counter negative impacts on the GDP and jobs in the economy. We notice a convergence in the carbon prices of both models in the 1.5°C FI and 1.5°C ECPC scenarios in 2050 at INR 4,000–5,000/tCO_2 in the EPS and at about INR 6,000/tCO_2 in GCAM, both at 2018 prices.

We need to design an equitable low carbon transition that is just and does not disproportionately impact low-income households. In the CGE model, RE is less labor intensive than fossil fuel industries. The laborers employed in the latter will face job losses, which would reduce private consumption, leading to higher income inequality and a ripple effect across the economy that could produce an economic downturn. Most current models do not explore in detail the socioeconomic impacts of the low carbon pathways and the ways to mitigate them. Thus, other non-modeling studies are required to support modeling results in order to understand the direction and extent of these impacts within various sectors and regions, identify potential affected parties, explore opportunities to create new jobs for them, and map the needed skilling and transition support.

A strong set of decarbonization policies holds the key. Both policy-based models (the EPS and SAFARI) in this study show that a small set of 8–10 policies have the largest impact (80–90 percent) on emissions reduction. These include the early retirement of thermal power plants and energy efficiency, demand reduction, and electrification measures in industry and transport in both models. The EPS additionally includes policies on carbon tax imposition, using hydrogen as an alternative fuel in industry and transport as well as producing hydrogen using electrolysis, all of which have a very high mitigation impact.

Industry becomes the largest source of emissions by the mid-2030s, and its decarbonization will need to be the key focus of government policies. We find that annual industry emissions grow 2.4–3.3 times from 2020–50 in the reference scenario, overtaking the power sector as the highest-emitting sector in the economy according to two models (SAFARI and the EPS) and making it increasingly expensive for the rest of the economy to align with the carbon budget. Further, in the low carbon scenario, CGE finds that a higher uptake of RE and new low carbon technologies in other sectors lead to an increase in the industrial production of emissions-intensive raw material to manufacture them, making it all the more important to explore industrial decarbonization options. Given the current financial and technological constraints on decarbonizing the industry sector, low carbon production processes that are not yet cost-competitive need policies and R&D to make them economical (our models do not provide insight into this cost reduction effect). However, we do find that electricity use by industry should triple by 2050 and hydrogen use should rise to 18–28 percent of the industry fuel mix to be 1.5°C compliant. We recommend a threefold approach in the short to medium term to achieving this:

- Mandate high energy efficiency, material efficiency, longevity, and reuse standards, and better urban design to reduce the demand for industrial production and energy, which the EPS and SAFARI find has a high mitigation impact, and in the case of energy efficiency, positive cost implications for the economy.

- Introduce policies that incentivize industry to switch to low carbon technologies that are currently too expensive, by reducing cost barriers and supporting the achievement of economies of scale.
- Promote, finance, and incentivize R&D on new or nascent technologies such as green hydrogen that have been theoretically proved to be capable of replacing fossil fuels, for example, in the steel manufacturing sector. Revenue from the carbon tax, as discussed above, can be used to finance this, and policy incentives can be given to enable companies to use their in-house savings from higher efficiency in the short run to ramp up in-house R&D.

Transport is the fastest-growing source of emissions and needs a multidimensional approach. We find that annual transport sector emissions will double or triple between 2020 and 2050 according to all four models, and 90–100 percent of the 2-wheeler and 3-wheeler segments, 70–80 percent of the 4-wheeler segments (passenger and freight), 40–60 percent of passenger HDVs (buses), and 10–15 percent of the freight HDV (trucks) segment will have to be electrified to align with the 1.5°C scenarios, which is already partially possible on a least cost basis according to GCAM and the EPS. This electrification can be achieved with some policy support. We also find that 70 percent of transport emissions in 2050 will come from the hard-to-abate freight HDV segment alone, and can be abated by mandating fuel efficiency targets, incentivizing a mode shift to freight rail, and financing R&D for new technologies (e.g., alternative fuels such as hydrogen or biofuels) in the short to medium run, so as to be able to start phasing in the new technologies and meet the abovementioned targets in the medium to long run. Finally, we also find that demand-side interventions such as mode shifting, better urban planning, shared mobility, and fuel efficiency, along with some electrification has the potential to reduce the transport sector's energy demand by 40–50 percent in the 1.5°C-aligned scenarios. However, this would require an integrated approach involving, for example, urban planners and consumer behavior interventions.

A least cost approach to capacity installment in the power sector leads to considerable decarbonization of the sector, but given the rising demand for electricity in an electrifying economy, a comprehensive RE strategy is required. Although least cost deployment could take the share of solar and wind energy in India's power capacity to 66–68 percent by 2050 in the reference scenario, it would need to rise to 80–90 percent to align with the carbon budgets. In absolute terms, this would mean an even higher increase because electricity demand is higher in the low carbon scenarios compared with the reference scenario, as the rest of the economy electrifies to decarbonize. Because RE imposes tremendous pressure on resources such as land, water, and finance (National Research Council 2010) that have other competing development demands, special attention needs to be paid to reducing the demand for energy in end-use sectors through efficiency measures and demand reduction policies as seen in SAFARI and the EPS. Also, efficiency in the power sector must be improved by supporting improvements in the CUF of solar energy through innovation and R&D, the ability of the grid to manage RE, reduction in transmission and distribution losses, and higher storage capacity to prevent the need for natural-gas- or hydro-based power plants to manage variability.

India will underconsume its fair share of the global carbon budget in the pursuit of low carbon development and thus should be supported with international financial and technological support to ensure that the low carbon transition is just for all and builds resilience to climate impacts. India is particularly vulnerable to the impacts of climate change, as well as the negative impacts of the low carbon transition on employment and income inequality. Because our models find that the low carbon pathways that approximately align with India's commitment to achieve net zero emissions in 2070 consume only 30–40 percent of the 1.5°C-aligned carbon budgets by 2050 (as seen in Table ES-15), the country is entitled to international financial and technological support to not only assist mitigation but also ensure a just transition, compensate for the loss and damage from the climate change that has already occurred (of which India is historically responsible for only 3 percent), build resilience to future impacts, and ensure that development priorities such as health and education are not lost sight of in the financial trade-off.

TABLE ES-15 | Share of carbon budgets consumed by the models up to 2050 and the corresponding approximate net zero

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	CARBON BUDGET VALUE, 2020–2100 ($GTCO_2$)	CUMULATIVE EMISSIONS, 2020–2050 ($GtCO_2$)	SHARE OF 2100 BUDGET CONSUMED BY 2050 (%)	APPROXIMATED NET ZERO YEAR
Reference		127, 116, 113, 133		
2°C ECPC	408	103, 111, 99, 104	24–27	After 2075
2°C FI	327	99, 110, 96, 101	29–34	After 2075
1.5°C ECPC	289	91, 94, 96, 84	29–33	2065–75
1.5°C FI	226	86, 91, 92, 81	36–40	2065–75
2°C PCC	132	81, 97, 92, 70	53–73	2060–70
1.5°C PCC	46	72, 39, 88, 60	–91 to 84	2050–2060 (with CDR)

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. CDR = carbon dioxide removal; $GtCO_2$ = gigatonnes of CO_2.

Source: Authors.

India's NDC and COP26 targets are a mixed bag. Table ES-16 summarizes India's enhanced NDC targets updated in August 2022 and those announced at COP26, and how they compare with the four models' outputs. We find the following:

- *The NDC target of a 45 percent reduction in CO_2e emissions intensity of GDP by 2030 with respect to the 2005 target* is ambitious. It is not met in the reference scenario according to three models, indicating the need for additional policy support, and falls within the range prescribed by the models to align with the carbon budgets (–41 to –56 percent). (Note: The target is in CO_2e terms whereas the model outputs are in CO_2 terms, so these numbers are only indicative. According to BUR 3, 78.5 percent of India's total national GHG emissions were from CO_2 in 2016 (MoEFCC 2021)).
- *The NDC target of achieving 50 percent of electricity capacity from non-fossil fuel sources by 2030* is overachieved in the reference scenario itself of the three models (GCAM, SAFARI, and the EPS), which use a least cost approach to build power plants. The range prescribed by all four models to align with the carbon budgets for India is 59–72 percent by 2030.
- *The COP26 target of installing 500 GW of electricity capacity from non-fossil fuel sources by 2030* is ambitious. It is not met in the reference scenario of any model, indicating the need for additional policy support, and falls within the range prescribed by the models to align with the carbon budgets (419–499 GW).
- *The reduction of 1 billion tonnes of CO_2e from 2021 to 2030 with respect to the reference scenario* is overachieved according to CGE and the EPS at –2 to –5.4 $GtCO_2$ across the low carbon scenarios. SAFARI's cumulative emissions rise compared to the reference scenario because development goals are prioritized to be met until 2030 and GCAM's annual emissions do not peak until 2030 in any scenario except 1.5°C PCC, indicating no decline. (Note: We only consider CO_2, whereas the target is specified in CO_2e, indicating that the overachievement of this target is underestimated.)
- *The scenarios that align with net zero emissions around 2070* are 2°C PCC, 1.5°C FI, and 1.5°C ECPC according to the maximum models. The other two 2°C scenarios reach net zero emissions after 2070, and 1.5°C PCC must reach NZ by 2050. SAFARI requires carbon dioxide removal (CDR) in all scenarios to reach net zero emissions.

Note that 1.5°C PCC indicators are excluded from the ranges because they are so stringent that they can be regarded as an outlier.

TABLE ES-16 | Assessing India's NDC and COP26 targets with model outputs

TARGET	TARGET TYPE		CGE	GCAM	SAFARI	EPS
–45% of CO_2e emissions intensity of GDP by 2030 with respect to 2005 (model outputs refer to CO_2 emissions intensity of GDP)	NDC	Reference	-40%	-55%	-37%	-32%
		Budgets (excluding 1.5°C PCC)	-51% to -56%	-55%	-39% to -41%	-39% to -49%
50% of electricity capacity from non–fossil fuels by 2030	NDC	Reference	45%	65%	62%	63%
		Budgets (excluding 1.5°C PCC)	59%–64%	65%–69%	62%–64%	64%–72%
500 GW of electricity capacity from non-fossil fuels by 2030	COP26	Reference	287 GW	432 GW	427 GW	475 GW
		Budgets (excluding 1.5°C PCC)	587–599 GW	447–543 GW	419–454 GW	440–498 GW
Reduction of 1 billion tonnes of CO_2e from 2021–30 with respect to the reference scenario (model outputs refer to CO_2)	COP26	Reference	No	No	No	No
		Budgets (excluding 1.5°C PCC)	-4 to -5.4 $GtCO_2$	0	0.6 to -0.2 $GtCO_2$	-2 to -4 $GtCO_2$
Net zero emissions by 2070	COP26	Reference	No	No	No	No
		Budgets	2°C PCC 1.5°C FI 1.5°C ECPC	2°C PCC	Requires CDR for NZ	1.5°C FI 1.5°C ECPC

Notes: Models: CGE = Computable General Equilibrium; GCAM = Global Change Analysis Model; EPS = Energy Policy Simulator; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. COP26 = 2021 United Nations Climate Change Conference; GW = gigawatts; $GtCO_2$ = gigatonnes of carbon dioxide; MSW = municipal solid waste; NDC = nationally determined contributions.

Source: Authors.

To support analytical studies and strategies on India's emissions intensity NDC target, further clarity is needed on the emissions intensity in the base year (2005), as well as the scope and coverage of this emissions intensity target. Without the official publication of India's 2005 emissions inventory and clarity on the sectors and gases included in the NDC, as well as the baseline for the land use, land use change and forestry (LULUCF) target, it is difficult for modeling studies such as this to compare the results with India's real targets and provide inputs to their trajectory in the coming milestone years.

THE WAY FORWARD

Despite India's low per capita emissions and the fact that it contributed only 3 percent of the cumulative global CO_2 emissions from 1751 to 2017 (Ritchie 2019), the country plays an important role in limiting global warming to 1.5°C given its projected growth of future emissions. Although this would involve a disruptive transformation in the economy requiring large quantities of finance and new technology, it also simultaneously provides an opportunity to tap into new economic opportunities, as we see in some of our models. It is also crucial to contribute to India's development goals, as climate change would exacerbate poverty and inequality and worsen the lives of India's vulnerable population.

To determine the scale of ambition needed at the country level to conform to the temperature targets, we use an approach grounded in the concept of carbon budgets and then back-cast them across the corresponding time frame to be able to align those long-term budget goals with short-term actions, and thus prevent deferring real ambition toward the second half of the century. This can act as a significant guide for India to avoid lock-in to high-emissions technologies, plan for just and equitable transitions, bolster technological innovation, build more resilient infrastructure, and send early and consistent signals to all actors within the economy around policy intent.

The scenario modeling undertaken in our study steered by these carbon budget approaches exposes the interlinkages and causalities between different sectors of the economy, allowing us to examine key short- and long-term outcomes and milestones that should be prioritized. We see that although the power sector is now on a more temperature-compliant pathway, major reforms are required in the sector to meet India's announced targets, including fixing the challenges currently plaguing it. Targets and efforts in the transport and industry sectors also need to be significantly accelerated, with a robust strategy for decarbonizing hard-to-abate segments in the medium-to-long term.

A small package of 8–10 cross-cutting as well as sectoral policies that reduce the consumption of energy through efficiency and physical demand reduction, and support the adoption of alternative low carbon fuels can be extremely effective, but support with R&D and cost reduction policies would be crucial to ensure their effectiveness. This requires finance, technology, capacity, and supporting infrastructure. Because we find that India underconsumes its fair share of the global carbon budget to achieve net zero emissions by 2070, an international transfer of finance and technology is called for to support not just mitigation but also a just transition, build resilience to future climate impacts, compensate for loss and damage due to current climate impacts, and ensure that other development priorities such as health and education are not jeopardized in the competition for public finances.

Aspects that our models do not cover but are crucial to develop India's long-term decarbonization strategies and that should be explored further include the investments required to achieve these low carbon pathways and the role of the removal of fossil fuel subsidies within them; the impact of the Carbon Border Adjustment Mechanism imposed by the EU on industrial competitiveness in India; the cost of inaction with respect to socioeconomic outputs, which is not captured in the reference scenarios of the models; the employment opportunities and associated costs of LULUCF sector interventions; and the political economy of imposing a tax on carbon emissions.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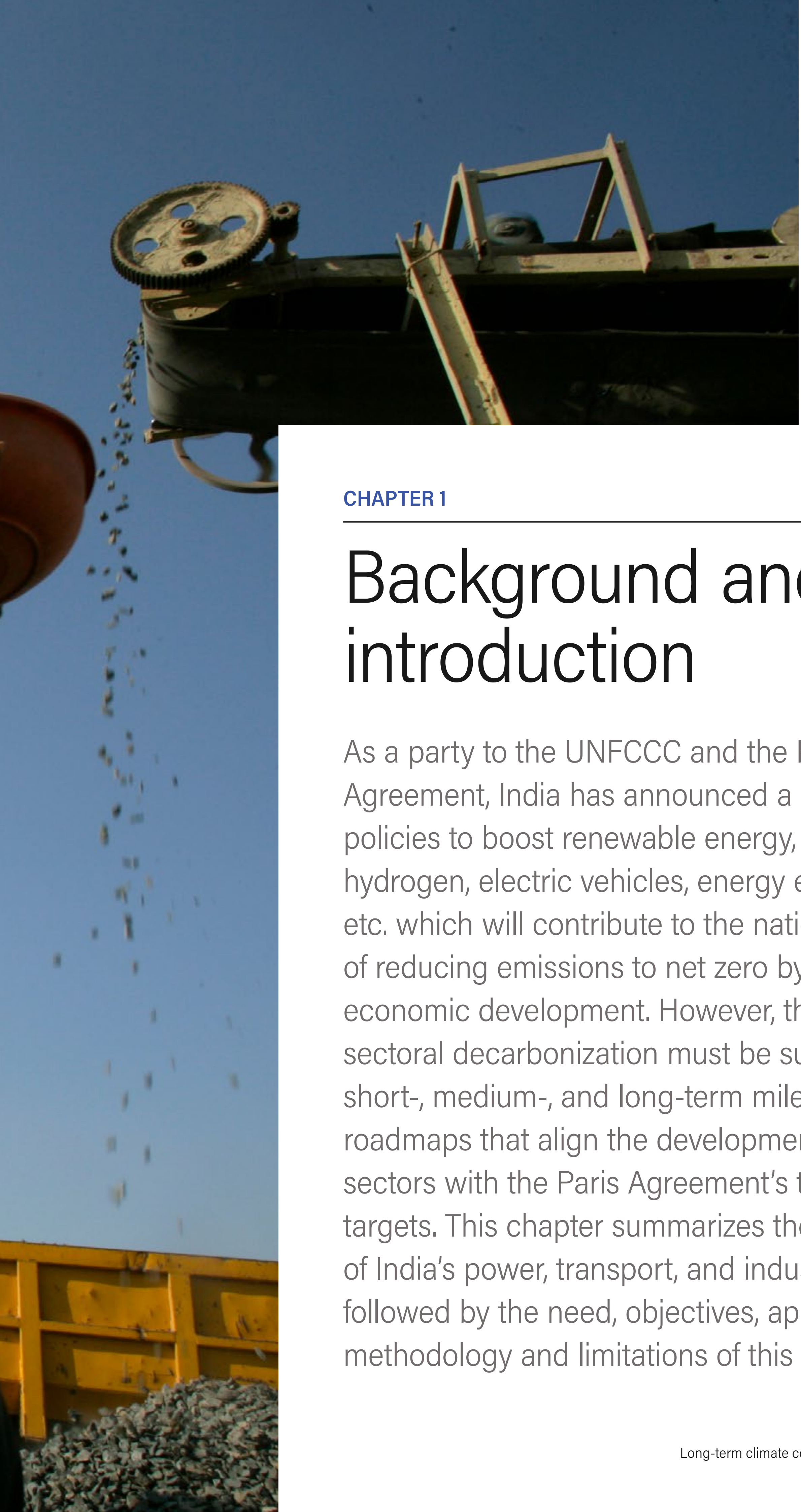


CHAPTER 1

Background and introduction

As a party to the UNFCCC and the Paris Agreement, India has announced a slew of policies to boost renewable energy, green hydrogen, electric vehicles, energy efficiency, etc. which will contribute to the national goals of reducing emissions to net zero by 2070 and economic development. However, the planning of sectoral decarbonization must be supported with short-, medium-, and long-term milestones and roadmaps that align the development of these sectors with the Paris Agreement's temperature targets. This chapter summarizes the current state of India's power, transport, and industry sectors, followed by the need, objectives, approach, methodology and limitations of this study.

INTRODUCTION AND GLOBAL CONTEXT

From heat waves and wildfires to unprecedented rainfall and floods, climate change is impacting every region of the world today, exacerbating the already disparate socioeconomic impacts of the energy crisis and the COVID-19 pandemic. The IPCC Assessment Report 6 (AR6) (IPCC 2022) confirms that the last decade was hotter than any period in the last 125,000 years, that temperatures have been rising faster than in the previous IPCC assessment cycles, and reports with a high level of confidence that concentrations of CO_2 in the atmosphere are at their highest levels in at least two million years.

The report highlights the nonlinearity of the relationship between additional atmospheric CO_2 and climate risk, and establishes that some impacts of rising temperatures on climate systems will be irreversible for millennia, such as sea level rise and the melting of ice sheets. It also draws attention to the increasing risk of compounding extremes—that is, combinations of hazards such as storms and rain—and to the decrease in the efficiency of carbon sinks at higher concentrations of CO_2 emissions.

The model simulations presented in the AR6 (IPCC 2021) are based on a core set of five Shared Socioeconomic Pathways (SSPs) scenarios, which span a wide range of plausible societal and climatic futures from potentially below 1.5°C best-estimate warming to over 4°C warming by 2100. In these simulations, all five scenarios have a central estimate of the 1.5°C mark being crossed by the early 2030s with probability ranges extending to an upper limit of 2040 in the intermediate, high, and very high emissions scenarios and *more likely than not* in a low emissions scenario (Carbon Brief 2021).

The increasing risk of compounding extremes, the irreversibility of impacts on certain climate systems, the imminent risk of crossing 1.5°C of average global warming in the near term, as well as the increased frequency of extreme weather events even as we hit warming of 1.1°C over preindustrial levels, together imply that there is a high degree of risk attached to delaying transformative action. The findings of the AR6 make it abundantly clear that unless ambitious and transformative action is urgently stepped up, achieving the goals of the 2015 Paris Agreement—that is, limiting the global average temperature rise to well below 2°C and pursuing efforts to keep it under 1.5°C—will be impossible.

THE INDIAN CONTEXT

India has an important role to play in the global efforts to combat climate change. It is the world's third-largest emitter of greenhouse gases (GHGs) and is also ranked among the world's most vulnerable countries to the catastrophic impacts of climate change (Eckstein et al. 2021). Moreover, India is set to experience significant growth in its population, economy, and energy consumption over the coming decades, making the transition to low carbon growth crucial for both meeting the global objective of decoupling economic growth from environmental destruction as enshrined in the Paris Agreement and for building domestic resilience to the increasing impacts of climate change.

As a party to the United Nations Framework Convention on Climate Change (UNFCCC) and having ratified the Kyoto Protocol as well as the Paris Agreement, India has committed to contribute to global efforts on climate change mitigation, albeit in accordance with the principle of *common but differentiated responsibilities and capabilities*, whereby India's GHG reduction targets take into account its development needs, and target achievement may be contingent upon international financial assistance. In its most recent update (in August 2022) to its first Nationally Determined Contribution (NDC) submitted to the UNFCCC under the Paris Agreement (Government of India 2022), India has committed to the following quantitative targets:

- Reduce the annual emissions intensity of its GDP by 45 percent relative to 2005 levels by 2030.
- Achieve about 50 percent of its cumulative installed capacity of electric power from non-fossil-fuel-based energy resources by 2030, with the help of transfer of technology and low-cost international finance, including from the Green Climate Fund (GCF).
- Create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2e through additional forest and tree cover by 2030.

In addition, non-quantitative NDC commitments include the following:

- Better adapt to climate change by enhancing investments in development programs in sectors vulnerable to climate change, especially agriculture, water resources, health, and disaster management; the Himalayan region; and coastal regions.

- Mobilize domestic and additional new funds from developed countries to implement the above mitigation and adaptation actions in view of the resources required and the resource gap.
- Build capacities and create a domestic framework and an international architecture for quick diffusion of cutting-edge climate technology in India and for joint collaborative R&D for such future technologies.
- Introduce and propagate a healthy and sustainable way of living based on the traditions and values of conservation and moderation, including through a mass movement for Lifestyle for Environment as a key to combating climate change.
- Adopt a climate-friendly and cleaner path than that followed up to now by others at a corresponding level of economic development.

Finally, at COP26 in November 2021, India announced three additional ambitions (PIB Delhi 2022b) which, although not enshrined in the NDC, have since acted as guiding light for climate action in the country:

- Install 500 GW of electric generation capacity from non-fossil fuel sources by 2030.
- Achieve a cumulative absolute reduction of 1 billion tonnes of GHG emissions over 2021–30.
- Achieve net zero annual emissions by 2070.

Further, although India does not have sector-specific emissions reduction targets, several key policies such as energy efficiency, renewable energy (RE) expansion, electric vehicles (EVs), and green hydrogen have been introduced to contribute significantly to emissions reductions.

The power sector

With the announcement at COP26 of installing 500 GW of power generation capacity from non-fossil fuel sources by 2030 (PIB Delhi 2022b), it is the power sector that will lead the ambition of India's efforts toward climate compatible growth. As of September 2022, 165 GW had been achieved (CEA 2022). To make adoption of RE financially viable, various capital- and generation-based incentives and state-level feed-in tariffs applicable for all renewables have been provided over the last decade. A renewable purchase obligation (RPO) to source a specified minimum percentage of electricity from renewable sources applies to power distribution companies and is currently specified at 24.6 percent of the total electricity consumption for FY2022–23 and increasing to 43.33 percent by FY2029–30 (comprising specific levels for wind, hydro, and others). A newly announced Energy Storage Obligation additionally requires 1 percent of solar/wind electricity to be sourced with/through energy storage in FY2022–23, rising to 4 percent in 2029–30 (Ministry of Power 2022). In August 2021, large hydro was added to the category of "RE sources" in a reform to promote large hydro power (PIB Delhi 2019a). India also imposes a tax on the coal produced and imported into India (called the GST compensation cess, formerly known as the clean environment/energy cess), currently at a rate of INR 400/tonne of coal since 2016, up from INR 50/tonne of coal at its inception in 2012 (India Climate Explorer n.d.).

However, 70 percent of India's total electricity generation still comes from coal-based thermal power generated from an installed capacity of 204 GW (IEA 2020), making the discussion on the future of coal in India an important one. The Optimal Generation Mix 2020 (OPGM) by the Central Electricity Authority forecasts that the most cost-optimal way of meeting India's energy needs in 2030 (CEA 2020a) is for the thermal power generation fleet to rise to 267 GW in 2029/30 to meet the demand. Of the additional 58 GW of coal power plants needed to meet this target from current levels, 36.6 GW is currently under construction, but studies suggest that the remaining capacity may not be needed to meet electricity demand if India achieves its 450 GW RE target (which is exceeded in the OPGM forecast when large hydro is included) (Lolla et al. 2021). Further, the achievement of this ambitious RE target is made feasible by several factors such as the record low prices for renewables, enabling them to absorb new incremental demand; the falling plant load factors of thermal power plants, which fell from 61 percent in 2018 to 53 percent in 2021 (Behl 2021), making them more expensive to run; expensive thermal purchase power agreements (PPAs), resulting in adverse impacts on the already ailing distribution companies, whose total outstanding debt exceeded INR 5 lakh crore (INR 5,000 billion) in FY2019–20 (PFC 2021), and the risk of stranded assets making financing for new coal-fired power plants unavailable (K. Shah 2021). As a result, since 2015, over 326 GW of coal projects have been canceled and 250 GW shelved (Behl 2021). Moreover, between 2019 and 2021, several entities announced that they would not build new coal-fired power plants. These entities included India's largest coal-fired power producer, the National Thermal Power Corporation (NTPC) (*Economic Times* 2020), and the four states of Gujarat, Chhattisgarh, Maharashtra, and Karnataka, which have shifted toward investments in solar parks and other cleaner, low-cost generation fleets (such as the 32 GW by 2032 renewable target set by NTPC). On the other hand, in 2020, India's historically nationalized coal industry was privatized, with private players allowed to mine and sell coal in the open market at market-determined prices, and 19 mines were successfully auctioned in each of the two auction tranches held in 2020 and 2021, out of the 38 and 67 mines on offer, respectively (Livemint 2021). Thus, although coal-fired power generation may have seen its historical peak in 2018 (Lolla 2021), and despite a fall in its share, coal is projected to continue to remain a dominant source in the primary energy mix of India, to enable it to maintain energy security as consumption rises in absolute terms (IEA 2021). This increasing consumption is due to the rising demand for electricity as the economy rebounds from the COVID-19 pandemic, the increased demand for cooling due to rising temperatures, and the electrification of other sectors such as buildings and transport.

The industry sector

The industry and manufacturing sector of India is a fast-growing and fundamental sector, and industry energy demand is poised to grow tremendously in the coming decades as the demand for cement, iron and steel, and other energy-intensive materials increases with India's rising population, urbanization, and higher levels of development. Traditionally the most difficult sector to decarbonize, India's industry sector has seen emissions reduction, primarily as a result of strong energy efficiency interventions by the government and industry.

Perform, Achieve and Trade (PAT), a market-based mechanism introduced by the Bureau of Energy Efficiency (BEE) in 2012, imposes energy efficiency targets on plants in certain energy-intensive sectors and allows them to be met through the trade in Energy Saving Certificates (ESCerts). As of 2020, PAT had covered 1,073 facilities from 13 subsectors over 6 trading cycles, with savings projected to be 26 megatonnes of oil equivalent (Mtoe), equal to 70 megatonnes of carbon dioxide equivalent ($MtCO_2e$), by 2023 (BEE n.d.-b). Moreover, the Energy Conservation (Amendment) Bill 2022 lays the legal basis for creating a national carbon market in India (which will be based on the PAT scheme) and mandates emissions reduction in industries (mining, steel, cement, textile, chemicals, and petrochemicals) (Ministry of Law and Justice 2022).

Further, India's cement sector—the second largest in the world—is said to be one of the most efficient in the world, with an average specific electrical energy consumption of 76.6 kWh/tonne of cement compared to the global average of 104 kWh/tonne (CMA 2021). On the other hand, India's iron and steel industry—also the second largest in the world and the most energy-intensive subsector, accounting for 16.65 percent (MoSPI 2022) of the total industrial energy consumption—falls behind, with an average specific energy consumption of approximately 6–6.5 gigacalories per tonne of crude steel (tcs) as opposed to 4.5–5 gigacalories/tcs in similar plants abroad (Ministry of Steel n.d.-a). This lag in the iron and steel sector is due to obsolete technologies and poor-quality raw materials, but the situation is slowly improving due to technology upgradations, the use of better-quality inputs, and utilization of waste heat (Ministry of Steel n.d.-a) As a result, the emissions intensity of the iron and steel sector in India improved from 3.1 tCO_2/tcs in 2005 to 2.6 tCO_2/tcs in 2020 (PIB Delhi 2022a).

To decarbonize the industry sector, a transformational shift will be needed toward electrification, higher energy efficiency, circular economy of materials, and the use of alternate fuels such as green hydrogen. Currently, electricity accounts for 14.45 percent of the industry's energy mix (MoSPI 2022), and material and energy efficiency is promoted through government policies such as the Steel Scrap Recycling Policy (PIB Delhi 2019b) and industry efforts to use alternative fuels and raw materials, waste heat recovery through cogeneration and substitution of clinker with fly ash and slag in the cement sector (CMA 2021), and adoption of best available technologies (BAT) and waste heat recovery in the steel sector (Ministry of Steel n.d.-a).

Further, the central government recently launched the National Green Hydrogen Mission (MNRE 2023), which lays the framework for boosting both the production and consumption of green hydrogen, which has decarbonization potential in the fertilizer, steel, refinery, and petrochemical industries. A policy proposal in February 2022 presented a spectrum of incentives, from financial and regulatory support to PPAs (MoP 2022), purchase obligations (Baruah 2022), inclusion in RPOs, and mega-tenders that can facilitate commercial production and reduce costs. Large players such as NTPC, Adani Enterprises, Reliance Industries, ACME Solar, and Indian Oil have also recently announced their entry into the green hydrogen space (Jai 2021).

The transport sector

The transport sector in India is evolving rapidly as rising per capita income, urbanization, and rural-to-urban migration increase the demand for both public and private passenger transport. Similarly, an increase in industrial output and manufacturing raises the demand for freight transport. As of 2022, less than 1 percent of the total vehicle sales was from EVs (BEE n.d.-a). However, the aggravating impacts of air pollution, India's dependence on expensive oil imports, and the business case for developing India as a hub for EV battery manufacturing (Saran 2021) as international climate commitments become increasingly ambitious have together led to a growing emphasis (at both the central and state levels) on incentivizing both the local demand for EVs as well as their local manufacturing to boost economic growth and job creation. Although no EV target has been spelled out in a policy, the following goals have been announced: increase the share of EVs in the total vehicle fleet to 30 percent by 2030 (R. Shah 2018), make 2-wheeler sales (a vehicle segment that dominated 76 percent of the total fleet in 2017) 100 percent electric by 2026 (Carpenter 2019), and electrify 100 percent of railways by 2023, from 66 percent in 2020 (Ministry of Railways 2021). To achieve these targets, under the National Electric Mobility Mission Plan (NEMMP), the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME India) Scheme Phase II (PIB Delhi 2021) by the central government provides subsidies to buyers for the purchase of EVs to increase the demand for electric 2-wheelers, 3-wheelers, 4-wheelers, and buses and has approved the installation of 2,636 EV charging stations across 62 cities in 24 states and union territories. It also directs developers to allot 20 percent of parking space in new residential and office projects to EVs (Saran 2021). Further, 17 states have also announced EV policies and incentives, PSUs such as Energy Efficiency Services Limited (EESL) are promoting demand-side aggregation through the procurement of 3 lakh (0.3 million) electric 3-wheelers, and the private sector has raised more than US$700 million in investments across 500 start-ups even as the race toward EVs intensifies among the existing automobile OEMs (Mulukutla and Pai 2021).

On the other hand, no policy signal has been given regarding the phasing out of internal combustion engine vehicles (ICEVs), although policies on fuel efficiency such as the Corporate Average Fuel Efficiency and fuel blending such as the National Biofuels Policy (20 percent biofuel blending target by 2025) (Sarwal et al. 2021) are in place. Finally, although freight trucks constituted only 10–20 percent of total vehicle activity in 2020, their contribution to transport sector CO_2 emissions was disproportionately high at 40–50 percent, with their mileage being projected to grow at a higher rate than other vehicle segments by 2050 according to most leading energy-economy modeling studies in India (Kumar 2021), implying the need for a special focus on decarbonizing medium- and heavy-freight trucks. Although no policy currently focuses on this, some private sector initiatives by OEMs have committed to voluntary emissions reduction targets, such as by Tata Steel (News18 2021). Moreover, green hydrogen fuel, which is being incentivized by the National Hydrogen Mission, also has applications in the heavy transport sector, although a roadmap is yet to be developed.

NEED FOR THIS STUDY AND ITS OBJECTIVES

The IPCC has clearly signaled the devastating impacts that different levels of temperature rise from pre-industrial levels will have on Earth's climatic systems (IPCC 2018). Informed by this science, the Paris Agreement was successful in winning a global political consensus in 2015 to aim to limit the average global temperature rise to well below 2°C along with pursuing efforts toward 1.5°C. Further, the IPCC has established a direct correlation between the accumulation of GHGs in the atmosphere and changes in mean surface air temperatures (also referred to as global mean surface air temperatures, GSAT) (IPCC 2022) in the form of a metric called the transient climate response to cumulative carbon emissions (TCRE) (MacDougall 2016). Using a calculation involving the estimated value of the TCRE, its uncertainty, estimates of historical warming, variations in projected warming from non-CO_2 emissions, and climate system feedbacks such as emissions from thawing permafrost, the temperature goals enshrined in the Paris Agreement can be translated into a trackable quantitative metric of CO_2e emissions (at different levels of probability of accuracy). Thus, a limit on global warming to a certain temperature would translate to a specific quantity of CO_2e emissions, known as the *global carbon budget*, and by adjusting that for the temperature rise that has already occurred (1.1°C per the IPCC's AR6 report), we can estimate the quantity of CO_2 emissions the world has left to emit before the temperature limits are breached, known as the "remaining global carbon budget." This implies that the world must together bring down annual global net emissions to zero in such a way that the cumulative emissions since the pre-industrial period are limited to the global carbon budget.

The challenge arises at the stage of translating these global goals into national commitments and policymaking. Researchers have proposed different methodologies on how to distribute the global carbon budget among nations, based on principles such as historical responsibility (for climate change), technical and financial capability to decarbonize, the need to develop, and the least cost method of decarbonizing. Moreover, in the private sector, there is a lack of clarity on which country should account for highly polluting transnational corporations whose decisions are made in one country and that are financially registered in another country but whose factories (which are a point source of emissions) are located in a third country, keeping in mind considerations such as the risk of carbon leakage and the corresponding adjustments of GHGs during national emissions accounting. The global carbon budget needs to be apportioned among nations in a fair, just, and equitable manner but given the highly political nature of the subject and the differing priorities of nations in this debate, there has been no global consensus up to now on a methodology for achieving this.

As a result, although 137 countries have now announced net zero targets covering 83 percent of the global emissions (Net Zero Tracker n.d.) (a huge leap in climate ambition compared to just a few years ago), the lack of global consensus on how to allocate mitigation responsibility among nations, as well as the lack of translation of national targets into long-term mitigation pathways (which would indicate the cumulative emissions used by nations to achieve their goals) has resulted in a lack of clarity and the estimated overshoot of the cumulative alignment of these long-term commitments with the remaining global carbon budget (UNEP 2021).

To address some of these gaps and develop long-term emissions reduction pathways for India that are aligned with science, this study aims to achieve the following:

- Impartially calculate India's share of the global carbon budget using multiple allocation methodologies, each based on different sets of fairness principles. By deploying multiple approaches, the study circumvents the question of which approach is the most appropriate.
- Use energy-economy modeling to translate each of these long-term national emissions budgets into short-, medium-, and implementable targets for the country's three most emissions-intensive and growing sectors: power, industry, and transport.

The objective of this study is to provide national and sectoral policymakers and industrial decision-makers with different sets of emissions reduction and low carbon technology pathways, each of which aligns with India's fair share of the global carbon budget. This can help provide them with actionable targets or milestones to work toward and plan policy packages around.

APPROACH OF THE STUDY

The back-casting approach

Forecasting of annual emissions—that is, translating past and current trends and behaviors into estimates of the future—has been used more commonly as a predictive method to delineate potential annual emissions pathways for countries. However, because the projection is based on past trends and policies, forecasting may not align with the desired outcome in the future. In contrast to forecasting, back-casting is an approach that begins with identifying the desired outcome and then assessing what is needed to get there.

The latest IPCC studies (IPCC 2022) find with a high level of confidence that the last decade saw an unprecedented spike in the atmospheric concentration of CO_2 emissions and that if current trends persist, the 1.5°C-aligned remaining carbon budget would be exhausted by the early 2030s in most SSP scenarios. Thus, forecast projections based on historical and current trends may not help us limit cumulative global CO_2 emissions to the remaining carbon budget. Instead, a back-casting approach would allow us to impose the remaining carbon budget as the primary constraint and arrive at pathways that limit cumulative emissions across the projected time period to the remaining carbon budget, thus presenting pathways of "what is needed" to achieve the desired outcome of temperature-aligned emissions pathways. Depending on the severity of the constraint, some interim outputs of "what is needed" may not seem technologically feasible, but the objective is not to restrict ourselves to what is perceived to be possible in the present time, but to highlight where we need to be in the short-, medium- and long- term to align our annual emissions trajectories with the remaining global carbon budget. Knowing what is needed can help spur innovative thinking, support robust long-term planning, and work toward the disruptive transformation that is needed to achieve the rapid and deep emission cuts required to align emissions pathways with the remaining carbon budget.

Multi-model analysis

Models constructed within the bounds of a single paradigm are not sufficient for modeling all aspects of complex systems (Fishwick et al. 1994). The sectoral roadmaps for this study are developed by conducting a multi-model back-casting exercise involving four energy-economy models hosted by four different organizations in India (see Table 1). Each of these models is rooted in different modeling paradigms, and the scenario-building approach for each utilizes distinct reasoning and simulation strategies, thus providing unique perspectives on budget pathway alignment. As a result, together they provide a range of scenarios encompassing varying economic growth, development, and emission scenarios for India—economy-wide and sectorally—underpinned by varying narratives of India's development story and implemented policy interventions, but for the same cumulative emissions constraint (carbon budget).

TABLE 1 | Names of models and their host organizations employed in the study

MODEL NAME	ORGANIZATION
Computable General Equilibrium (CGE) Model	KPMG
Global Change Analysis Model (GCAM)	Council on Energy, Environment and Water (CEEW)
Sustainable Alternative Futures for India (SAFARI)	Centre for Study of Science, Technology and Policy (CSTEP)
Energy Policy Simulator (EPS)	World Resources Institute India (WRII)

Source: Authors.

METHODOLOGY OF THE STUDY

In this study, we begin by calculating India's share of the remaining global carbon budget using multiple budget allocation methods. By using multiple approaches, we avoid singling out any single approach as the most appropriate. We then employ four energy-economy models to back-cast these calculated carbon budgets for India to highlight where India must be in the short, medium, and long term in the power, industry, and transport sectors to align their growth with India's calculated carbon budgets. Using four models for the same analysis allows us to capture their different strengths (such as their calculation of the impact on jobs, GDP, health, development goals, cost optimization, income inequality, and so on), model paradigms, and assumptions regarding India's future development. The projections are made across a 30-year time horizon (2020–50), which is a long enough period to allow for the prospect of necessary transformative changes, but realistic enough to fit the time frames that the models deployed within this study can accommodate. Finally, we make recommendations in terms of both energy/technology milestones that each of the three sectors must strive to align their growth with to remain climate compatible and policy recommendations on how to achieve them.

The methodology employed to conduct this study is as follows (summarized in Figure 1):

1. **Determining India's fair share of the global carbon budget**

    i. **Understanding the available global carbon budget up to 2100:** Because carbon budgets are, by definition, a global concept, a country's carbon budget is determined as its share of the global total. Thus, we first reviewed the latest IPCC literature to understand global carbon budget estimates.

    ii. **Assessing the various approaches to determining country-specific carbon budgets:**

        a. Through an extensive literature review, we identified the existing approaches for apportioning the global carbon budget among countries and studied them in detail.

        b. We then ruled out some approaches on the following bases:

            - Emissions reduction pathway approaches: Approaches that provided emissions reduction pathways and/or sectoral emissions reduction targets, because the focus of this exercise was to determine countries' share of the total pie.
            - Principles of allocation (i.e., approaches that do not use equations): Approaches that describe only the ethical grounds for

allocation without having an associated methodology or equation-based method of calculation.

- Similar to other approaches (already under consideration): These approaches were similar to other approaches in the study, with just a different name.

c. Thus, we shortlisted 10 approaches to be explored further in the Indian context.

iii. **Identifying principles for the "fair" allocation of the global carbon budget to India:** To identify the principles that govern the "fair" allocation of the carbon budget from the country perspective, first, we explored several country viewpoints as outlined in their NDCs and published research papers, including the overarching UNFCCC principles of CBDR-RC. The identified principles important for India were Responsibility, Equity, Capability/Need, Sovereignty, Cost-effectiveness, and Stringency of carbon budget.

iv. **Shortlisting four approaches for India based on the chosen criteria:** We developed comprehensive criteria to assess and evaluate each of the 10 allocation approaches shortlisted in Step 1.2 on their inclusion of the principles identified in Step 1.3. Weights were assigned to each of the principles based on their recognition as "fair" and India's point of view, but were kept equal for all five principles in accordance with stakeholder feedback. We then weighted the 10 approaches against the principles, and the top 4 approaches with the highest scores (determined by the maximum number of principles included in the approach) were selected to calculate India's share of the global carbon budget.

v. **Calculating carbon budgets for India:** We then used the four shortlisted approaches to calculate India's share of the global carbon budget. Each approach was used to calculate budgets under the two temperature scenarios of 1.5°C and 2°C, each under a 50 percent and 67 percent probability of meeting the corresponding temperature target. Thus, a final set of 16 carbon budgets were determined for India.

2. **Back-casting India's carbon budgets using four energy-economy models**

i. **Harmonizing assumptions across models:** We ensured that socioeconomic drivers such as population and urbanization fell within the same range in all models, but GDP growth rates were not harmonized across models. This was to accommodate the different ways in which the models treated GDP as a variable (it was endogenously calculated in some models and exogenously inputted in others) and the different growth scenarios of India's future.

ii. **Developing the reference scenario:** A reference scenario represents a projection of the economy when no additional effort is made toward achieving any goals. This allows us to compare the level of effort required to achieve the low carbon scenarios by providing a reference comparison. The Computable General Equilibrium (CGE) and Sustainable Alternative Futures for India (SAFARI) models' reference scenario represents BAU; that is, future trends are an extrapolation of historical trends without any additional effort. Global Change Analysis Model's (GCAM's) reference scenario represents "progress as usual," wherein higher levels of electrification and decarbonization occur based on current prices and technology trends and assumptions regarding their future evolution. The Energy Policy Simulator (EPS) uses a combination of least cost allocation of technologies (in the power and transport sectors) and the demand growth trends from the India Energy Security Scenarios (IESS) v2.0 (in the other sectors).

iii. **Identifying the budget scenarios to be modeled:** Of the 16 carbon budgets determined for India in Step 1.5, we opted to model only the budgets following a 66 percent probability, because it represents higher accuracy in meeting its corresponding temperature target and is the most common scenario used in the literature. Next, from within the eight remaining budgets, the two based on the Greenhouse Development Rights (GDR) approach exceeded all four models' reference scenarios' cumulative emissions, and thus did not need to be modeled. This left each modeling team with six budgets to project, representing three allocation approaches (ECPC, FI, and PCC) in two temperature scenarios each.

iv. **Assessing the modeling time frame and net zero years:** The global carbon budget is, by definition, an end-of-century concept; that is, it spans the period 2020–2100. Because India's calculated carbon budgets are a fraction of the global budget, they also span the same time frame. However, three of the four models were not set up to make projections beyond 2050 (GCAM being the exception). Thus, the discrepancy between their modeling time frame and the time frame of the carbon constraint had to be addressed. To broadly assess what share of the global 2100 budget is consumed by 2050, we aggregated the cumulative emissions from 2018–50 in the global net zero scenarios developed by IIASA (Huppmann et al. 2018) and published in the IPCC SR1.5 report (IPCC 2018) (for each temperature scenario). We then used the four shortlisted budget allocation approaches to calculate India's share of the cumulative emissions until 2050 in these low carbon scenarios in both temperature scenarios. We found that in the IIASA global scenarios, in the 1.5°C-aligned scenarios, most of the 2100 carbon budget was fully consumed by 2050, leading to global net zero emissions around the same period. Because India's budgets are a fraction of the 2100 global budget, they follow the same trajectory and most of the 1.5°C budgets are consumed by 2050, implying a net zero for India by 2050. Similarly, in the 2°C scenarios, global net zero occurs from 2070 to 2085, and so more than half the 2100 budget is consumed by 2050, which therefore also applies to India. However, the sizes of these calculated 2050 "budgets" for India are larger than India's cumulative BAU emissions until 2050 because of the equity principles underlying the allocation approaches. Thus, we allowed for all scenarios to peak before 2050 (with the peaking year depending on the size of the budget) but reach net zero after the global net zero years.

v. **Modeling the budget scenarios in the four models.** In GCAM, the carbon budget can be inputted as a constraint, and the model then strives to achieve demand in the least cost manner to the economy while satisfying the carbon constraint. SAFARI was developed to meet certain development goals (such as housing for all) whose achievement drives demand in the various sectors of the economy (such as cement and steel). The modelers identified a fixed set of goals to be met in all six budget scenarios but different ways of meeting their energy demand under the six different carbon constraints. The EPS develops "what-if" scenarios; that is, switching on one or more policy levers drives changes in the economy with respect to the reference scenario. Policy packages were chosen in such a way that the cumulative emissions are restricted to the carbon budget. CGE is inherently a forecasting model, and so the budget scenarios were also created by adjusting investments toward low carbon technologies to increase their diffusion such that the resultant cumulative emissions are restricted to the carbon budget.

vi. **Modeling the land use, land use change, and forestry (LULUCF) sector:** As all the models did not have the capacity to explore the LULUCF sector, we conducted a separate assessment to understand the potential cumulative carbon sinks available from the sector and enrich the obtained overall insights for long-term planning. This would give policymakers an idea of the additional leeway available if the levels of technology and finance needed to constrain cumulative emissions to a particular carbon budget are infeasible, or if negative unintended socioeconomic impacts (such as impacts on jobs in conventional/fossil fuel industries) that occur as a result of excessively rapid decarbonization require the transition to occur at a slower pace (resulting in higher GHG emissions).

vii. **Comparatively analyzing the four models' scenarios:** Because the four models are built using very different socioeconomic paradigms and assumptions, their outputs are analyzed compared to their own reference scenario, while the four models are compared with each other by interpreting the outcomes in the context of their individual assumptions. In particular, we analyzed the energy needs, carbon intensities, mitigation potential, interdependence for decarbonization, and high-impact mechanisms/interventions of three emissions-intensive and fast-growing sectors in India: power, transport, and industry. Each model also yielded some additional unique insights into the impact of the low carbon scenario with respect to the reference scenario on a variety of parameters such as the GDP, jobs, and health (EPS); development goals (SAFARI); the minimum economy-wide carbon price required to satisfy the carbon constraint (GCAM); and income inequality (CGE).

3. **Recommending sectoral milestones and policy insights for climate compatible growth in India**

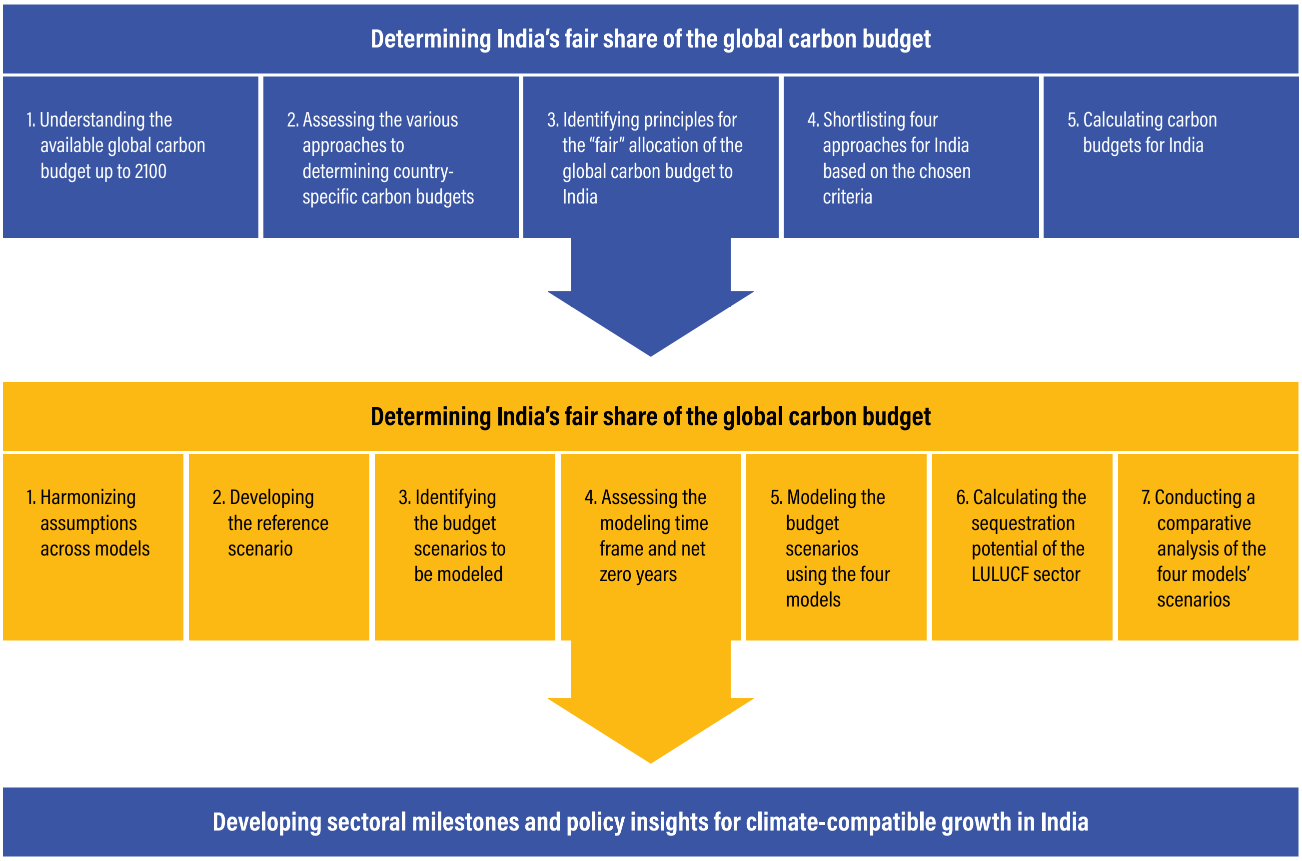
On the basis of the above analysis, we make three sets of recommendations to readers:

   i. A set of plausible carbon budgets for India based on different sets of fairness principles, along with a time range for economy-wide peaking of annual emissions and a subsequent decrease to net zero.

   ii. Short-, medium-, and long-term energy and technology milestones in the power, industry, and transport sectors that are compatible with each of these carbon budgets calculated for India.

   iii. Policy recommendations on some high-impact policy interventions that could achieve these milestones and insights into how they interact with each other, and trade-offs and socioeconomic impacts that policymakers should keep in mind while developing an emissions reduction strategy/policy package.

FIGURE 1 | Methodology of the study



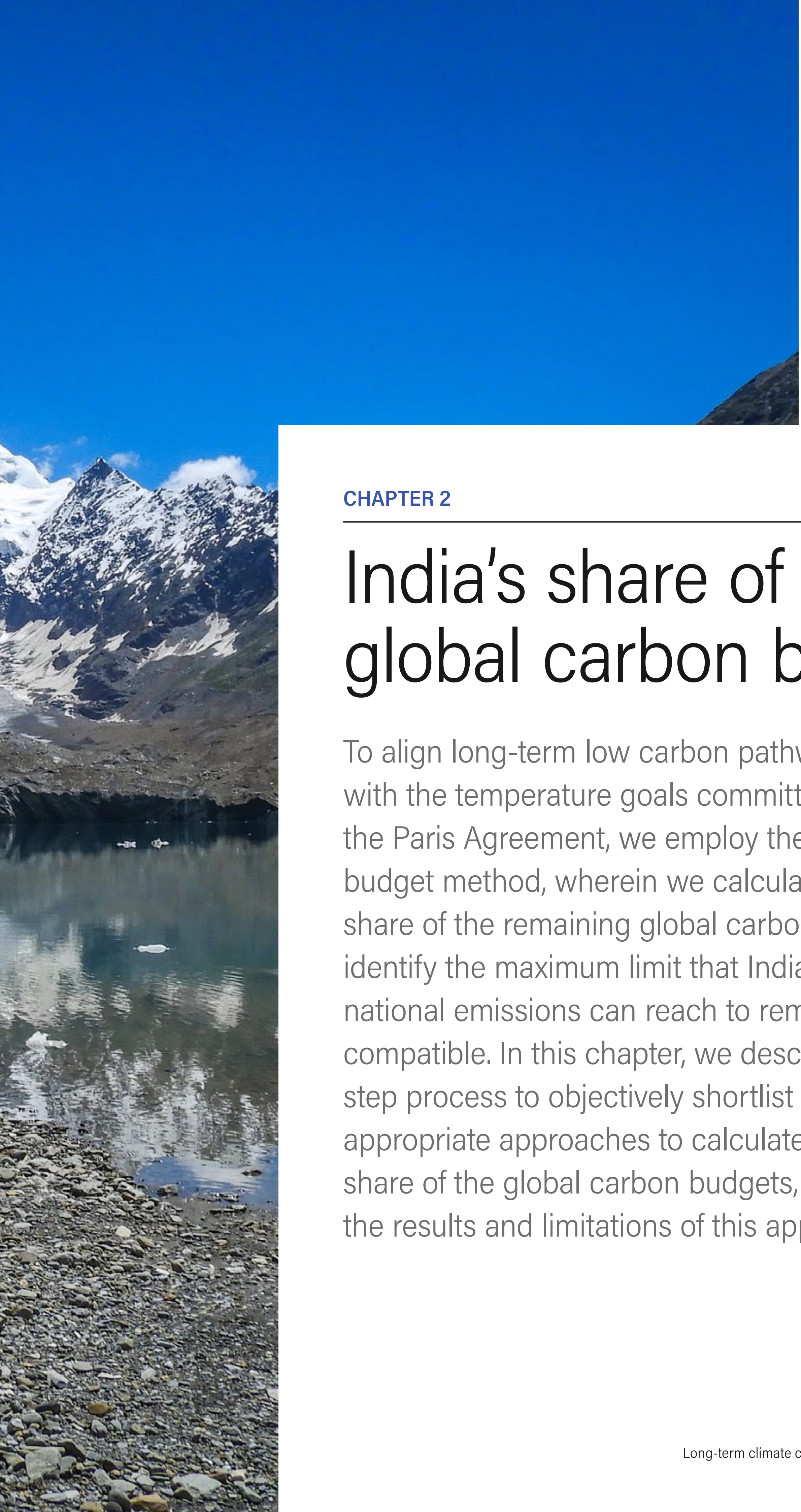
Source: Authors.

LIMITATIONS OF THE STUDY

Some limitations of the approaches employed in this study are as follows:

- Actual cumulative global emissions will only be aligned with the remaining global carbon budget if all countries employ the same allocation method for their countries. This is unlikely to happen in practice, as evidenced by Winkler et al. (2018), and especially because many approaches assessed for India imply negative cumulative emissions for industrialized nations from 2020 to 2100.
- Although the emission budgets account for cumulative emissions up to the end of the century, three of the models do not make projections beyond 2050 given the low degree of accuracy. Thus, this study cannot comment with precision on the net zero year for India (if it occurs after 2050) in the budget scenarios.
- Advances in disruptive technologies, such as hydrogen, battery storage, and sequestration, and changes in their actual costs would significantly impact their uptake (and the cost thereof). Although the EPS has tried to capture the declining costs of technologies as they scale up, it is still not possible to predict actual costs and actual adoption. Hence, cost trade-offs may be more conservative in our pathways than in reality, but to an unknown degree.
- Models cannot capture every socioeconomic interlinkage in the economy and so may not capture the unintended impacts (both positive and negative) of the low carbon pathways. Some of our models calculate some impacts (such as on jobs, GDP, and health in the EPS), but even these outputs are a function of the underlying assumptions, quality of data, and the framework. On the other hand, none of the four models include the negative impact of the climate change that has already occurred on macroeconomic indicators such as the GDP of the reference scenario. Thus, the reference scenario is likely an overestimation (given BAU levels of adaptation measures), and so the negative impacts to these indicators in the low carbon scenario compared to the reference scenario are likely to be lower in reality. However, this is not captured in the models and is thus a caveat of this study.
- Although modeling is the most scientific method of simulating the economy and assessing the impacts of policies and interventions, all outputs are essentially a result of the underlying assumptions, data, and framework. Thus, although modeling can be invaluable in scientific decision-making, the outputs must be used as a guide rather than a fixed isolated milestone. It must also be an iterative process with the models and scenarios being updated every few years to reflect real-world trends and the data quality improved to maintain accuracy.
- Our models do not comment on the financial implication/needs of the policy scenarios.

> Actual cumulative global emissions will only be aligned with the remaining global carbon budget if all countries employ the same allocation method for their countries. Additionally, this must also be an iterative process with the models and scenarios being updated every few years to reflect real-world trends and the data quality improved to maintain accuracy.



CHAPTER 2

India's share of the global carbon budget

To align long-term low carbon pathways for India with the temperature goals committed to under the Paris Agreement, we employ the carbon budget method, wherein we calculate India's fair share of the remaining global carbon budget(s) to identify the maximum limit that India's cumulative national emissions can reach to remain climate compatible. In this chapter, we describe a three-step process to objectively shortlist the most appropriate approaches to calculate India's fair share of the global carbon budgets, followed by the results and limitations of this approach.

THE GLOBAL CARBON BUDGET

The IPCC Sixth Assessment Report (AR6) estimates the remaining global carbon budget (Table 2) that limits global warming to 1.5°C and 2°C above pre-industrial levels with a certain probability and the implications of this increase for the global average temperature. The remaining carbon budget is typically estimated by calculating the amount of CO_2 emissions that results in additional warming, given the transient climate response to cumulative emissions (TCRE) (IPCC Sixth Assessment Report, 2021).

APPROACH AND METHODOLOGY

Keeping in view the objective of this study, the approaches to global carbon budget allocation (see Table A-1 and the explanation preceding it in Appendix A) identified in the literature review were thoroughly assessed to shortlist approaches that focus on global budget sharing. The emissions pathway approaches that essentially look at the emissions trajectory to understand the mitigation effort required are excluded from the analysis. Further, qualitative or welfare-based approaches have also been omitted, because although these approaches lay out the basis for allocation of the carbon budget, they do not specify a formula or quantifiable analysis to estimate the numerical value of the carbon budget for each country. These approaches are usually based on an estimation of the change in welfare due to reallocation of the budget vis-à-vis the BAU scenario, and hence do not provide a direct mathematical basis for allocation of the budget in the first place. Approaches that use both the methodologies (the emissions pathway and the carbon budget) were taken into consideration with respect to only the carbon budget approach. Thus, the following nine approaches were shortlisted for a detailed evaluation and assessment:

- Grandparenting (GP)
- Immediate Emissions Per Capita (IEPC)
- Per Capita Convergence (PCC)
- Equal Cumulative Per Capita Emissions (ECPC)
- GDR
- Ability to Pay (AP)
- Uniform Carbon Price
- Fairness Index (FI)
- Economic Equity

TABLE 2 | Remaining carbon budget estimates (2020–2100)

ADDITIONAL GLOBAL WARMING RELATIVE TO 1850–1900 UNTIL TEMPERATURE LIMIT	ADDITIONAL GLOBAL WARMING RELATIVE TO 2010–2019 UNTIL TEMPERATURE LIMIT	REMAINING CARBON BUDGET (GTCO$_2$ FROM JANUARY 1, 2020)			KEY UNCERTAINTIES AND VARIATIONS				
					Non-CO_2 scenario variation	Non-CO_2 forcing and response uncertainty	Historical temperature uncertainty	Zero emissions commitment uncertainty	Recent emissions uncertainty
(°C)	(°C)	33rd	50th	67th	($GtCO_2$)	($GtCO_2$)	($GtCO_2$)	($GtCO_2$)	($GtCO_2$)
1.5	0.43	650	500	400	Values can vary by at least ±220 due to choices related to non-CO_2 emissions mitigation	Values can vary by at least ±220 due to uncertainty in the warming response to future non-CO_2 emissions	±550	±420	±420
1.7	0.63	1,050	850	700					
2.0	0.93	1,700	1,350	1,150					

Source: IPCC 2021.

Next, to assess the shortlisted approaches, burden-sharing principles/frameworks based on equity presented in the Fifth Assessment Report of the IPCC (IPCC 2014) were considered. These include the capability, equality, responsibility-capability-need, equal cumulative per capita, and staged approaches. Extreme positions within the policy debates range from allocation based on current emission patterns (sovereignty) to equal-per-capita allocations (Böhringer and Welsch 2006). For this reason, we have also considered sovereignty (van den Berg et al. 2020). Further, after evaluating the relative significance of each of the principles, we assigned equal weights to them. To objectively evaluate all the shortlisted approaches and prevent inadvertent biases in the selection procedure, we then assessed the nine shortlisted approaches against the six principles mentioned here. Table A-2 in Appendix A shows the assessment results and a brief explanation of whether a parameter is included in the approach under consideration.

After the assessment, the four approaches with the highest score—GDR, ECPC, FI, and PCC—were selected. The high scores imply that these approaches consider the most number of the aforementioned chosen principles of budget sharing and are hence more inclusive than the other approaches. They are likely to achieve greater acceptability among countries due to their inclusion of the various viewpoints on budget sharing highlighted in the scientific literature and espoused by countries.

CALCULATING INDIA'S CARBON BUDGETS USING THE SHORTLISTED APPROACHES

We thoroughly analyzed each of the shortlisted approaches using similar databases. Each of the four allocation approaches has its own formula that can be used to calculate India's share of the global carbon budget according to that approach. This section summarizes the principles underlying each of the four allocation approaches and the results they yield in terms of India's share of the global carbon budget. The formulas and sensitivity analysis for each approach can be found in Appendix A.

GDR

GDR is an effort-sharing framework that is basically designed to calculate the allocation of the cost of rapid climate stabilization for limiting the average global temperature rise to the temperature thresholds under the Paris Agreement. It uses a "development threshold" to calculate this, which is defined as a level of welfare below which people are not expected to share the costs of the climate transition. The development threshold is set at 25 percent above the global poverty line at a per capita annual value of $7,500 purchasing power parity (PPP) (Kemp-Benedict and Kartha 2010).

Principle: The GDR methodology is based on the following principles:

- **Responsibility**
  A country's responsibility is defined as the contribution that it has made to climate change. It is calculated as the country's cumulative emissions since 1850 (the start of the Industrial Revolution) over the development threshold. The "responsibility start date" needs to be fixed by negotiation.
- **Capacity**
  Capacity is simply defined as the income above the development threshold that is available for investment in climate adaptation and mitigation. It can also be interpreted as the total income above the development threshold value.
- **Responsibility and Capacity Index**
  When Responsibility and Capacity are combined (based on the average values), we obtain a value called the Responsibility and Capacity Index (RCI), which shows a country's obligations in combating the climate challenge. We combine Responsibility and Capacity based on the weighted sum:

$$\mathrm{RCI} = a{*}R + b{*}C$$

where:

- RCI is the Responsibility and Capacity Index
- a and b are the weighted values
- R stands for Responsibility
- C stands for Capacity

The data inputs, assumptions considered in the analysis, and sensitivity analysis are discussed in Appendix A.

ECPC

ECPC is a methodology that is used to allocate carbon budgets based on the cumulative emissions per capita in a certain period that is equal across all countries.

Principle: The ECPC methodology is based on the following principles:

- **Responsibility**
  Historical cumulative emissions are incorporated. The historical dimension of the ECPC helps address the responsibility for future damage to people in developing nations caused by the past emissions of people in industrialized countries, mediated by global warming.
- **Equality**
  Allocation is based on the share of the population, which includes both historical and future population shares.

FI

The FI is developed as a simple equation for guiding the international distribution of the burden of the climate policy. The index is built on different equity principles, which are combined to formulate the allocation rule. It derives its motivation from the Montreal Protocol, adopted in 1987, which has been a highly successful example of the implementation of equity principles in the domain of international environmental issues.

Principle: The FI methodology is based on the principles shown in Table 3.

PCC

According to the PCC approach, countries, regardless of their development or emissions levels, agree to converge their per capita emissions from the current level to a level equal for all countries by a predefined year, ensuring that the global aggregated cumulative emissions remain within the global carbon budget.

Principle: The PCC methodology is based on the following principles:

- **Sovereignty**
  This principle essentially implies that the global carbon space may be allocated among countries based on their current emission trajectories. In other words, it implies distribution of the global common atmospheric resources among countries in proportion to their BAU emissions.
- **Equality**
  The basic premise of the principle is that the physical carbon space has been over-occupied in the past by developed countries, restricting its availability for developing nations. Emissions per capita converge to, or immediately reach, the same level for all countries.

RESULTS

The four approaches—GDR, ECPC, FI, and PCC—have been analyzed for the latest estimates of the global carbon budget. The results are tabulated in Table 4 and represented graphically in Figure 2.

TABLE 3 | Principles underlying the Fairness Index allocation approach

PRINCIPLE	DEFINITION	CONTRIBUTION TO FAIRNESS INDEX
Egalitarian Principles	Equal *per capita* right to atmospheric resources	Calculate per capita carbon claims throughout *time* (use the individual as a unit of analysis)
Ability to Pay Principle	Future allocation of carbon emissions *inversely related* to the ability to pay for emissions reduction	Calculate budget as a measure of purchasing power (carbon-efficient technologies)
Efficiency Principle	*Minimized* cost of carbon policy	Calculate budget based on different abatement costs
Desert Principle	Higher individual claim on the carbon space based on factors like *economic income and wealth*	Calculate budget based on carbon-saving technical progress
Polluter Pays Principle	Burden of the *climate* policy proportional to actual pollution	Calculate budget by deducting past emissions from the overall carbon budget

Source: Authors.

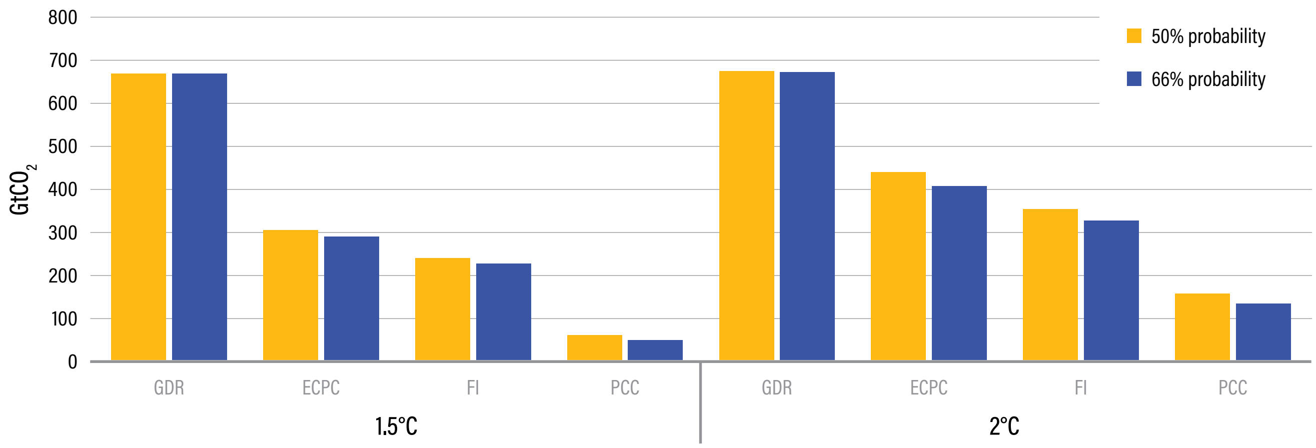
TABLE 4 | India’s remaining carbon budget until 2100

TEMPERATURE THRESHOLDS	**1.5°C**					**2°C**				
India’s carbon budget under the approach (in GtCO$_2$)	**Total Global**	**GDR**	**ECPC**	**FI**	**PCC**	**Total Global**	**GDR**	**ECPC**	**FI**	**PCC**
50% probability	**500**	672	305	239	58	**1,350**	677	440	354	155
66% probability	**400**	672	289	226	46	**1,150**	675	408	327	132

Notes: Scenarios: GDR = Greenhouse Development Rights; ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GtCO$_2$ = gigatonnes of CO$_2$.

Source: Authors.

FIGURE 2 | India’s calculated carbon budgets using four approaches



Notes: GDR = Greenhouse Development Rights; ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GtCO$_2$ = gigatonnes of CO$_2$.

Source: Authors.

> Although the concept of global carbon budget is recognized globally, countries around the world are yet to develop a consensus on how this finite carbon budget should be distributed fairly to stay within the desired levels of global temperature rise.

Some other studies that calculate India's share of the global carbon budget are shown in Table 5.

CONCLUSION

The Paris Agreement allows countries to formulate their own national targets in the form of NDCs to limit the increase in global mean temperature to well below 2°C, with concerted efforts to limit it further to 1.5°C above pre-industrial levels. Given these global targets, "fair" country-level budgets based on effort-sharing approaches can be derived. Carbon budgets have the advantage that countries have more flexibility in deciding their own pathway given the allocated budget—should countries attempt to incorporate equity principles. Although the concept of global carbon budget is recognized globally, countries around the world are yet to develop a consensus on how this finite carbon budget should be distributed fairly to stay within the desired levels of global temperature rise. Approaches such as GDR, which consider the distribution of incomes in countries relative to their development threshold, provide a higher budget to India and negative

TABLE 5 | Carbon budget estimates for India according to other studies

OTHER STUDIES (GTCO$_2$)						
IIASA - Van den Berg study (2011–2100) (van den Berg et al. 2020)						
66% probability	**BAU**	**GDR**	**Ability to Pay**	**Immediate ECPC**	**Grandparenting**	**PCC**
1.5°C	694	266	115	108	6	65
2°C		300	163	181	29	128
IRADe - German Advisory Council on Global Change Methodology (2010–2050) (IRADe et al. 2014)						
Equal Per Capita Budget Approach: 2°C						
1. Historical Responsibility: 75% probability (Base year: 1990)					156	
2. Future Responsibility: 67% probability (Base year: 2010)					133	
TISS: TISS-DSF Model (2010–2050) (Kanitkar and Jayaraman 2013)						
50% probability – 2°C (Base year: 1850)					250	

Notes: Scenarios: GDR = Greenhouse Development Rights; ECPC = Equal Cumulative Per Capita Emissions; PCC = Per Capita Convergence. BAU = business as usual; DSF = Delhi Science Forum; IIASA = International Institute for Applied Systems Analysis; IRADe = Integrated Research and Action for Development; TISS = Tata Institute of Social Sciences.

Source: Authors.

budgets for some developed countries. On the other hand, in the PCC approach, allocations are independent of the development levels of countries and are based only on the convergence of per capita emissions from the current level to a level equal for all countries by a predefined year; this approach provides a much lower budget for India. This study presents a range for India's remaining carbon budget, because a single value may lead to a bias toward a particular approach.

LIMITATIONS

The limitations of the carbon budget calculation chiefly pertain to the parameter settings for the short-listed approaches. The major limitations of the study are as follows:

- The equity principles underlying various frameworks in various studies are highly contested, as many of them fail to clarify the ethical choices informing their indicators (Dooley et al. 2021). For the purpose of this study, the focus has been on resource-sharing approaches to carbon budget allocation. The study distributes the physical carbon space among countries based on a set of predefined equations and parameters (where the starting point is the global carbon budget), but another way of arriving at carbon budgets for countries is to calculate the area under the curve, that is, the area under the emissions trajectories. In the latter approach, countries can select the considerations on which to base emissions trajectories, such as development levels, sectoral capabilities, and mitigation potentials.
- The databases (such as for historical emissions and population) and parameters chosen for the calculations will affect the results of the study.
- The carbon budget allocation approaches used in the study do not include non-CO_2 greenhouse gases, because the global carbon budget estimates in the AR6 report are available only for CO_2. Consideration of non-CO_2 greenhouse gases may impact the allocations to different countries.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CHAPTER 3

Overview of models

Energy-economy models provide a scientific and robust method to translate the carbon budgets calculated for India into long-term low carbon pathways disaggregated by sector. They also help assess how these pathways would impact different socioeconomic indicators important to a developing economy like India, such as jobs, GDP, development parameters, etc., which can help plan for a just low carbon transition. In this chapter, we describe the narratives, framework, underlying assumptions, and unique characteristics of the four energy-economy models employed in this study.

This study uses energy-economy models to distribute the carbon budgets calculated for India across their corresponding time frame to assess how they translate into low carbon pathways across the different sectors of the economy. The four models used are shown in Table 6.

Each model is unique, and the models collectively offer different narratives of the future of India's economy based on their individual framework and underlying assumptions. Thus, an inter-model comparison of the four models yields a range for sectoral milestones while meeting the same climate goal, each in the context of its own unique narrative (such as cost optimization, meeting development goals, and the impact on socioeconomic indicators such as jobs, the GDP, and health).

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TABLE 6 | Models used in the study and the organizations that developed them

MODEL	ORGANIZATION
Computable General Equilibrium Model (CGE)	KPMG Assurance and Consulting Services LLP
Global Change Analysis Model (GCAM)	Council on Energy, Environment and Water (CEEW)
Sustainable Alternative Futures for India (SAFARI)	Centre for Study of Science, Technology and Policy (CSTEP)
Energy Policy Simulator (EPS)	World Resources Institute India (WRI India)

Source: Authors.

COMMON MODELING PROTOCOL

The models are based on their own subjective assessment of the economy and use vastly different frameworks; in fact, variables that may be inputs for some models are outputs for other models. Thus, although assumptions regarding socioeconomic drivers such as population and urbanization fall within the same range, no variable has been explicitly harmonized to reflect the exact same values, so as to retain their differences.

Thus, the policy scenarios of the four models present a diversity of outcomes for the same climate goals based on the variation in their modeling methods and assumptions, and are meant to be analyzed as such rather than directly compared with each other. Each model's results are thus analyzed relative to its own reference scenario, and the four models' scenarios are compared with one another in the context of their unique setups and narratives.

Finally, in line with the objective of the paper, all four models project the same set of carbon constraints (eight possible carbon budgets for India based on four different allocation approaches, each approach allocating both the 1.5°C- and 2°C-compliant remaining global carbon budgets with a 66 percent probability). However, each model is left free to project these budgets and generate low carbon pathways on the basis of their chosen policy packages.

TABLE 7 | Key characteristics of the four models

CHARACTERISTIC	CGE	GCAM	SAFARI	EPS
Framework	Top-down macroeconomic	Global integrated assessment model	Systems dynamics	Systems dynamics
Type of model	Recursive dynamic	Recursive dynamic	Recursive dynamic	Recursive dynamic
Partial/Full equilibrium	Full equilibrium	Partial equilibrium	Partial equilibrium	Partial equilibrium
Sectoral coverage	Economy, energy, industries, households, AFOLU, and services	Economy, energy, water, agriculture and land use, and climate	Industries, housing, water, land, transport, agriculture, and power	Buildings, industry, transportation, hydrogen, electricity, and AFOLU
Drivers in the model	Population growth, investment growth, improvements in total factor productivity, energy efficiency.	Population growth rate, GDP growth rate, technology characteristics, labor force participation and productivity, and emission constraints	SAFARI: Development goals such as food and water security, housing for all, healthcare, education, power for all, access to clean cooking, and transport. Linked CGE: Investment (sectoral capital stock growth), labor supply (driven by population), and productivity growth	IESS v2.0: Sectoral energy demand based on the GDP, population, and urbanization (supply-side drivers include technology costs)
Unit of flows	Monetary	Physical	Physical	Physical and monetary
Impacts captured	Energy; emissions; direct, indirect, and induced impacts across the economy; household income and expenditure	Energy and emissions	Energy, emissions, land, water, and material resources	Energy; emissions; direct, indirect, and induced economic impacts on jobs, the GDP, health, and costs

Notes: AFOLU = Agriculture, Forestry, and Other Land Use; GDP = gross domestic product; IESS = India Energy Security Scenarios. Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

OVERVIEW OF THE FOUR MODELS

Table 7 summarizes the key characteristics of the four models.

CGE

CGE, developed by KPMG Assurance and Consulting Services LLP, is a top-down macroeconomic model that simulates the interactions between the economy, energy systems, and the environment. It models the whole economy, which consists of production sectors, households, government, and the rest of the world. In the CGE framework, households are owners of the factors of production; firms rent factors from households to produce commodities; these commodities are subsequently purchased by households and other firms, and the government; and the government collects direct and indirect taxes from households, firms, and the foreign sector.

Although CGE is a recursive dynamic model similar to GCAM, it is a full equilibrium model; that is, it operates on the principle of achieving equilibrium in all sectors of the economy together such that the demand of each commodity equals its supply. For this, the model solves optimization problems of all economic agents (households/production-firms, etc.) using specifications of market clearing, resource supplies, trade balances, and other constraints, with inter-industry linkages and special linkages to energy and the environment. The model solves for equilibrium demand, prices, and so on, for each sector by solving simultaneous sets of equations that are first-order conditions of profit and utility maximization by various firms and households, respectively.

Some of the drivers of the CGE model are population growth, investment growth, improvements in total factor productivity, and energy efficiency. All flows in CGE are captured in monetary terms (and not in physical quantities as in GCAM).

CGE also allows for substitution between factors of production (labor/capital), fuels/energy sources in the economy (coal, oil gas, electricity), and modes of electricity generation (such as wind, solar, and thermal) under different policy settings or technological innovations. Because the prices of these factors of production are determined endogenously within the CGE framework, this helps in developing a detailed understanding of the direct, indirect, and induced impact of policies. The effects of a policy intervention in a particular sector (e.g., transport) on other sectors (such as electricity, coal, and oil), which provide intermediate inputs, are called *direct effects*. For example, an increase in electricity demand caused by EV penetration is a direct effect. Direct effects may induce another round of impacts on other sectors, which are called *indirect impacts*. For example, increased electricity demand may give an impetus to additional upstream sectors of the power sector that supply and support the core activities of electricity generation. Lastly, with increased demand for electricity and indirect impacts in other sectors, overall employment as well as income in the economy may rise, leading to further growth. These changes are known as *induced impacts*.

In a CGE framework, different energy/emission scenarios can be simulated through appropriate interventions, for example, by directing additional investments in sectors such as RE under the government's developmental policies, introducing technological changes in the functioning of various sectors (transport and industry) to capture disruptions such as electrification, and incorporating gradual energy efficiency improvements over time. To develop the carbon budget scenarios in this study, different levels of these three types of interventions are used with the cumulative emissions constrained to the budget.

GCAM

GCAM, developed by the Council on Energy, Environment and Water (CEEW), is a global integrated assessment model (Joint Global Change Research Institute n.d.) representing the behavior and interactions between five systems: the economy, energy, water, agriculture and land use, and climate. It is a recursive dynamic model, unlike intertemporal optimization models, which assume that agents know the future with certainty when they make decisions. For each model solution period (in five-year time steps), the model solves to meet the demand across model sectors (as determined by the economic activity in the given period) after incorporating information on capital stocks and prices of the last period, as well as exogenous information on non-energy cost and efficiencies of technologies in the solution period.

GCAM operates on the principle of partial equilibrium, as the market equilibrium is reached in a few sectors individually rather than in the economy as a whole. It reads in external "scenario assumptions" about key drivers (e.g., population growth rate, GDP growth rate, technological characteristics, labor productivity, and emission constraints) and then assesses the implications of these assumptions on key scientific or decision-relevant outcomes such as energy demand, prices, and annual emissions at 5-year intervals.

In the GCAM structure, population, labor force participation, and labor productivity growth set the scale of economic activity and together drive a range of different demands from end-use sectors. This sets the scale of macroeconomic activity within the model. Within the economy, the energy system is a detailed representation of the sources of energy supply, modes of energy transformation, and energy service demands such as passenger and freight transport, industrial energy use, and residential and commercial sector demands. The price of the energy sources is then determined endogenously through demand and supply forces. Also, the energy markets represent physical flows for energy/electricity in GCAM.

On the emissions front, the carbon constraints/carbon budgets are provided exogenously in GCAM to induce a climate policy restricting emissions to a given specific level. In the emission constraint approach, the model estimates the price of carbon needed to satisfy the constraint in each period. After applying the endogenously calculated cost of carbon, the model framework iterates to find the most cost-effective way to stay within the carbon budget. GCAM's operations are similar to emissions trading systems (ETSs) in the sense that as in ETSs, GCAM imposes a national cap on emissions; thus, the easiest-to-mitigate sectors will be mitigated first. However, in contrast to ETSs, there are no sectoral allocations that determine how many credits need to be sold or purchased. An alternative method in GCAM is to introduce the carbon tax exogenously and let the model find the implications of the carbon tax on emissions. However, the feedback impact of the carbon budget/emission constraint pathway on the overall macro economy is not linked through a feedback loop and so is not captured by GCAM.

SAFARI

SAFARI (Ashok et al. 2021), developed by the Centre for Study of Science, Technology and Policy (CSTEP), is a system dynamics model that estimates the energy, resource, and emissions implications of achieving developmental targets. SAFARI employs a bottom-up approach to capture the demands arising from meeting goals. The key drivers of the energy demand needed to service development goals are from the industry and residential sectors, due to high construction activity (and the consequent demand for cement and steel) and the high operational energy demand from the steadily increasing usage of appliances.

The economic and energy activity in sectors not directly impacted by the achievement of development goals are driven by investment (sectoral capital stock growth) assumptions in a macroeconomic CGE model. The CSTEP CGE model is based on the 2012–13 Input-Output Tables–Social Accounting Matrices (IOT-SAM) and has representations of 66 activities, 51 commodities, and 20 household types (income deciles) in a recursive dynamic framework with a multi-period simulation. The nonlinear model solves for the economy on an annual basis and charts sectoral and overall economic trajectories based on capital accumulation, labor supply (driven by population), and productivity growth (Lofgren-International Food Policy Research Institute Model consumption elasticities and production). The CGE model's exogenous investment trajectories have used published historical trends and, where necessary, have been adjusted to align with the government's sectoral vision targets or development policy narratives from the SAFARI framework. Hence, for example, the demand drivers for sectors such as crude steel and cement production are also soft-linked to macroeconomic activity exogenously. In the reference scenario setup on SAFARI for this exercise, we do not factor in increased ambition to achieve development goals or the investments needed for additional infrastructure to meet development benchmarks. Developmental gaps in many of India's key sectors, such as housing, agriculture, power, and transport, are assumed to be met by being progressively linked to economic growth in the reference scenario. For the policy scenarios, the premise is that to stake a claim to the global carbon budget, India will need to prioritize development goals early on (up to about 2040), and hence a "boost" over reference investment levels in sectors such as construction, housing, health, education, and agriculture is assumed. This in turn drives the material and resource needs for achieving the goal benchmarks (not met under the reference scenarios).

Hence, in the overall SAFARI framework, developmental goals and the GDP drive materials and energy demand in the agriculture, residential, commercial, industry, and transport sectors. The energy (and electricity) demand arising from these sectors drives SAFARI's power sector, which explores fossil (coal and natural gas) and fossil-free (hydro, nuclear, biomass, solar, and wind) energy sources. Capacity addition in the power sector is based on a least cost

> Developmental gaps in many of India's key sectors, such as housing, agriculture, power, and transport, are assumed to be met by being progressively linked to economic growth in the reference scenario. For the policy scenarios, the premise is that to stake a claim to the global carbon budget, India will need to prioritize development goals early on (up to about 2040), and hence a "boost."

algorithm. The SAFARI model is a goal-seeking model where each sector is driven by the goal to be met and is constrained by the availability of various resources. For example, in the power sector, the goal is to meet electricity demand, and the constraints are the availability of water, land, and energy reserves. Therefore, under extreme conditions of water shortage in a particular year, there will be a gap between electricity supply and demand.

Due to the limitation of the current CGE I-O table, which does not explicitly disaggregate energy commodities into thermal and electrical uses, and the absence of new production sectors such as renewable power and allied manufacturing, the CSTEP CGE model does not assess emissions and resource constraints and their macroeconomic impact. In the SAFARI model, the carbon budgets in the policy scenarios are modeled mainly using technology and policy levers to examine the synergies and trade-offs related to the achievability of development goals and the impact of the decarbonized energy system on land, water, and material resources.

> The EPS model does not necessarily present the most cost-optimal scenario to meet the desired objective but rather assesses the impact of alternative policy choices at different timelines and levels of implementation on various socioeconomic and environmental outcomes such as jobs, the GDP, energy consumption, and health impacts.

EPS

The EPS (Energy Policy Solutions n.d.) is a systems dynamics model that assesses the effect of policy packages on a variety of environmental, economic, and social metrics. It constructs supply in a bottom-up manner by choosing the least cost technology options, and demand trajectories are based on exogenous sectoral demand from the IESS but is subject to feedback effects due to interaction between economic sectors within the model. The EPS does not assume that the system is in equilibrium but rather replicates the economy using various interactions within the economy. Similar to CGE and GCAM, the EPS is also recursive dynamic in nature as it uses the state of the system calculated in a previous time step as an input for estimating the state of the system in the next time step.

The BAU scenario in the EPS is constructed by using end-use demand trajectories from existing independent models, projected based on endogenous growth drivers. On the supply side, a cost optimization logic is used in the electricity and transport sectors to meet demand; that is, the technology for electricity generation and vehicles added to the fleet are chosen on a least cost basis to serve the estimated demand. The user can then build the policy scenarios by switching on different policies at different timelines and levels of implementation as desired. The output is a reflection of the impact of these policies on different socioeconomic and environmental outputs relative to the BAU scenario.

The model is best suited for constructing what-if scenarios aimed at evaluating the impact of alternative policy actions. It does not necessarily present the most cost-optimal scenario[2] to meet the desired objective but rather assesses the impact of alternative policy choices at different timelines and levels of implementation on various socioeconomic and environmental outcomes such as jobs, the GDP, energy consumption, and health impacts. It can serve as a powerful tool for policymakers to understand the implications (including cost implications) of implementing new policies in different time frames and explore the impacts holistically on a variety of outputs.

In the EPS framework, the amount of electricity required by the system is calculated bottom-up, driven by the demand sectors of buildings, industry, transportation, and the hydrogen supply sector. The electricity sector then estimates the installed power capacity required to meet this demand on a least cost basis based on an endogenous learning mechanism, also taking into consideration specific constraints such as the mandated capacity construction for meeting RE targets.

Also, as in the CGE framework, where the impact of various policies endogenously determines economic activity, the EPS also has a fully integrated macroeconomic input-output model (IO model), which assesses the impacts of various policy settings on the GDP, jobs, and employee compensation relative to the BAU scenario. In addition to the direct and indirect impacts[3] of policies the IO model estimates the effects on induced economic activity caused by re-spending money paid to workers or the government as a result of the growth of any industry impacted by a policy. Further, it incorporates feedback loops on the effect of the growth or shrinkage of different sectors in the economy (relative to the BAU scenario) from the IO model into the main energy-demanding sectors. For example, if there is economic growth in an energy-intensive sector such as iron and steel, energy demand in the industry sector (and its direct, indirect, and induced impacts across the economy) will increase due to the feedback effect. It does not consider the effect of energy price changes on energy demand (CGE models usually do this).

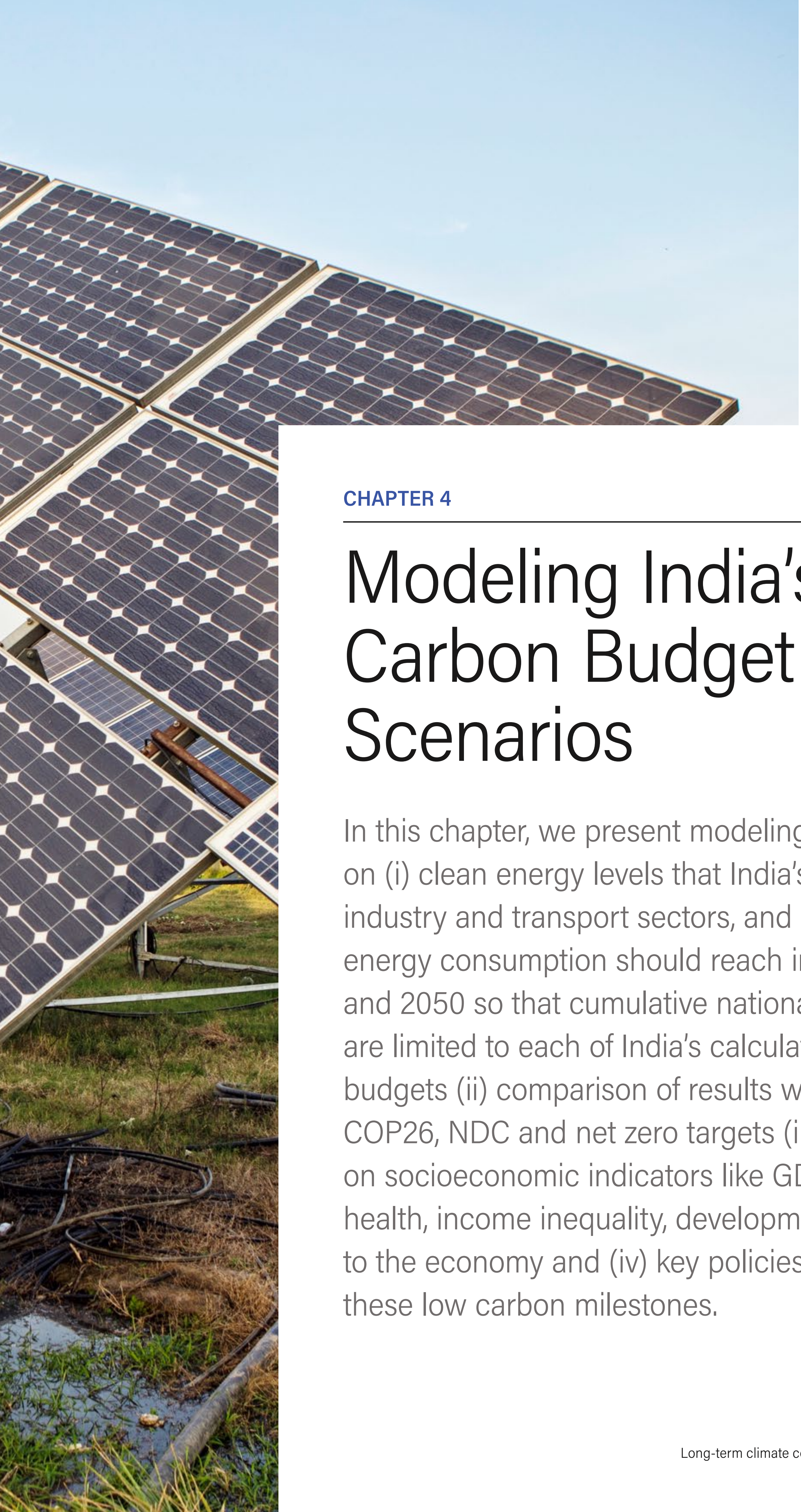
UNIQUE FEATURES OF THE MODELS

Because a CGE framework models all the sectors of the economy together in a total equilibrium framework, it captures the impacts and effects of the chosen policies within the economy and individual sectors. This includes direct, indirect, and induced impacts as discussed above, as well as the substitution effect, in which a policy-induced fall in the demand for a fuel in a particular sector (say, coal in the power sector) lowers its price, leading to other sectors (say, industry) picking it up due to its cost-effectiveness. Thus, outputs from a CGE model include the direct effects of different non-fossil energy development paths on the energy and power sectors, as well as their indirect and induced effects in the rest of the economy. CGE also gives the impact of a change in technology on household income in different segments, which helps assess income inequality in the economy.

GCAM is the only one of the four models where the end-of-century carbon budgets are input as constraints and thus carbon trajectories are back-casted over the corresponding time frame (as opposed to the other models, which are inherently forecasting models and so develop budget scenarios by adjusting policy levers such that the resultant cumulative emissions align with the carbon budget). The model solves for this carbon constraint by iterating and using the least cost pathway. Thus, external policy targets may or may not be met by the model, as the choice of technology to meet energy demand always follows a least cost pathway.

SAFARI explores the achievement of various development goals such as food, housing, healthcare, and education instead of using only the GDP as the primary metric for development. Competition for resources between different sectors and objectives can also be evaluated using SAFARI, which helps explore cross-sectoral policy trade-offs.

The EPS works on the principle of endogenous learning where the cost of technologies gradually declines as they achieve scale over time. It endogenously calculates cost declines based on the cumulative deployment of that technology up through each year of the model run. This helps in understanding the overall cost associated with the chosen policy package. The EPS also yields the impact of the chosen policy package on other socioeconomic variables such as the GDP; direct, indirect, and induced jobs; and health outcomes, as well as the impacts on the cash flows of other cost impacts on different actors in the economy with respect to the BAU scenario.



CHAPTER 4

Modeling India's Carbon Budget Scenarios

In this chapter, we present modeling results on (i) clean energy levels that India's power, industry and transport sectors, and primary energy consumption should reach in 2030, 2040 and 2050 so that cumulative national emissions are limited to each of India's calculated carbon budgets (ii) comparison of results with India's COP26, NDC and net zero targets (iii) their impact on socioeconomic indicators like GDP, jobs, health, income inequality, development and cost to the economy and (iv) key policies to achieve these low carbon milestones.

TABLE 8 | Carbon budgets calculated for India

CALCULATED CARBON BUDGETS UNDER THE FOLLOWING APPROACHES (2020–2100) IN $GTCO_2$	1.5°C (66% PROBABILITY)	2°C (66% PROBABILITY)
Per Capita Convergence (PCC)	46	132
Fairness Index (FI)	226	327
Equal Cumulative Per Capita Emissions (ECPC)	*289*	408
Greenhouse Development Rights (GDR)	672	675

Notes: $GtCO_2$ = gigatonnes of CO_2.
Source: Authors.

In the earlier section titled "India's share of the global carbon budget," we determined 16 different carbon budgets for India based on four allocation approaches, each aligned with the 1.5°C and 2°C temperature targets, each under a 50 percent and 66 percent probability of being met. Because the budgets with a 66 percent probability are more accurate in meeting their corresponding temperature target and are thus more commonly used in the literature, those eight budgets were shortlisted for modeling. Table 8 gives a snapshot of the eight budgets available for modeling.

Because three of the four models do not go beyond 2050 (GCAM being the only exception), Table 9 presents the cumulative emissions from 2020 to 2050 according to each model.

TABLE 9 | Cumulative emissions from 2020 to 2050 of the four models

CUMULATIVE EMISSIONS OF EACH MODEL UNDER THE REFERENCE SCENARIO (2020–2050) IN $GTCO_2$	
CGE	127
GCAM	114
SAFARI	113
EPS	133

Notes: $GtCO_2$ = gigatonnes of CO_2.
Source: Authors.

To compare the models' 2050 cumulative emissions with the 2100 budgets, the modeling teams linearly extrapolated[4] their reference scenario annual emissions up to 2100 (except for GCAM, whose modeling time frame extends to 2100). In all four models, we observed that their cumulative reference scenario emissions up to 2100 were lower than the budgets calculated by the GDR approach, and thus did not need to model them. Next, because the four budgets following the FI and ECPC approaches were lower than the models' extrapolated 2100 cumulative emissions but higher than their modeled 2050 cumulative emissions, annual emissions were made to peak before 2050, given our assessment that the share of the 2100 budget that is consumed by 2050 is more than half of the total budget (as discussed in the earlier section titled "Methodology of the study") with not much left beyond 2050 (implying net zero in the decades soon after 2050). In the two PCC scenarios, given the considerably smaller size of the budgets, almost nothing would remain beyond 2050. Therefore, these budgets had to be almost fully spent by 2050, with at best a small fraction remaining beyond 2050 that can be negated used the carbon dioxide removal (CDR) options. Keeping this in mind, six scenarios each were developed with the four models, namely, those that referred to the budgets calculated using the PCC, FI, and ECPC budgets and aligning each budget with the 1.5°C and 2°C temperature targets.

Note that at maximum capacity and considering the feasibility of interventions, CGE, SAFARI, and the EPS were unable to meet the 46 $GtCO_2$ carbon budget of the 1.5°C PCC scenario, with cumulative emissions reaching 77, 93, and 60 $GtCO_2$, respectively. This highlights the need for the simultaneous deployment of negative emission technologies and measures in the LULUCF sector in these three models for alignment with the carbon budget prescribed by the PCC approach in the 1.5°C temperature scenario.

SCENARIO NARRATIVES

Reference scenario

The reference scenario is either the BAU or progress-as-usual scenario, with the performance of the economy projected into the future based on current trends and policies. CGE and SAFARI use a BAU scenario; that is, future trends are extrapolated based on historical trends without any additional effort being exerted (2013–18 in CGE and from 1990 in SAFARI). Thus, the BAU scenario would be more carbon intensive than other scenarios, and more effort would be required to align the policy scenarios with the carbon budget. On the other hand, GCAM uses a progress-as-usual scenario in which higher levels of electrification and other decarbonization efforts are considered, based on the current price and technology assumptions, and so would require less effort (compared to CGE and SAFARI) to meet the carbon budget. The EPS uses demand growth trends from the IESS v2.0 for demand-side sectors and a least cost approach to meet demand in the power and transport sectors to develop its reference scenario. Least cost allocation in the power and transport sectors leads to a certain amount of RE and EVs in the EPS reference scenario given their increasing cost competitiveness with traditional technologies.

Of the four models, GCAM, SAFARI, and the EPS are demand-driven partial equilibrium models in which overarching socioeconomic parameters such as the GDP, population, and urbanization drive the demand trajectories of end-use sectors such as industry, transport, and buildings. The energy demand (including the electricity demand) of these sectors then drives the supply of fuels and electricity in the economy. Together, these sectors contribute to overall annual emissions and primary energy consumption in the economy. CGE is an exception because it is a full equilibrium model in which demand and supply forces act simultaneously to achieve equilibrium in the economy.

Carbon budget scenarios

As each model employed in this study is based on a unique framework, the interventions used by it to develop the six budget scenarios were also unique. The key interventions used by each of the four models to develop the carbon budget scenarios are as follows.

In CGE, the budget scenarios are built by calibrating the levels of policy implementation: for example, 80 percent of the RE target (of 450 GW by 2030) is achieved, EVs constitute only a certain fraction of vehicles by a certain year, industries are able to electrify their processes by a certain percentage, and energy efficiency is improved by a certain amount. These differing levels of policy implementation under the different carbon budget constraints in the different scenarios help analyze the impacts on the economy, the environment, energy security, and income disparities between various types of households.

In GCAM, in each budget scenario, a carbon constraint is applied across all model time steps to reflect its own unique climate policy, which in this study, ensures that cumulative economy-wide emissions meet the exogenously described carbon budget for India. Because GCAM is a recursive dynamic model, per the underlying algorithm, under the constraint of this climate policy, the model implements the energy system transformation required to ensure that demand in the economy is met in the most cost-effective manner. In other words, to meet the economy-wide emissions constraint, sectors transform in the least cost fashion: that is, decarbonization first occurs in the sector where it is cheapest, then moves on to the next cheapest sector, and so on. The cost of mitigation is reflected in terms of a carbon price in the model. Because the carbon price makes fossil fuel more expensive, there would be a shift toward renewable sources of energy. Across end-use sectors, GCAM is not currently structured to highlight the price changes of commodities such as steel or chemicals and the consequent impact on households. However, in the electricity generation/power sector, higher penetration of solar, which has a lower levelized cost of electricity (LCOE), will lower the cost of electricity across end-use sectors.

In SAFARI, the premise is that to stake claim to the global carbon budget, India will need to prioritize development goals early on (up to about 2040). To be able to meet the material and resource needs for achieving these goal benchmarks, a “boost” in investment will be required in sectors such as construction, housing, health, education, and agriculture over the reference investment levels.[5] The key drivers of the energy demand needed to service development goals are the industry and residential sectors, due to the high levels of construction activity (and the consequent demand for cement and steel) and operational energy demand from steadily increasing appliance usage. As a result, after 2023–25, there is an increased focus on the infrastructure and construction sectors to achieve goals in housing, education, and healthcare. Additional investment in construction, agriculture, and allied sectors (food security) boosts the demand for energy- and emissions-intensive activities and conventionally used production processes early on. Per capita income targets are met earlier. Economy-wide linkages drive the demand for materials in other key energy-intensive sectors such as roadways and automobile production. Thus, the key sector-wise distinctions in the assumptions underlying the policy scenarios are as follows:

- Primary agriculture sector: Historical trends continue, but productivity is marginally improved.
- Education and health care service sectors: "Operational" investments to support requirements are assumed to be consistent with historical trends of about 10–11 percent annual growth (higher than the reference scenario levels, which are low due to the impact of COVID-19 and a slowdown in recent years).
- Construction activities to support the physical infrastructure needed for achieving "goals" are catered to by doubling investments in construction and allied manufacturing. This corresponds to sectoral construction growth volume for housing, education, and health infrastructure in the SAFARI model.[6]

These assumptions relating to the "goals to be met" are kept consistent across the six budget scenarios, but will be met under different carbon constraints by using different mitigation interventions. In other words, SAFARI's outputs across the scenarios represent how the total demand and corresponding fuel mix would vary (vis-à-vis the chosen interventions) in key sectors under different carbon constraints to meet the same set of development goals.

In the EPS, because it enables the forecasting of "what-if" scenarios that reveal the impact of a chosen policy package on different socioeconomic and environmental outcomes, the policy packages chosen for each budget scenario can be grouped into two overall storylines corresponding to the two temperature scenarios. In the 1.5°C scenarios, as stated in the Special Report on Global Warming of 1.5°C (the SR1.5 report), the world must, on average, reach global net zero by 2050 (IPCC 2018). Thus, a more ambitious approach and timeline to emissions reduction has been taken according to which India's total annual emissions peak latest by about 2035 and begin to decline thereafter, reaching net zero emissions in 2050–60. This ambition is characterized by a higher uptake of technologies that are currently in a nascent stage of development but have a high potential for emissions reduction in the future, such as industry electrification, hydrogen from electrolysis, and carbon capture and storage (CCS). On the other hand, for the 2°C scenarios, which allow for reaching national net zero emissions approximately 1–1.5 decades beyond the 1.5°C timeline, ambition has been characterized by the achievement of high levels of current policies but low uptake of the abovementioned advanced technologies. This includes RE in the power sector, energy efficiency in the industry sector, and fuel efficiency and some level of EVs in the transport sector. Further, within the three budget approaches, the PCC approach is several times more stringent than those of FI and ECPC. As a result, the 2°C PCC budget scenario is more ambitious than the 1.5°C FI and 1.5°C ECPC budgets in terms of their budget values. Thus, an exception is made for the 2°C PCC scenario in terms of the distinction between the narratives of the two temperature scenarios discussed above, and more ambitious policies, similar to those in the 1.5°C scenarios, are used to be able to stay within the budget.

A comparison between the reference scenario and policy scenarios that achieve the desired outcomes helps analyze how India's energy mix must change to meet its calculated carbon budget. Given each model's unique overall framework, methodology, and assumptions regarding macroeconomic trends, technology costs, the cost of fuels, speed of implementation, and so on, their policy scenarios are analyzed with respect to their own reference scenario and in the context of the narrative of the varying policy interventions across the six policy scenarios (wherever applicable). This section thus gives an overview of the models' major assumptions, key reference, and low carbon scenario outcomes, and discusses the similarities and difference between them.

It is important to note that the achievement of these targets will be influenced by other external factors not captured within the scope of our national models, such as international trade, the falling global costs of technologies, financial flows, and the impact of the European Union's Carbon Border Adjustment mechanism on Indian industry.

SOCIOECONOMIC INDICATORS

The evolution of India's socioeconomic and demographic profile determines economic development and demand growth in the economy, impacting overall emissions as well as the mitigation efforts required to reduce them. Hence, this section provides a broad overview of the assumptions made by the four models regarding socioeconomic parameters such as the GDP, population, and urbanization.

GDP

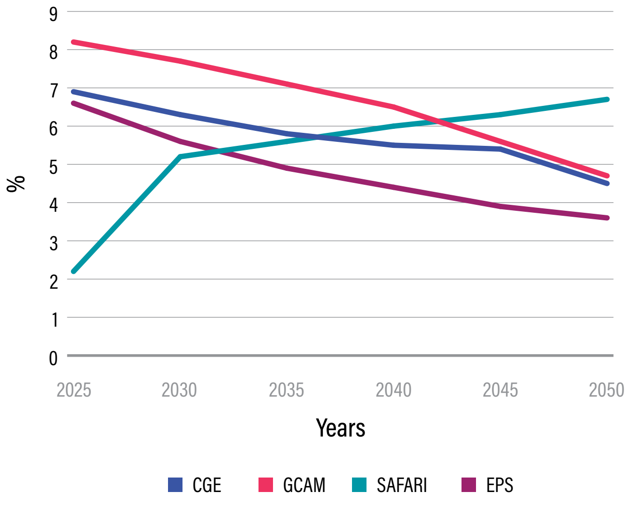
Reference scenario

Except for KPMG's CGE, where the GDP is endogenously calculated, all the models use an exogenous forecast of GDP growth applied to the base year data in their reference scenarios. GCAM assumes a high GDP growth rate in the long term, aligned with the Shared Socioeconomic Pathway 5 (SSP5) (Riahi et al. 2017) scenario, applied to the historical base year data from the Ministry of Statistics and Programme Implementation (MoSPI) (MoSPI n.d.). SAFARI uses the endogenously calculated GDP trajectory taken from its own soft-linked CGE and unlike the other models yields continued rising growth up to 2050 due to sustained investments in the future. The EPS takes BAU GDP projections from the Organisation for Economic Co-operation and Development (OECD) up to 2050 (OECD 2018). These projections are not used to build the BAU demand trajectory (which is taken from IESS v2.0) but are used in the fully integrated IO model to estimate the impact of the chosen policy package on the GDP relative to the BAU scenario based on the cash flows of the various actors in the economy (Swamy et al. 2021). GDP growth rates for future years thus vary significantly across models. GDP growth rates for the four models have been plotted in Figure 3 at 5-year time steps. Assumptions regarding the impact of COVID-19 on the GDP are given in Appendix B.

Carbon budget scenarios

In CGE, the GDP is endogenously determined in the model based on the overall consumption, investment, expenditure, exports, and imports in the economy. Thus, the GDP changes with the rate of implementation of various policies and hence is different in every scenario. The GDP growth rate is highest in the reference scenario and decreases in the policy scenarios, as the policies are made more aggressive (see Figure 4). This is because of the way CGE treats the shrinking of fossil fuel sectors (coal, petroleum, thermal power, etc.).

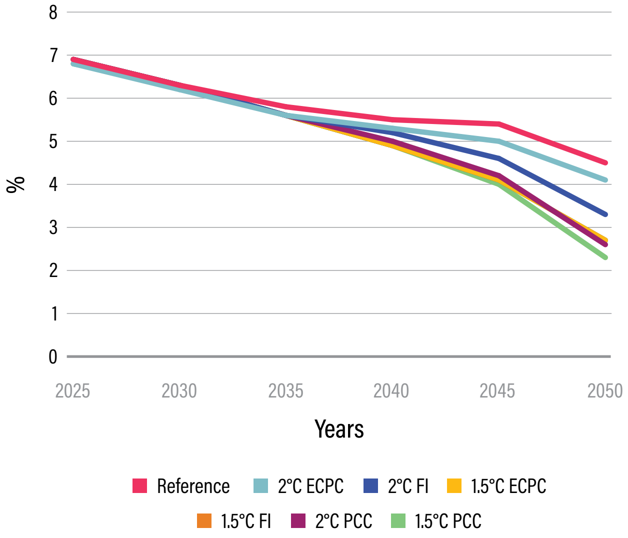
FIGURE 3 | Reference scenario: Five-year GDP growth rate (%) across models



Notes: Model: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator. Scenarios: GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. GDP = gross domestic product.

Source: Authors.

FIGURE 4 | CGE: Five-year GDP growth rate (%) across scenarios



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

Source: Authors.

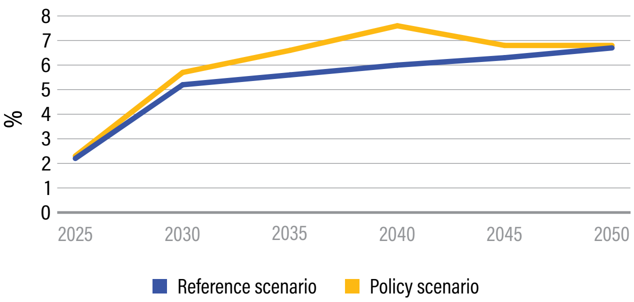
As the fossil fuel sectors decline over time, the model captures not only the direct impacts from the loss in income/employment (and thus consumption) in these sectors, but also indirect impacts in their supply chains and induced impacts through production linkages (ripple effects across the economy from lower private consumption and lower public expenditure from the lost tax revenues). As a result, private consumption in the CGE model falls from a compound annual growth rate (CAGR) of 5 percent between 2020 and 2050 in the reference scenario to 2.4 percent in 1.5°C PCC, which in turn impacts the GDP. A part of this negative impact can be alleviated by the income and consumption from the new jobs created in the new RE sectors. However, the model assumes that RE technology is more advanced and energy efficient and therefore less labor intensive than the fossil fuel industry.[7] In CGE, new investments in RE crowd out investments in other fossil fuel sectors, and these new RE investments are mostly funded from disinvestments (retirements) in fossil-fuel-based assets. Hence, a very small fraction of the investments in the policy scenarios are additional to those in the BAU scenario, because of which the investment (from RE) flowing into the economy is not able to compensate for the loss in GDP due to falling private consumption.

To mitigate these impacts, there is a clear and urgent need to ensure a just transition in India's fossil fuel industries to re-employ those who lose their jobs in the transition. Up to now, RE power plants have been located in different locations than the coal sector, and new jobs created for impacted workers in either the RE or other sectors would require reskilling as well as social protection in the intermediate term (Roy et al. 2019). This will require carbon finance (from different sources, including international grants) and planning regarding how to use it to support the development of new alternative local sectors to employ the impacted communities, retrain people accordingly, compensate them for any transitionary losses in income, and so on. Additional financial flows into the economy will also be needed to boost the GDP and growth.

In GCAM, the GDP is an exogenous input for all scenarios. Because the impact of the low carbon shifts on the overall macroeconomy are not captured within GCAM, the GDP series remains the same for the reference and all policy scenarios. It is aligned with the SSP5 (Riahi et al. 2017) scenario, applied to the historical base year data from MoSPI (MoSPI n.d.).

In SAFARI (see Figure 5), it is assumed that overall developmental goals in the policy scenarios would have to be met faster than in the reference scenario, thus requiring higher investments. This rise in investments causes the GDP to rise in the policy scenarios up to 2050 compared with the reference case (unlike in the other models). Because the same set of "goals" is met across all policy scenarios, one GDP growth rate taken from their CGE soft linkage applies to all policy scenarios, at about 6 percent per annum from 2020–50 (as opposed to 5.3 percent per annum from 2020–50 in the reference scenario). This socioeconomic story line converges with the description of middle-income countries in the global Shared Socioeconomic Pathway (SSP2). These narratives are then refined by using different technology and policy levers in the different budget scenarios to examine faster decoupling of energy emission/use and economic growth. The impact of the policy levers on various economic drivers and sectoral consumption in the economy (and thus on the GDP pathway) are not accounted for in the CGE modeling framework due to its one-way linkage with the SAFARI model.

FIGURE 5 | SAFARI: Five-year GDP growth rate (%)

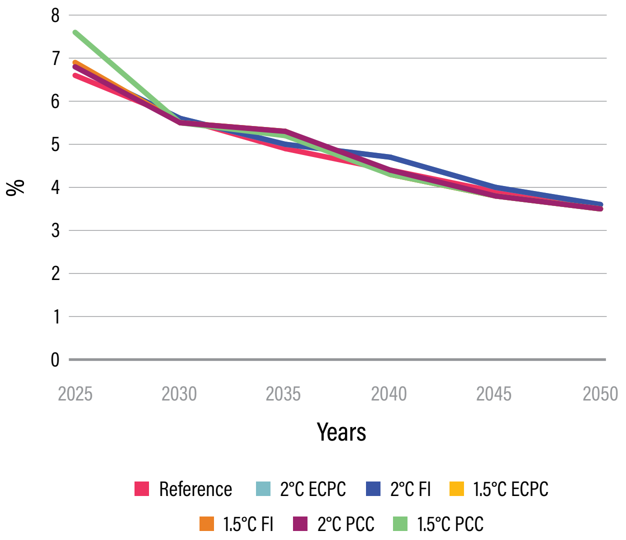


Notes: Models: SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

In the EPS (see Figure 6), the GDP in the reference scenario is exogenous, taken from the OECD (OECD 2018). In the policy scenarios, the model then endogenously calculates the impact of the chosen policy package on the reference GDP, using which the GDP in the policy scenario can be calculated. In the policy scenarios, there are two major reasons, among others, for a negative impact on the GDP. One is the material efficiency policies that reduce the demand for raw materials such as cement and steel. Although this yields savings in material costs, it also contracts the manufacturing sector. This leads to a fall in direct, indirect, and induced jobs, which lowers income and thus consumption, consequently impacting the GDP (similar to the impacts seen in CGE). The other reason is a fall in taxes from the sale of liquid fossil fuels (petrol and diesel), which currently constitute a significant source of government revenue. A shift away from fossil fuels significantly reduces the government's cash inflows, which in turn reduces public expenditure (a part of which would have been spent on job-creating areas such as public infrastructure, which would then have induced effects on income, consumption, and thus on the GDP). However, the modelers observed that the fall in government fuel taxes can be offset through a carbon tax (discussed in detail in the later section titled "Socioeconomic impacts and other unique outcomes of the models") (if other components of government revenue remain constant), thus alleviating the negative impacts on job and GDP growth. Moreover, the EPS also shows that some high-investment policies such as hydrogen significantly boost jobs and GDP growth. As a result of these measures, the GDP growth rate in the policy scenarios is approximately the same as that in the reference scenario, indicating that low carbon pathways do not adversely impact the GDP growth rate. In fact, absolute GDP in the policy scenarios is higher than that in the reference scenario, as discussed in detail in the later section titled "Socioeconomic impacts and other unique outcomes of the models."

FIGURE 6 | EPS: Five-year GDP growth rate (%)



Notes: Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

Source: Authors.

Takeaways for policy

Putting all the four models together, it can be observed that although a shift away from fossil fuels may negatively impact the GDP (as seen in CGE and the EPS), additional investments in infrastructure sectors (renewables, construction of low-energy-consuming buildings, etc.) can alleviate these negative impacts (as seen in SAFARI and the EPS). Further, a carbon tax (as seen in the EPS) can also help create public revenue (while simultaneously incentivizing operations away from fossil fuels), which can then be reinvested by the government in low carbon technologies that are currently in a nascent stage of development and therefore not cost-competitive in the free market (as seen with green hydrogen in the EPS), which will in turn boost the GDP and compensate for the loss in tax revenue due to a shift away from fossil fuels. Finally, a large-scale plan for reskilling and ensuring a just transition will be necessary to ensure that job losses in the fossil fuel sectors do not lead to an overall fall in private income (as seen in CGE).

Population

Population is an exogenous input to all four models. CGE and GCAM consider the population projection from UN DESA's World Population Prospect 2019 (United Nations, Department of Economic and Social Affairs, Population Division 2019a), which takes a CAGR of 0.6 percent between 2018 and 2050, reaching 1.64 billion in 2050. SAFARI considers the UN DESA's World Population Prospects 2017 (United Nations, Department of Economic and Social Affairs, Population Division 2017), reaching 1.66 billion in 2050. In the EPS, because the demand trajectories are taken from the IESS level 2 High Growth trajectory, population is an implicit and not explicit driver of demand. However, to estimate macroeconomic changes in its I-O model, the EPS uses the World Bank's population projections (World Bank n.d.-a), which also reaches 1.66 billion in 2050. These assumptions do not change in the carbon budget scenarios.

Urbanization

Urbanization is an important driver for India as it is closely linked to overall economic growth and energy consumption patterns. In CGE, urbanization is indirectly captured through higher future investments in the services/commercial building sector. GCAM and SAFARI align their future urbanization projections with UN DESA's "World Urbanisation Prospect" (United Nations, Department of Economic and Social Affairs, Population Division 2019b). In the EPS, demand growth in the buildings sector implicitly drives the urbanization rate and is taken from the IESS level 2 High Growth trajectory (NITI Aayog 2015). In GCAM, SAFARI, and the EPS, urbanization is assumed to grow from about 35 percent in 2020 to 51 percent in 2050. These assumptions do not change in the carbon budget scenarios.

Assumptions regarding other drivers are given in Appendix B.

ECONOMY-WIDE EMISSIONS

This section discusses metrics important to India's emissions such as emissions intensity, notably with respect to 2005, which is the base year chosen in India's NDC submitted to the UNFCCC, and per capita emissions, as well as metrics important to this study such as the distribution of emissions across sectors.

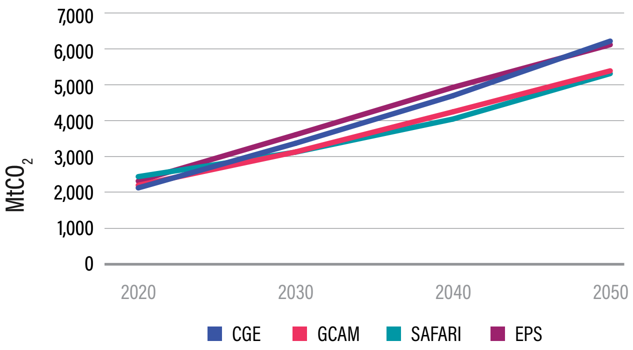
Annual and cumulative emissions

Reference scenario

As India is a developing economy, energy consumption will continue to grow rapidly up to 2050, which would correspondingly increase emissions. However, given India's commitments in its NDC submitted to the UNFCCC, along with efforts in all key sectors toward energy efficiency, electrification, and exploring clean fuels such as RE and green hydrogen, India is already on the path to some emissions reduction. Yet, India's economy-wide annual emissions do not peak in either model's reference scenario until 2050, as seen in Figure 7, which presents the annual emissions in the four models' reference scenario.

As a result, India's cumulative emissions from 2020 to 2100 per current trends will exceed its share of the global carbon budget according to three of the four approaches calculated above, GDR being the exception. Table 10 summarizes the cumulative emissions in each decade in the four models.

FIGURE 7 | Annual emissions (2020–2050) in the reference scenario from the four models



Notes: Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

Source: Authors.

TABLE 10 | Reference scenario cumulative emissions ($GtCO_2$)

MODELS	2020–2030	2020–2040	2020–2050
CGE	30.8	71.7	127.3
GCAM	28.8	65.6	113.8
SAFARI	29.5	66.0	113.1
EPS	33.5	76.9	132.8

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

Carbon budget scenarios

The cumulative emissions of each scenario from 2020 to 2050 according to each model is predetermined by the calculated carbon budgets for India as discussed above (keeping in mind that CGE, SAFARI, and EPS exceed the 1.5°C PCC budget at the maximum model capacity and would need CDR (nature-based or technological) to sequester the excess emissions). Table 11 gives a snapshot of the cumulative emissions of the four models in the reference and six carbon budget scenarios from 2020 to 2050 and how the budgets are consumed by the power, transport, and industry sectors.

It can be observed that by 2050, 1.5°C PCC is overconsumed in three models; 50–75 percent of 2°C PCC is consumed; 30–40 percent of the two 1.5°C scenarios (FI and ECPC) is consumed (thus approximately aligning with net zero in 2070, which is further discussed in the section below titled "Net zero emissions in 2070"); and 25–35 percent of the 2°C scenarios (FI and ECPC) is consumed across the four models. If India underconsumes its fair share of the global carbon budget, its climate ambition must be supported by international finance and technology, not only for mitigation but also to ensure that development priorities are not lost sight of in the trade-off, the low carbon transition does not negatively impact the livelihoods of people employed in current fossil fuel industries, and the loss and damage due to the impacts of the climate change that has already occurred are fairly compensated.

Emissions intensity of GDP

India's unconditional target in its NDC to the UNFCCC under the Paris Agreement, per its update in 2022, is to reduce its emissions (CO_2e) intensity of GDP by 45 percent by 2030 from 2005 levels (Government of India 2022) and per the third Biennial Update Report (2021), the emissions intensity of GDP in India fell by 24 percent in 2016 relative to 2005 levels (MoEFCC 2021). With the caveat that this study only looks at CO_2 emissions, an assessment of India's CO_2 emissions intensity of GDP using our models can help understand how it needs to evolve over time to remain compatible with the chosen carbon budgets.

We find that the 45-percent-reduction NDC target is higher than the reference scenario levels in three models (GCAM being the exception), and so enhanced policy support would be needed to meet it. Further, to comply with the calculated carbon budgets, India's CO_2 emissions intensity of GDP in 2030 should be 51–56 percent per CGE, 55 percent per GCAM, 39–41 percent per

TABLE 11 | Share of carbon budgets consumed by the four models up to 2050 and their split across sectors

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	CARBON BUDGET VALUE, 2020-2100 (GTCO$_2$)	CUMULATIVE EMISSIONS, 2020-2050 (GTCO$_2$)	SHARE OF POWER SECTOR (%)	SHARE OF INDUSTRY SECTOR (%)	SHARE OF TRANSPORT (%)
Reference		127, 116, 113, 133	40, 52, 39, 27	23, 34, 37, 51	21, 14, 22, 19
2°C ECPC	408	103, 111, 99, 104	40, 52, 34, 20	24, 34, 41, 50	20, 14, 23, 21
2°C FI	327	99, 110, 96, 101	44, 52, 35, 19	22, 34, 40, 50	20, 14, 22, 21
1.5°C ECPC	289	91, 94, 96, 84	47, 49, 36, 14	23, 35, 40, 51	18, 16, 21, 22
1.5°C FI	226	86, 91, 92, 81	44, 48, 37, 13	24, 35, 39, 51	19, 17, 22, 22
2°C PCC	132	81, 97, 92, 70	45, 49, 36, 11	25, 36, 40, 52	17, 16, 21, 22
1.5°C PCC	46	72, 39, 88, 60	39, 34, 36, 9	28, 45, 41, 52	19, 21, 21, 21

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GtCO$_2$ = gigatonnes of CO$_2$.

Source: Authors.

SAFARI, and 39–49 percent in the EPS across all scenarios except 1.5°C PCC.[8] By 2050, this reduction in CO_2 emissions intensity of GDP with respect to 2005 levels must rise to 69–84 percent according to CGE, 78–100 percent according to GCAM, 82–87 percent according to SAFARI, and 72–91 percent according to the EPS (for reduction levels aligning with specific budget scenarios, see Table 12).

In CGE, reductions in all scenarios are the highest among the four models in the early years as low-hanging fruit such as energy efficiency are achieved, but toward 2050, they become the lowest due to technological barriers in the industry and transport sectors. Conversely, in SAFARI, reductions are lowest in the early years but rise significantly after 2030 as decarbonization picks up pace.

Per capita emissions

In 2018, India's annual per capita emissions were 1.8 megatonnes of carbon dioxide ($MtCO_2$). In comparison, the world average was 4.2 $MtCO_2$, the United States' was 15.2 $MtCO_2$, Russia's 11.5 $MtCO_2$, China's 7.4 $MtCO_2$, South Africa's 7.5 $MtCO_2$, Brazil's 2.1 $MtCO_2$, and Indonesia's 2.2 $MtCO_2$ (World Bank n.d.-b). As India develops over the coming decades, increasing infrastructure, urbanization, and demand-induced power and material consumption will cause the country's energy demand to grow. In the reference scenario, all models project per capita emissions to rise to 3.2–3.8 $MtCO_2$ up to 2050. Although this is considerably lower than not only most developed countries in the world even today, but also the world average, India's per capita emissions do grow 1.8–2.4 times from 2020 to 2050 across the four models.

In the context of per capita emissions, the PCC and ECPC approaches to calculating India's carbon budgets are especially relevant as they consider equity in terms of per capita emissions among all countries while allocating the global carbon budget among different countries, including to India, as done in this study.

In PCC, the budget is allocated such that all countries' current per capita emissions converge to a common point by a predefined year. The budgets in both temperature scenarios are stringent and so require per capita emissions to peak between 2030 and 2040 and decline thereafter to reach net zero emissions around 2050. In ECPC, the budget is allocated such that the cumulative per capita emissions over a certain period are equal for all countries, and as a result, India's share of the global carbon budget is much higher. However, to comply with the 1.5°C ECPC budget, per capita emissions in all the models also need to peak by 2040 and begin to decline thereafter (see Table 13).

TABLE 12 | Percentage reduction in CO_2 emissions intensity in milestone years with respect to 2005

	CGE			GCAM			SAFARI			EPS		
Scenario	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Reference	−40	−52	−61	−55	−68	−76	−37	−54	−68	−32	−41	−49
2°C ECPC	−51	−60	−69	−55	−68	−78	−39	−66	−82	−39	−55	−72
2°C FI	−52	−62	−70	−55	−68	−79	−38	−67	−83	−40	−57	−75
1.5°C ECPC	−53	−65	−74	−55	−73	−84	−39	−68	−83	−44	−67	−83
1.5°C FI	−53	−66	−79	−55	−74	−86	−40	−69	−84	−45	−69	−84
2°C PCC	−56	−68	−83	−55	−68	−90	−41	−68	−85	−49	−76	−89
1.5°C PCC	−59	−73	−84	−79	−97	−100	−39	−70	−87	−60	−80	−91

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $GtCO_2$ = gigatonnes of CO_2.

Source: Authors.

TABLE 13 | Per capita emissions ($MtCO_2$/million population)

	CGE			GCAM			SAFARI			EPS		
Scenario	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Reference	2.3	3.0	3.8	2.1	2.7	3.3	2.1	2.5	3.2	2.4	3.1	3.7
2°C ECPC	1.8	2.4	2.9	2.1	2.7	3.0	2.1	2.2	2.2	2.1	2.4	2.0
2°C FI	1.8	2.3	2.6	2.1	2.7	2.9	2.1	2.1	2.0	2.1	2.3	1.8
1.5°C ECPC	1.8	2.1	2.1	2.1	2.3	2.2	2.1	2.1	2.0	2.0	1.7	1.3
1.5°C FI	1.8	2.0	1.7	2.1	2.2	1.9	2.0	2.0	1.9	1.9	1.7	1.2
2°C PCC	1.7	1.9	1.4	2.1	2.7	1.3	2.0	2.0	1.8	1.8	1.3	0.8
1.5°C PCC	1.6	1.6	1.3	1.0	0.2	—	2.1	1.9	1.5	1.5	1.1	0.7

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

Peaking years of emissions

A brief analysis of the distribution of the pre- and post-2050 carbon budgets showed that a very small fraction of the budget would be left over for consumption after 2050. Thus, although emissions do not peak by 2050 in the reference scenario of any model, they must do so in all policy scenarios with a decline in emissions thereafter to be able to reach net zero in the near decades after 2050 and comply with their corresponding carbon budgets. However, the timeline for peaking is different across scenarios, depending on the size of the carbon budget; that is, the larger the budget, the greater the likelihood of delaying peaking (and net zero) and vice versa.

In CGE, peaking occurs later than in the other models because of lower levels of electrification in industry and transport due to technological constraints. In GCAM, the peak years were chosen in line with the temperature scenario such that the 1.5°C scenarios peak by 2035 and 2°C scenarios peak by 2045. The only exception is 1.5°C PCC, which would need to peak immediately, by 2025, to stay within its budget and reach net zero by 2050. On the other hand, in the EPS, the peak years were chosen based on the size of the carbon budget, because of which the peak year of each carbon budget is advanced by approximately five years as it becomes more stringent, ranging from 2045–50 in 2°C ECPC to 2020–2025 in 1.5°C PCC. In SAFARI, a combination of the two approaches was used: all three 2°C scenarios peak between 2035 and 2045, but 1.5°C ECPC also peaks in this time frame, given the similarity of its budget size with that of 2°C FI. The remaining scenarios (1.5°C FI and PCC) peak earlier, between 2031 and 2035. Table 14 summarizes the peak years of the four models in all the scenarios.

TABLE 14 | Peaking years across the scenarios in the four models

	2020-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Reference	n/a	n/a	n/a	n/a	n/a	n/a
2°C ECPC	n/a	n/a	n/a	n/a	GCAM SAFARI	CGE EPS
2°C FI	n/a	n/a	n/a	SAFARI	GCAM EPS	CGE
1.5°C ECPC	n/a	n/a	GCAM	SAFARI EPS	n/a	CGE
1.5°C FI	n/a	n/a	GCAM SAFARI EPS	n/a	CGE	n/a
2°C PCC	n/a	n/a	EPS	GCAM SAFARI	CGE	n/a
1.5°C PCC	GCAM EPS	n/a	SAFARI	CGE	n/a	n/a

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $GtCO_2$ = gigatonnes of CO_2; n/a = not applicable.

Source: Authors.

Net zero emissions in 2070

In the enhanced NDC released in August 2022, India announced a long-term goal of reaching net zero emissions by 2070 (Government of India 2022). Three of our models (CGE, SAFARI, and the EPS) project scenarios only up to 2050. Therefore, to assess the alignment of their carbon budget scenarios with India's 2070 net zero target, we extrapolated their emissions decline (from the peak year to 2050) beyond 2050 to get an estimate of when they would reach net zero. Table 15 summarizes the approximate time span within which the scenarios of each model reach net zero. We do not comment on the exact net zero years, because they are not outputs of the models.

We find that 2°C PCC, 1.5°C FI, and 1.5°C ECPC are aligned with the 2070 net zero target by the greatest number of models. SAFARI is not mentioned in Table 15 because some form of CDR would be needed to reach net zero in any scenario, as would CGE for 1.5°C PCC.

TABLE 15 | Approximate years of net zero emissions of the low carbon scenarios per three models

	NZ BETWEEN 2050 AND 2065			NZ BETWEEN 2065 AND 2075			NZ AFTER 2075		
Reference	No	No	No	No	No	No	No	No	No
2°C ECPC	No	No	No	No	No	No	CGE	GCAM	EPS
2°C FI	No	No	No	No	No	No	CGE	GCAM	EPS
1.5°C ECPC	No	No	No	CGE	No	EPS	No	GCAM	No
1.5°C FI	No	No	No	CGE	No	EPS	No	GCAM	No
2°C PCC	No	No	EPS	CGE	GCAM	No	No	No	No
1.5°C PCC	No	GCAM	EPS	No	No	No	No	No	No

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $GtCO_2$ = gigatonnes of CO_2; n/a = not applicable; NZ = net zero.

Source: Authors.

Sectoral distribution of emissions

Although the models show similar cumulative emissions in the reference scenario, the break-up of their emissions varies considerably by sector. This variation helps predict where the bulk of emissions will come from in the future, which is important for determining short- and medium-term policies.

We find that in the reference scenario, the share of emissions from the power sector (historically the largest source of emissions in India) declines over time in all the four models, although at different rates, driven by the falling technology costs of solar energy and the government policy push over the last decade.

In CGE, the transport and building sectors play a stronger role as their emission shares rise considerably over time due to low-emissions-reduction policies and fast urbanization, making the shares of all the four sectors approximately equal by 2050. In the policy scenarios, the shares of power and buildings fall because higher decarbonization and electrification increase industrial and transport activity.

In GCAM, in the reference scenario, the power sector, although declining, continues to be the highest source of emissions, followed by industry, transport, and buildings, whose shares rise marginally over time. In the low carbon scenarios, by 2050, there is a steep fall in the share of power sector emissions in both PCC scenarios as it becomes the first sector to decarbonize and achieve net zero by mid-century.

In SAFARI and the EPS, industry plays the largest role in India's reference scenario energy emissions profile due to low electrification, the rising demand for energy-intensive manufacturing, and the inclusion of process emissions in their assessment of the sector. In the policy scenarios, in SAFARI, the "no new coal" intervention in the power sector starting from 2025 leads to a fall in the share of power sector emissions by 2030, making industry the highest source of emissions, followed by power, transport, and buildings. In the EPS, the main contributor to emissions is industry in both the reference and policy scenarios, at varying levels. In the low carbon scenarios, transport, which begins to decarbonize after 2040 but does not get decarbonized by 2050, comes next, followed by the power sector, which is initially the highest source of emissions but is largely decarbonized by 2050. Another source of emissions in the EPS is hydrogen (under the category "Other"), which rises significantly in the more stringent policy scenarios due to its increased use as an alternative fuel in the industry sector. A parallel intervention on producing hydrogen using RE for electrolysis then slowly decreases hydrogen emissions in later years.

Figures C-1 to C-4 in Appendix C represent the data on these trends in the four models.

Takeaways for policy

Putting all the four models together, in the low carbon scenarios, the industry sector replaces the power sector as the primary source of emissions, followed by transport (in all the models, although at differing levels). This is because decarbonization of the power sector occurs the first and fastest, in line with current trends, whereas the industry sector remains the hardest to abate, followed by some subsectors of transportation (such as freight trucks and domestic aviation) due to the technological difficulties related to electrification.

> Increased electrification in industry, transport, and buildings would increase electricity demand, which would lead to the construction of additional renewable power plants and solar panels, which would in turn increase the demand for construction materials such as cement, steel, and aluminum, thus increasing demand projections in the industry sector.

KEY SECTORS

The industry sector

India's industrial sector is expected to grow significantly in the coming decades, driven by increasing income, urbanization, and mobility. Although the energy efficiency of India's industry is improving due to policy efforts over the last decade, given industry's high growth rate, its energy use increases in all models up to 2050 in the reference scenario. Growth and energy efficiency assumptions are given in Appendix B.

Currently, India's industry's energy mix is dominated by fossil fuels at approximately 75 percent, and this trend is predicted to continue up to 2050 in the reference scenario. Decarbonizing the industry sector would require higher energy and material efficiency to reduce the overall demand for energy, as well as electrification and the use of alternative green fuels such as green hydrogen to decarbonize the energy that is used.

Note that emissions from energy use in the agriculture sector have been included in the industry category.

CGE

In the reference scenario, CGE assumes no additional electrification beyond historical and current trends, and so coal constitutes about 65 percent of the industry fuel mix.[9] In the low carbon scenarios, CGE assumes that technological changes occur in industry's production function to increase its reliance on electricity for its energy needs. This has been achieved by introducing an exogeneous electricity augmenting parameter, which is gradually increased over time. The level of the electricity augmenting parameter in each policy scenario is chosen such that total economy-wide emissions align with its corresponding carbon budget. The unique assessment of CGE is that as it attempts to achieve full equilibrium in the economy, it causes the demand for industrial production to change endogenously in response to changes in other sectors. For example, increased electrification in industry, transport, and buildings would increase electricity demand, which would lead to the construction of additional renewable power plants and solar panels, which would in turn increase the demand for construction materials such as cement, steel, and aluminum, thus increasing demand projections in the industry sector. In partial equilibrium models, the additional demand for industrial materials from increased power generation is not captured. No additional energy efficiency is assumed in the policy scenarios compared to the reference scenario.

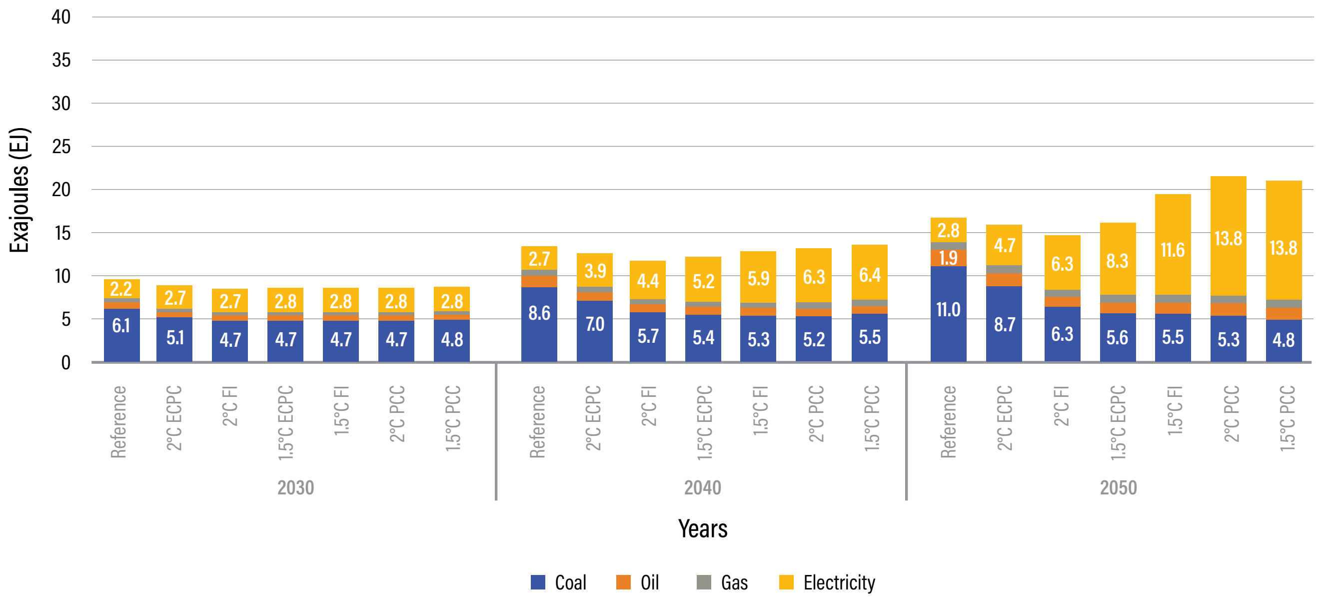
Given the inter-sectoral linkages discussed above, we find that compared to the reference levels, the total industry energy consumption in 2050 falls slightly in the less ambitious scenarios (2°C ECPC, 2°C FI, and 1.5°C ECPC) due to the higher efficiency of electric technologies, but rises in the more ambitious scenarios (1.5°C FI, 2°C PCC, and 1.5°C PCC) because of the overall higher electricity consumption in the economy. This energy demand is increasingly met using electricity instead of coal, reaching 30–33 percent in 2030 in all policy scenarios compared to 22 percent in the reference scenario. Table 16 gives an overview of the key energy trends in the industry sector per CGE across the different scenarios, and Figure 8 gives the data points.

TABLE 16 | CGE: Industry growth rate and share of electricity and coal in the industry fuel mix

CGE	GROWTH RATE: TOTAL INDUSTRY ENERGY CONSUMPTION (2020-2050)	SHARE OF ELECTRICITY (%)			SHARE OF COAL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×3	23	20	17	64	65	66
2°C ECPC	×2.8	30	31	30	57	56	55
2°C FI	×2.6	32	38	43	56	49	43
1.5°C ECPC	×2.8	33	43	52	55	44	35
1.5°C FI	×3.4	33	46	60	55	41	28
2°C PCC	×3.7	33	48	64	55	40	25
1.5°C PCC	×3.7	33	48	66	55	41	23

Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

FIGURE 8 | CGE: Industry fuel mix (EJ)



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

GCAM

Although coal has historically dominated the industry energy mix and does so even currently, in the reference scenario itself its share of the total declines over time, as electrification and gas use are assumed to increase by 2050 as a result of falling costs and lower technological barriers. In the low carbon scenarios, GCAM assumes disruptive transformation in processes to build the capacity required to shift to electrification at the least cost to the economy. Moreover, it assumes that natural gas will play a significant role in India's energy transition debate as the shift in the global gas market lowers gas prices across sectors. GCAM also explores hydrogen as an alternative fuel, but due to its technical and economic constraints, assumes that it may be infeasible to adopt in many industrial applications. Demand for industrial production remains approximately the same in the policy scenarios as in the reference scenario because the drivers of change such as GDP growth, population, and urbanization do not change. No additional energy efficiency is assumed in the policy scenarios compared to the reference scenario.

In GCAM, the total industry energy consumption in the policy scenarios falls slightly compared with that in the reference scenario because electricity is inherently more efficient than coal as a fuel. The fall in industry energy consumption is proportional to the level of electrification. The share of electrification increases over time and across scenarios as the emissions constraint becomes more stringent. Although hydrogen is perceived by many studies to be the cornerstone of industrial decarbonization, given the absence of any major breakthroughs in the technology, its share in industrial energy use is limited to 1 percent by 2050.[10] Table 17 gives an overview of the key energy trends in the industry sector per GCAM across the different scenarios, and Figure 9 gives the data points. The timelines and shares indicate the extent and pace of the disruptive transformation needed to decarbonize the industry sector in alignment with the carbon budgets.

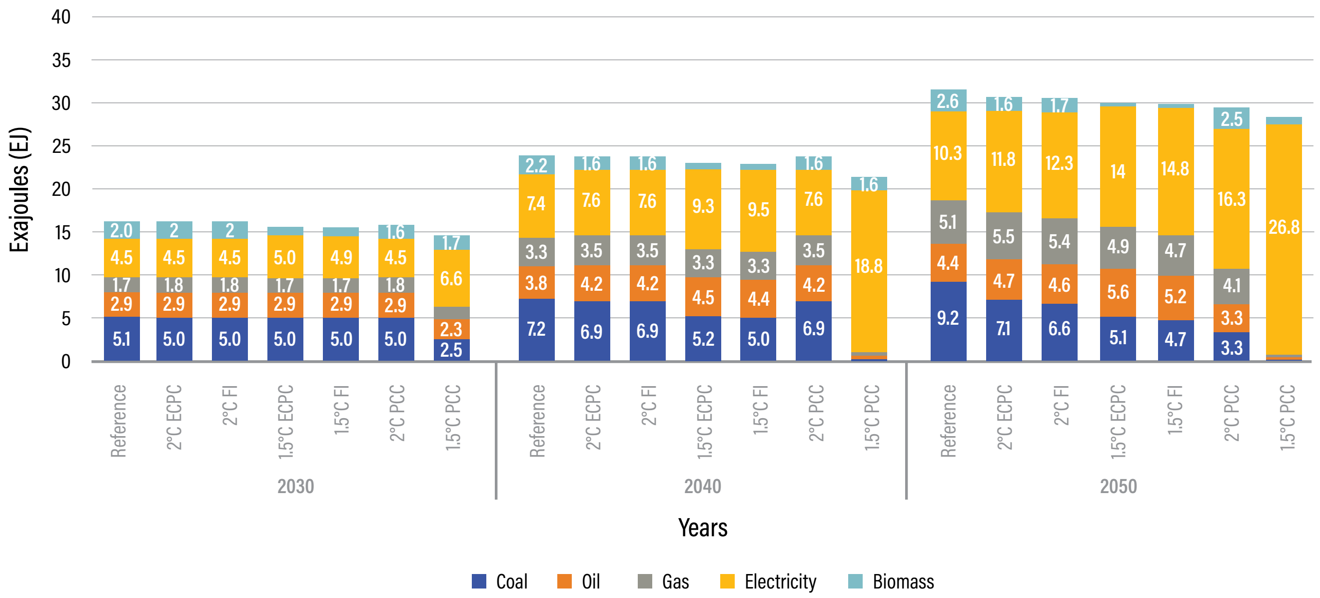
TABLE 17 | GCAM: Industry growth rate and share of electricity and coal in the industry fuel mix

GCAM	GROWTH RATE: TOTAL INDUSTRY ENERGY CONSUMPTION (2020–2050)	SHARE OF ELECTRICITY (%)			SHARE OF COAL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×3.4	28	31	32	32	30	29
2°C ECPC	×3.3	28	32	38	39	32	29
2°C FI	×3.3	28	32	40	32	29	22
1.5°C ECPC	×3.2	32	40	47	32	23	17
1.5°C FI	×3.2	32	41	49	32	22	16
2°C PCC	×3.1	28	32	55	32	29	11
1.5°C PCC	×3	45	88	95	17	1	0

Notes: Models: GCAM = Global Change Analysis Mode. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE 9 | GCAM: Industry fuel mix (EJ)



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

SAFARI

In the reference scenario, SAFARI assumes no additional electrification beyond historical and current trends; therefore, coal constitutes about 80 percent of the industry fuel mix. In the low carbon scenarios, in SAFARI, demand for industrial products such as cement, steel, and fertilizer are determined bottom-up, based on requirements from housing, healthcare, and educational infrastructure, and "food for all," which are the development goals met in the policy scenarios. Of these, cement and steel are the most important subsectors in terms of decarbonizing the industry sector. Common interventions in both subsectors include adoption of the current production best practices in India by 2050 (in terms of percentage improvement of the specific energy consumption (SEC) with respect to the best possible levels), which improves energy efficiency; a shift of electricity consumption from thermal captive power plants to grid electricity; and a shift in the share of production from conventional to less emissions-intensive production practices, such as electrification. Further, two other interventions in the cement sector are demand reduction in the housing sector, especially in middle- and higher-income households, because cement demand is largely driven by the residential sector, and an induced shift away from coal to other fuels such as natural gas and alternative fuels, for example, waste-based fuels. Finally, captive-to-grid and fuel switching interventions are also carried out in the aluminum sector but because the contribution of this industry to industrial emissions is quite small, these measures have a negligible impact on cumulative emissions. The level of stringency of these interventions varies across the policy scenarios, depending on their corresponding carbon budgets.

In SAFARI, industrial energy consumption decreases in the policy scenarios relative to the reference scenario because of the policies on energy efficiency and demand reduction in the cement sector. The extent of the fall is proportional to the stringency of the carbon budget, as the stringency of the policies is set to be proportional to the stringency of the carbon budget. In terms of the fuel mix, because the most impactful interventions are toward more material and energy efficiency, the share of electricity in the total fuel mix stays similar across scenarios over time, although the share of coal declines due to interventions in fuel switching, a switch from captive thermal to grid electricity, and a shift to less emissions-intensive technologies. However, the share of natural gas increases due to technological limitations in switching to alternative green fuels/electric technologies to a large extent. Other fuels such as oil, naphtha, and biomass do not have a big impact on the industry energy mix. Table 18 gives an overview of the key energy trends in the industry sector per SAFARI across the different scenarios, and Figure 10 gives the data points.

EPS

In the EPS, in the reference scenario, fuel use is based on the trend underlying the IESS level 2 trajectory high-growth pathway: coal dominates the industry energy mix at 55 percent in 2050, followed by gas and electricity at

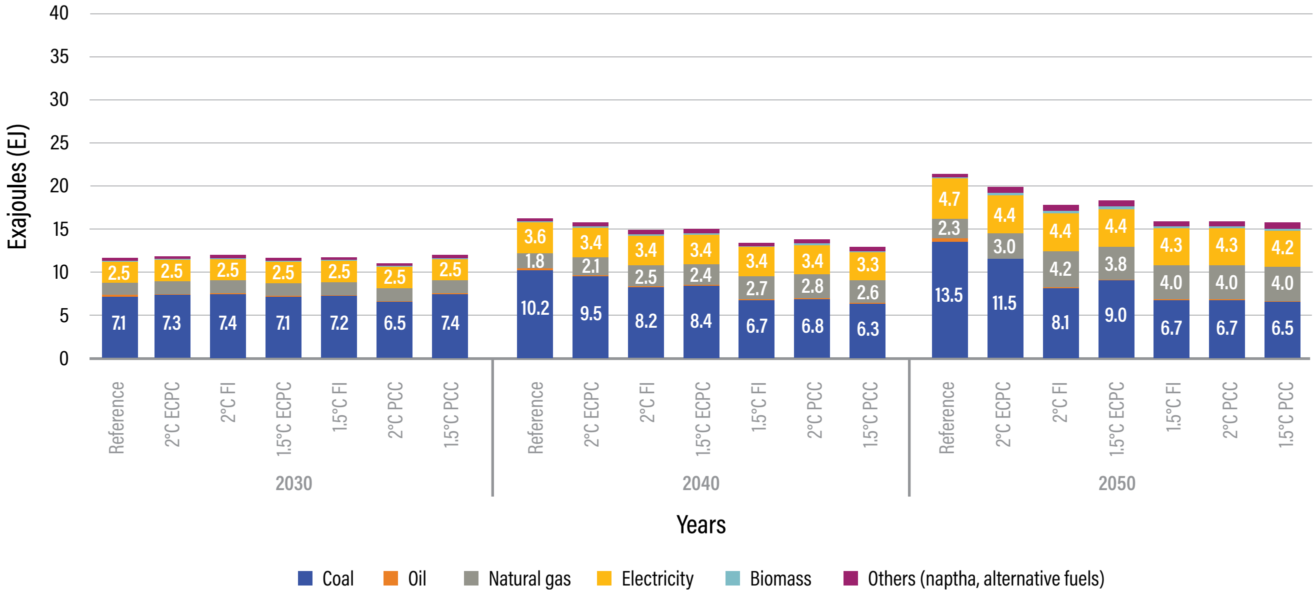
TABLE 18 | SAFARI: Industry growth rate and share of electricity and coal in the industry fuel mix

SAFARI	GROWTH RATE: TOTAL INDUSTRY ENERGY CONSUMPTION (2020–2050)	SHARE OF ELECTRICITY (%)			SHARE OF COAL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×2.5	22	22	22	62	63	63
2°C ECPC	×2.3	21	22	22	61	60	58
2°C FI	×2.1	21	23	24	61	55	45
1.5°C ECPC	×2.1	22	23	24	61	56	50
1.5°C FI	×1.9	21	25	27	61	50	42
2°C PCC	×2	22	25	27	59	49	42
1.5°C PCC	×1.9	21	25	27	61	48	41

Notes: Models: SAFARI = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE 10 | SAFARI: Industry fuel mix (EJ)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

about 24 percent and about 15 percent, respectively. Two sets of policy levers have been employed in the policy scenarios, the first relating to material and energy efficiency and the second relating to technologies for deep decarbonization. Energy efficiency policies have been set such that high shares of the maximum potential are met from 2020 to 2050, while material efficiency in cement and steel that impact the demand for these materials is limited to moderate-to-low levels because of their negative impact on jobs and the GDP. Further, to achieve deep decarbonization of the industry sector, electrification and the use of hydrogen as an alternative to fossil fuels (backed by another intervention, electrolysis-generated hydrogen) play the primary role. However, because this technology is currently in a nascent stage of development, it has been employed to a large extent only in the ambitious scenarios (both PCC scenarios), a moderate level in the 1.5°C FI and 1.5°C ECPC scenarios, and low levels in the 2°C FI and 2°C ECPC scenarios.

As in SAFARI, energy consumption in the EPS falls in the policy scenarios over time and across scenarios (in order of increasing stringency) relative to the reference scenario because of material efficiency and energy efficiency, and the latter is applied as follows: a 40 percent reduction in energy use[11] in the two PCC scenarios, 30 percent in the other two 1.5°C scenarios, and 20 percent in the other two 2°C scenarios. In terms of the fuel mix, the Hydrogen + Electrification policy is the main driver, which is switched on after 2030 (given its current nascent stage of development), and that is when the shares of hydrogen and electricity start rising and the share of coal starts falling in the industry energy mix. The share of oil stays constant at 5 percent across all scenarios in 2050, but the share of gas (natural gas, LPG, propane, and butane) falls slightly. Table 19 gives an overview of the key energy trends in the industry sector per the EPS across the different scenarios, and Figure 11 gives the data points.

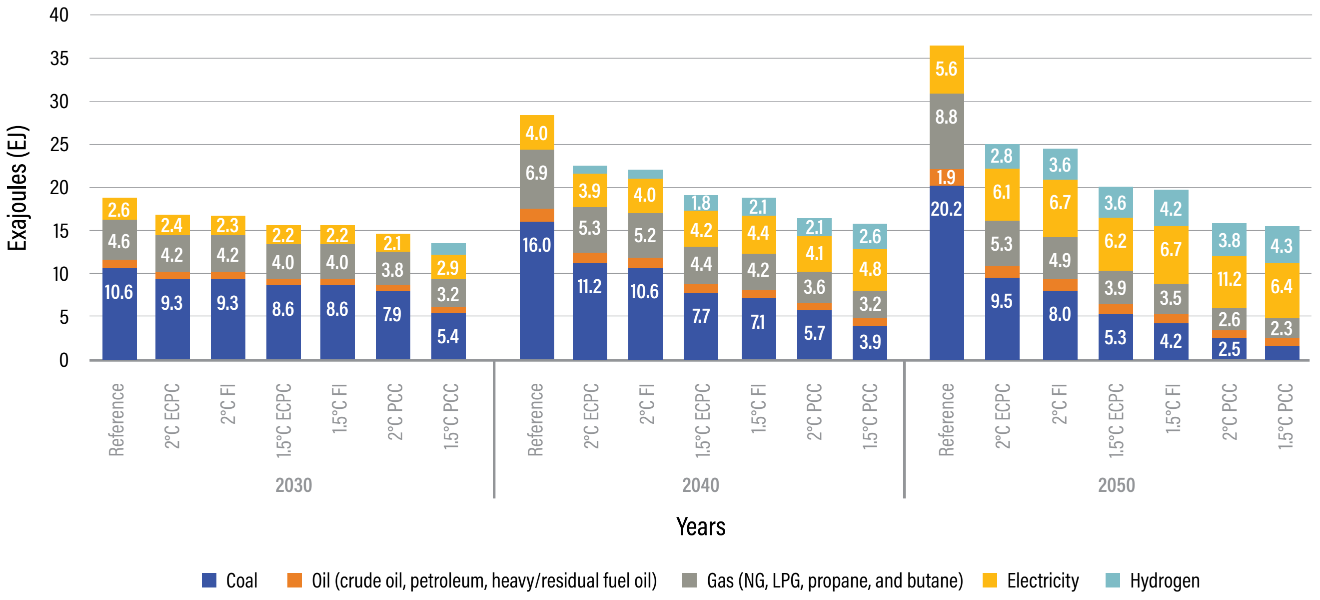
TABLE 19 | EPS: Industry growth rate and share of electricity and coal in the industry fuel mix

EPS	GROWTH RATE: TOTAL INDUSTRY ENERGY CONSUMPTION (2020–2050)	SHARE OF ELECTRICITY (%)			SHARE OF COAL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×3.3	14	14	15	56	56	55
2°C ECPC	×2.3	14	17	24	56	50	38
2°C FI	×2.3	14	18	27	56	48	33
1.5°C ECPC	×1.8	14	22	31	55	41	26
1.5°C FI	×1.8	14	23	34	55	38	21
2°C PCC	×1.4	14	25	38	54	35	16
1.5°C PCC	×1.4	22	30	41	40	25	10

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE 11 | EPS: Industry fuel mix (EJ)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

Takeaways for policy

Putting all the four models together, industry is the hardest sector to abate, because limited low carbon options are available now. In the short-to-medium term, improving energy and material efficiency and reducing cement demand through better urban design can significantly impact energy and emissions, as seen in SAFARI and the EPS. It may also be possible to immediately electrify some industrial processes, for example, by shifting from the emissions-intensive coal-based basic oxygen furnace to electric furnaces in steelmaking. Electric furnaces accounted for 54 percent of India's steel production in 2017–18 (Ministry of Steel n.d.-b). Meanwhile, policy and private sector support for R&D on electrification and alternative green fuels such as green hydrogen must increase so that in the medium to long term, as current machines begin to reach their end of life, the new capacities added will be low carbon. This is especially important because, first, the consumption of gas as a transitional fuel may increase in intermediate years as seen in GCAM and SAFARI, which would either jeopardize India's long-term net zero goals or run the risk of stranded assets. Second, as seen in CGE, in the medium to long term, higher levels of electrification and thus electricity demand from across the economy will further boost the growth of energy-intensive industrial sectors such as cement, steel, and

> Putting all the four models together, industry is the hardest sector to abate, because limited low carbon options are available now. In the short-to-medium term, improving energy and material efficiency and reducing cement demand through better urban design can significantly impact energy and emissions.

aluminum. CCS may also be needed to sequester emissions that cannot be abated until the long term, such as process emissions. Table 20 summarizes the four models' outputs in each scenario for the shares of electricity that should be reached in industry in 2030, 2040, and 2050 to align with their corresponding carbon budgets.

Industry sector emissions

Industry is one of the most economically crucial and hard-to-mitigate sectors of the Indian economy. According to the four models, direct emissions from industry grow 2.4–3.3 times from 2020–50 in the reference scenario, which is almost the same as the energy consumption growth rates discussed above, proving that decoupling of industry sector growth from emissions does not occur in the reference scenario. Only in GCAM is the growth in emissions lower than the growth in energy consumption, as a result of the comparatively higher level of electrification assumed in the reference scenario. However, it is important to note that electrification of heating processes would increase the quantity of energy used compared to coal/gas because it is not as efficient. There is thus a need to focus efforts on low carbon solutions for industry, if the more ambitious climate goals are to be achieved.

In the low carbon scenarios, in CGE and SAFARI, industry sector emissions do not peak in any policy scenario by 2050, although their growth rates decline compared to that of the reference scenario. However, the absolute industry emissions of their policy scenarios are the lowest among all the four models: about 700–1,200 $MtCO_2$ in 2050 (Figure 12) in CGE and 1,400–1,700 $MtCO_2$ in 2050 (Figure 14) in SAFARI. In GCAM (Figure 13), industry emissions in 1.5°C PCC peak by 2030 and in 2°C PCC by 2040, for both scenarios to be able to reach net zero by 2050. The rise in 1.5°C emissions after 2040 is not from industries but from the refinery sector, because greater quantities of biomass need to be refined in the stringent policy scenarios close to mid-century. The 2°C policy scenarios do not peak by 2050, although they decline compared to the reference scenario and grow at a lower rate. In the EPS (Figure 15), industry emissions in all policy scenarios except for 2°C ECPC are made to peak by 2040 for economy-wide emissions to reach net zero in the decades beyond 2050. This is done by introducing a correspondingly appropriate level of green hydrogen penetration. However, absolute industry emissions in the EPS are the highest among the four models, with non-PCC scenario industry emissions ranging between 1,330 and 2,400 $MtCO_2$ in 2050.

TABLE 20 | Industry sector: Percentage of electricity in fuel mix

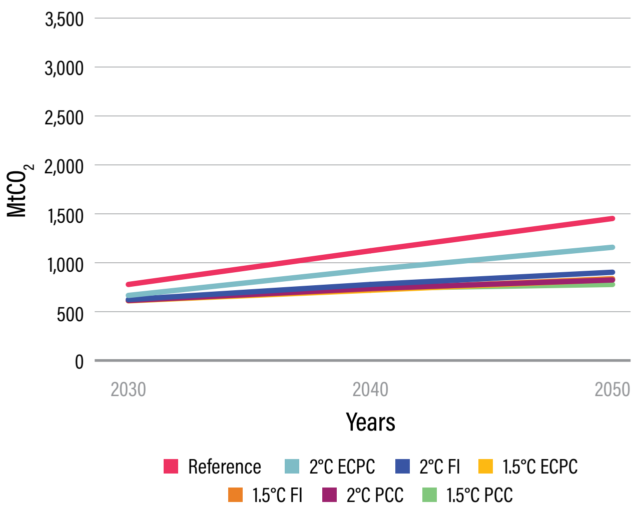
🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	14.45	23, 28, 22, 14	20, 31, 22, 14	17, 32, 22, 15
2°C ECPC		30, 29, 21, 14	31, 32, 22, 17	30, 36, 22, 24
2°C FI		32, 29, 21, 14	38, 32, 23, 18	43, 38, 24, 27
1.5°C ECPC		33, 34, 22, 14	43, 41, 23, 22	52, 47, 24, 31
1.5°C FI		33, 34, 22, 14	46, 42, 25, 23	60, 49, 27, 34
2°C PCC		33, 29, 22, 14	48, 32, 25, 25	64, 64, 27, 38
1.5°C PCC		33, 54, 21, 22	48, 92, 25, 30	66, 95, 27, 41

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Sources: Authors; a. (MoSPI 2022).

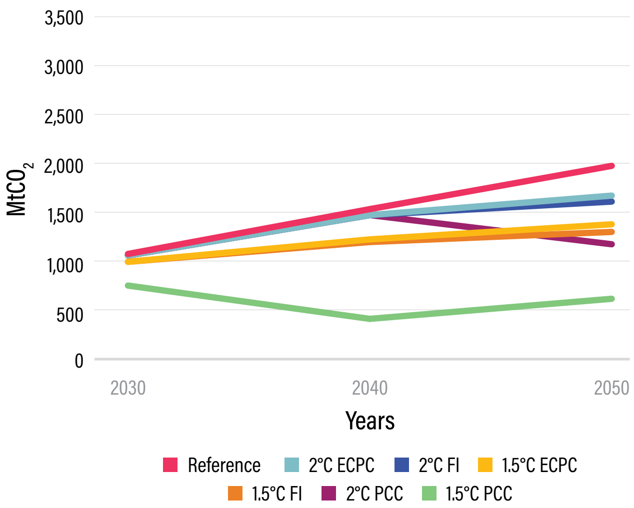
FIGURE 12 | CGE: Industry sector emissions across scenarios ($MtCO_2$)



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

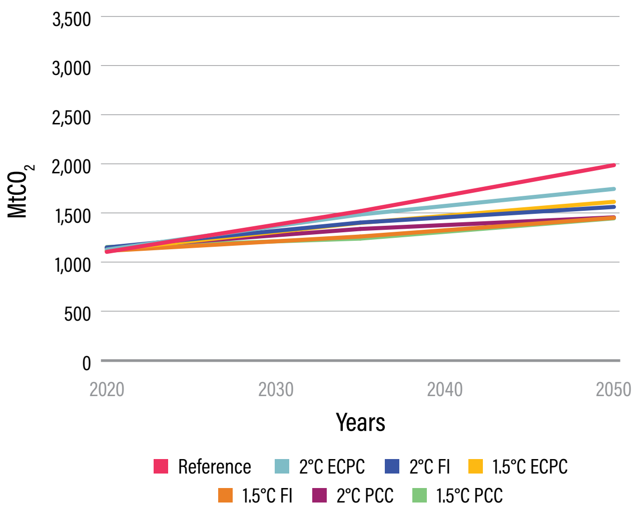
FIGURE 13 | GCAM: Industry sector emissions across scenarios ($MtCO_2$)



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

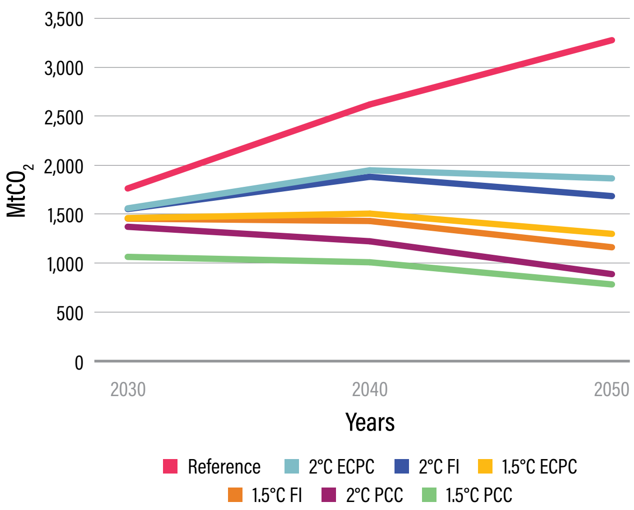
FIGURE 14 | SAFARI: Industry sector emissions across scenarios ($MtCO_2$)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

FIGURE 15 | EPS: Industry sector emissions across scenarios ($MtCO_2$)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

Note that apart from emissions due to industry and agriculture energy use, CGE and GCAM include emissions from refinery but not process emissions. SAFARI and the EPS include process but not refinery emissions.

The transport sector

As India develops, growing income, consumption, economic activity, and improved access to transport infrastructure will stimulate a greater need for motorized mobility. Similarly, with growth in industrial activity, the demand for the movement of materials and goods will also increase. This will lead to massive growth in the use of passenger, freight, private, and air transportation. The assumptions underlying the growth of transport demand in the four models are given in Appendix B.

The most important mitigation option in the transport sector is electrification, followed by using alternative fuels such as hydrogen or biofuels in heavy vehicles, aviation, and maritime vessels. In India, the NEMMP lays out the policy framework for EV development, and each state has its own EV targets and policies. Each of the four models employed in this study models the transformation of the transport sector uniquely.

CGE

In the reference scenario, because CGE follows historical trends, there is negligible penetration of EVs in the reference case. As a result, the share of oil dominates the transport energy mix at about 98 percent up to 2050. In the low carbon scenarios, CGE assumes technological changes in land transport's production function to improve its utilization of electricity for its energy needs. This has been achieved by introducing an exogeneous electricity augmenting parameter, which is gradually increased over time to create the policy scenarios. As the model strives to achieve full equilibrium, it also captures the negative impacts of the fall in household income (caused by the decline in the fossil fuel industry, as discussed in the subsection titled "GDP" in the section titled "Socioeconomic indicators" earlier in this section) on the transport sector. We find that the fall in income shifts their choice of transport from private to public and other cheaper modes of transport. This reduces the total energy consumption of the transport sector, as seen in Table 21. A small share of the fall can also be attributed to the inherently higher energy efficiency of EVs than that of ICEVs. Further, a conservative level of EV penetration is assumed in the policy scenarios (rising marginally with the carbon stringency of the scenarios) because of their current nascent stage of penetration and uncertainty regarding the complete phase-out of conventional ICEVs and development of charging infrastructure on the scale required for a complete shift to EVs. As a result, the share of electricity rises over time and across scenarios compared to that in the reference scenario but remains low, as seen in Table 21 and Figure 16.

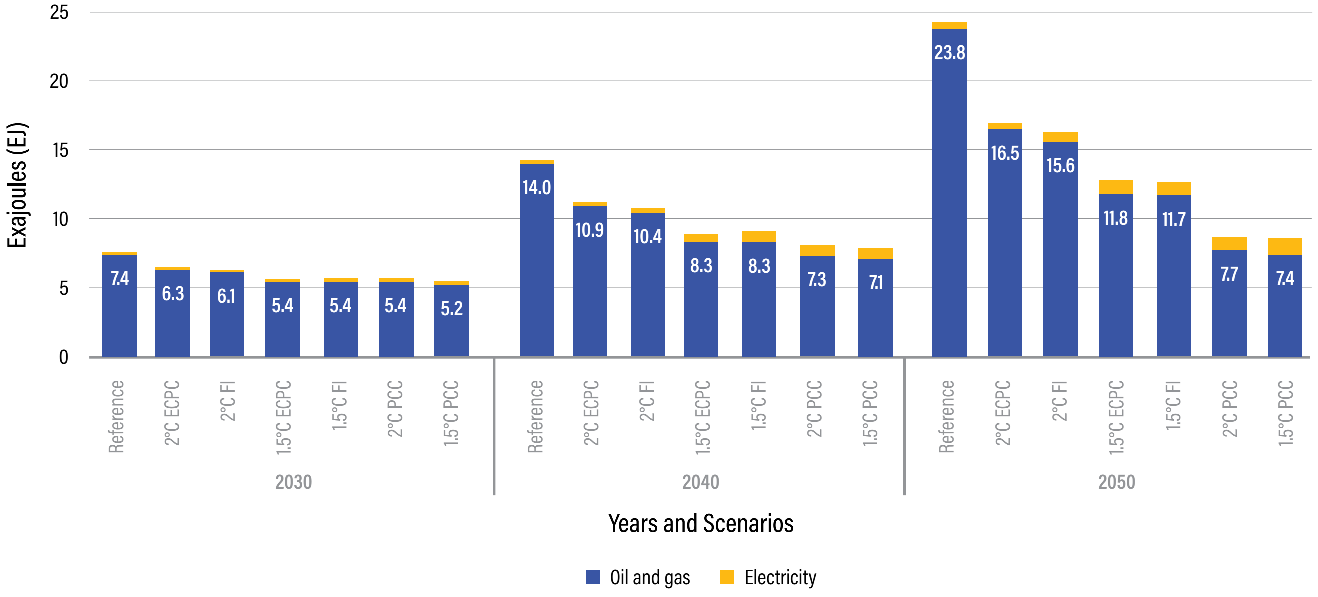
TABLE 21 | CGE: Transport growth rate and share of electricity and O&G in the transport fuel mix

CGE	GROWTH RATE: TOTAL TRANSPORT ENERGY CONSUMPTION (2020–2050)	SHARE OF ELECTRICITY (%)			SHARE OF COAL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×6.6	2	2	2	98	98	98
2°C ECPC	×4.5	2	2	3	98	98	97
2°C FI	×4.4	3	4	4	97	96	96
1.5°C ECPC	×3.4	4	7	7	96	93	93
1.5°C FI	×3.4	5	8	8	95	92	92
2°C PCC	×2.3	6	10	12	94	90	88
1.5°C PCC	×2.3	6	11	14	94	89	86

Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. EJ = exajoule; O&G = oil and gas. a. Oil and gas have not been disaggregated in the model.

Source: Authors.

FIGURE 16 | CGE: Transport fuel mix (EJ)



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

GCAM

In GCAM, sales by technology type are determined in a bottom-up manner based on consumer behavior vis-à-vis price. The total cost of ownership (TCO) of the vehicle determines the sale of commercial vehicles, while the initial capital cost determines the sale of private cars and premium two-wheelers. However, because taxis hold a significant share of the 4-wheeler segment, the weighted average of TCO and capital by sales is used instead. In general, the assumptions are in line with declining battery costs across the segments, leading to parity in the capital cost of EVs and conventional vehicles by 2030. In the reference scenario, progressive assumptions are considered for the growth of EVs in the country, such as relaxation of charging and technical bottlenecks as well as rapidly declining EV costs that soon reach parity with those of ICEVs. Thus, EV sales of 2-wheelers, 3-wheelers, 4-wheelers, and buses reach 91 percent, 93 percent, 73 percent, and 58 percent of their total sales respectively by 2050. This reduces the reliance on oil, whose share drops to 64 percent in 2050. As for freight trucks, which grow to dominate the transport sector energy mix, only 1 percent of new sales is electric in 2050. The focus on gas also increases, especially for 4-wheelers and trucks, and its share is likely to increase from a current share of 3 percent to 29 percent in 2050.

In the policy scenarios, the carbon price determined by the model (based on the carbon constraint of the scenario) drives up the TCO of fossil-fuel-based vehicles, leading to a shift toward electrification (hydrogen has not been included as an alternative owing to the uncertainty around its application). Given the high levels of EV penetration in the reference scenario, the share of EV sales does not rise much in the policy scenarios except for the two PCC scenarios. Table 22 gives the share of EVs in total vehicle sales across time in each vehicle segment in all the scenarios.

TABLE 22 | GCAM: New electric vehicle sales share (%)

SCENARIO	2-WHEELERS			3-WHEELERS			4-WHEELERS			BUSES			TRUCKS		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	52	80	91	26	85	93	30	58	73	4	40	58	0	0	1
2°C ECPC	52	80	92	27	84	94	30	58	74	4	40	59	0	0	1
2°C FI	52	80	92	27	84	95	30	58	74	4	40	60	0	0	1
1.5°C ECPC	53	82	92	31	90	95	30	59	74	5	43	60	0	0	1
1.5°C FI	53	82	92	31	90	96	30	59	74	5	43	62	0	0	1
2°C PCC	52	80	95	27	84	98	30	58	75	4	40	69	0	0	3
1.5°C PCC	64	99	100	63	100	100	32	71	85	7	92	98	0	97	100

Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

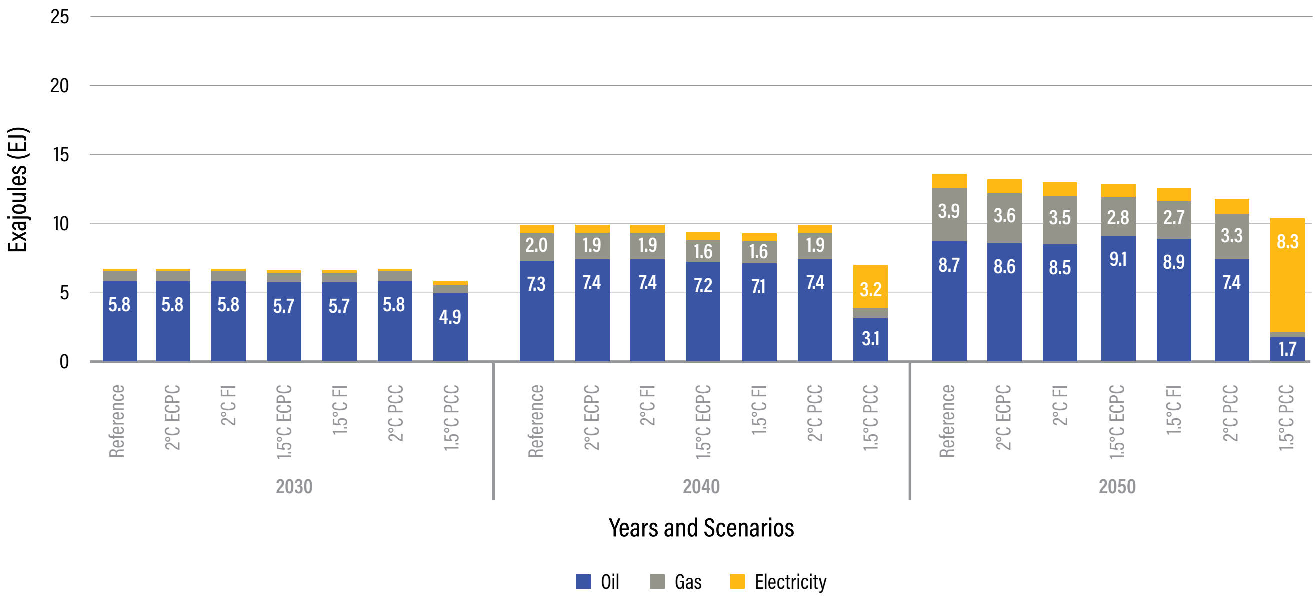
TABLE 23 | GCAM: Transport growth rate and share of electricity and oil in the transport fuel mix

GCAM	GROWTH RATE: TOTAL TRANSPORT ENERGY CONSUMPTION (2020–2050)	SHARE OF ELECTRICITY (%)			SHARE OF OIL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×3.3	3	6	7	87	74	64
2°C ECPC	×3.2	3	6	7	87	75	66
2°C FI	×3.2	3	6	7	87	75	65
1.5°C ECPC	×3.1	3	6	8	87	76	71
1.5°C FI	×3.1	3	6	8	87	76	70
2°C PCC	×2.9	3	6	9	87	75	63
1.5°C PCC	×2.5	4	46	80	85	44	17

Notes: Models: GCAM = Global Change Analysis Mode. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

In terms of energy, the total consumption decreases slightly over time (with the fall steepening as the carbon stringency of the scenarios increases) due to the inherently higher efficiency of EVs that that of ICEVs. The share of electricity remains the same as in the reference level because high levels of EV penetration are achieved in the reference scenario itself. Total electrification of the sector remains low because the maximum share of energy consumption comes from the trucks segment, which is technologically difficult to electrify. Therefore, its consumption of oil continues up to 2050 in all scenarios except in 1.5°C PCC, where the economy forces it to electrify to reach net zero by 2050. Gas also plays an increasingly important role. Table 23 summarizes the energy consumption growth rate and shares of electricity and oil in the total fuel mix of the transport sector per GCAM in all scenarios. Figure 17 gives the transport fuel mix in the different scenarios across time per GCAM.

FIGURE 17 | GCAM: Transport fuel mix (EJ)



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

SAFARI

Because SAFARI follows historical trends, there is negligible penetration of EVs in the reference case. As a result, oil dominates the transport energy mix with an 87 percent share up to 2050. In the low carbon scenarios, several interventions have been made in the policy scenarios at varying speeds to meet their corresponding carbon constraints. These interventions impact the total demand, mode share, and technology mix of each mode. The key interventions used are varying degrees of mode share shifts toward more efficient travel (road-based freight to rail and water, higher public and non-motorized transport, passenger transport away from road transport and toward rail transport); electrification of passenger transport (varying degrees across modes); better urban planning (compact cities, transit-oriented development); shared mobility (increasing occupancy); and improved fuel efficiency. As a result of the strong interventions to reduce the demand for transport, the total energy consumption falls considerably across scenarios over time compared to that in the reference scenario. In terms of the energy mix, the share of electricity, gas, and biofuels rises to induce a shift away from oil, but the sector still falls short of full decarbonization by 2050 in all scenarios, as seen in Table 24 and Figure 18.

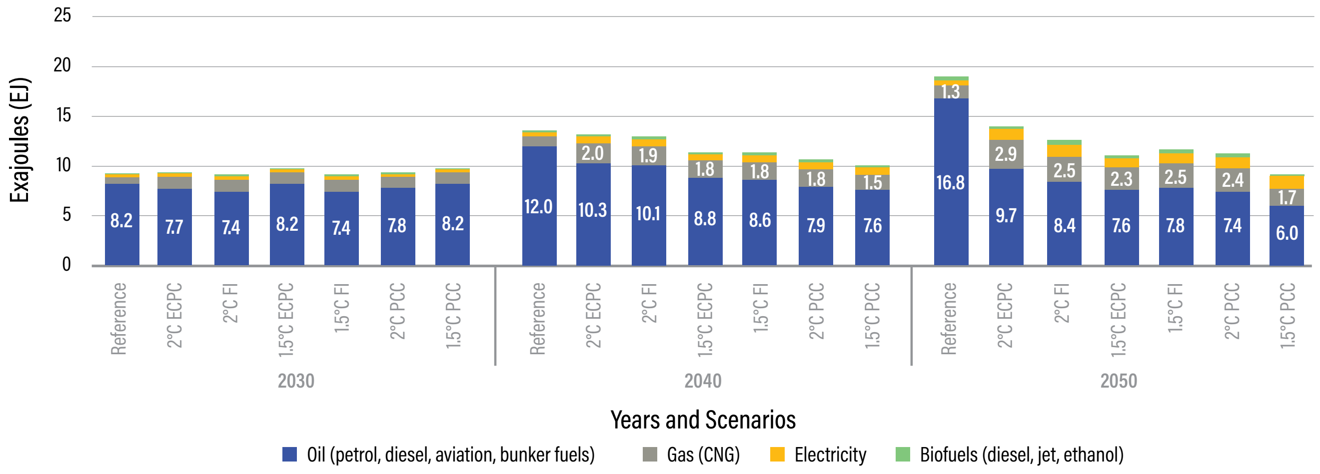
TABLE 24 | SAFARI: Transport growth rate and share of electricity and oil in the transport fuel mix

SAFARI	GROWTH RATE: TOTAL TRANSPORT ENERGY CONSUMPTION (2020–2050)	SHARE OF ELECTRICITY (%)			SHARE OF OIL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×3.3	3	6	7	87	74	64
2°C ECPC	×3.2	3	6	7	87	75	66
2°C FI	×3.2	3	6	7	87	75	65
1.5°C ECPC	×3.1	3	6	8	87	76	71
1.5°C FI	×3.1	3	6	8	87	76	70
2°C PCC	×2.9	3	6	9	87	75	63
1.5°C PCC	×2.5	4	46	80	85	44	17

Notes: Model: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE 18 | SAFARI: Transport fuel mix (EJ)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

EPS

In the EPS, the reference scenario transport sector assumes improvements in vehicle fuel efficiency in line with current improvements and targets, an increase in fuel blending per the National Policy on Biofuels (2018), and subsidies for EVs per the Faster Adoption and Manufacturing (FAME) scheme. Thereafter, demand is met based on an endogenous cost-optimization mechanism that prioritizes technology uptake according to the net present value of the vehicle's TCO. As a result, as the TCO of EVs becomes cost-competitive with ICEVs over time in the reference scenario itself, sales of electric LDVs rises from a less than 5 percent share in 2020 to about 35 percent in 2050. The share of electric HDVs also rises, although to a smaller extent. Freight HDVs (trucks) account for the bulk of the share of transport oil consumption and emissions (and their rise) from 2020 to 2050, followed by passenger HDVs (buses).

The policy scenarios are created by mode shift interventions, improved fuel efficiency, electrification, and alternative fuels. The model calculates that the mode shift[12] and fuel efficiency policies have a negative abatement cost through 2050; that is, the net present value of the costs associated with the abatement of each tonne of emissions as a result of these policies is negative and not an expense for the economy. Thus, these policies are considered with ambition levels based on recommendations from previously conducted expert consultations. Next, to drive deep decarbonization in the transport sector, the policy on mandated sales for EVs, light vehicles, and buses and hydrogen vehicles for heavy vehicles such as freight trucks, buses, and ships is set according to the carbon budget of each scenario. However, given the current nascent stage of hydrogen as a fuel for vehicles, the hydrogen policy is phased in starting only in 2030 and kept at low levels.

> The model calculates that the mode shift and fuel efficiency policies have a negative abatement cost through 2050; that is, the net present value of the costs associated with the abatement of each tonne of emissions as a result of these policies is negative and not an expense for the economy.

In the EPS, because the scenarios are based on the user's chosen policy setting, "EV sales mandate" is a policy lever that is set such that the total emissions align with the desired carbon budget. As in GCAM, the share of EVs in total vehicle sales is higher in the reference scenario than the current actual level of less than 1 percent, due to falling costs. This is highest for 2-wheelers, 3-wheelers, and 4-wheelers at about 30–40 percent in 2050, followed by bus EV sales at 23 percent and truck EV sales at 4 percent. In the policy scenarios, EV sales mandates are raised across scenarios in accordance with the stringency of their carbon budget. Table 25 gives the share of EV sales in the different vehicle segments across time in all scenarios per the EPS.

TABLE 25 | EPS: Electric vehicle sales share (%)

EPS	2-WHEELERS			3-WHEELERS			4-WHEELERS			BUSES			TRUCKS		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	18	36	38	13	28	30	17	31	33	9	20	23	1	3	4
2°C ECPC	27	53	80	27	53	80	17	33	51	10	19	25	1	3	5
2°C FI	30	60	90	30	60	90	16	31	52	10	19	30	2	6	10
1.5°C ECPC	40	80	100	40	80	100	18	43	71	10	24	40	3	9	15
1.5°C FI	40	80	100	40	80	100	18	43	71	10	27	45	3	9	15
2°C PCC	40	80	100	40	80	100	22	62	82	24	48	60	5	15	20
1.5°C PCC	50	100	100	50	100	100	50	100	100	38	75	75	12	25	25

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

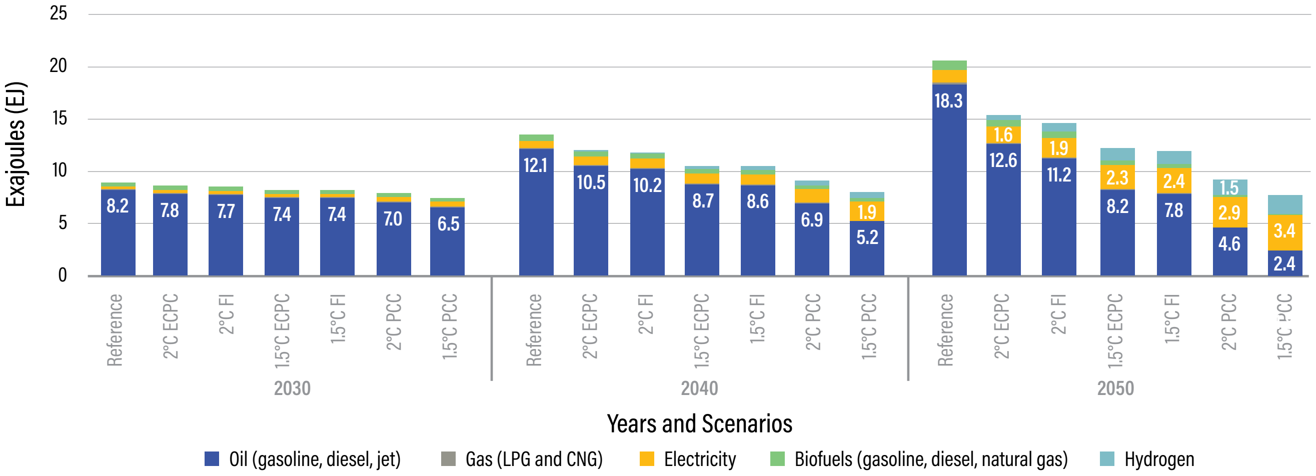
In terms of energy, the total consumption falls dramatically across scenarios relative to the reference scenario due to both a fall in demand as a result of the mode shift policy and improved fuel efficiency as well as the inherently higher efficiency of EVs than that of ICEVs. Concurrently, the shares of electricity and hydrogen rise in the policy scenarios in proportion to their carbon stringency and replace oil in the transport sector's fuel mix. However, as seen in GCAM, electrification of light vehicle segments has a limited impact on large-scale electrification of the transport sector because freight trucks, which are difficult to decarbonize, become the largest source of transport emissions beyond 2030. As a result, oil continues to play the most dominant role in the transport sector up to 2050 in all scenarios (except 1.5°C PCC, where higher levels of electrification and hydrogen are used to meet the tight carbon constraint). Gas and biofuels do not play a significant role in the EPS's transport sector. Table 26 summarizes the energy consumption growth rate and shares of electricity and oil in the total fuel mix of the transport sector per EPS in all scenarios. Figure 19 gives the transport fuel mix in the different scenarios across time per the EPS.

TABLE 26 | EPS: Transport growth rate and share of electricity and oil in the transport fuel mix

EPS	GROWTH RATE: TOTAL INDUSTRY ENERGY CONSUMPTION (2020–2050)	SHARE OF ELECTRICITY (%)			SHARE OF OIL (%)		
		2030	2040	2050	2030	2040	2050
Reference	×4.5	3	5	6	91	89	89
2°C ECPC	×3.3	3	6	10	91	88	81
2°C FI	×3.1	3	7	13	91	87	77
1.5°C ECPC	×2.6	4	9	19	90	82	68
1.5°C FI	×2.5	4	10	20	90	82	66
2°C PCC	×2	5	15	31	89	76	50
1.5°C PCC	×1.7	7	24	44	87	65	32

Notes: Model: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

FIGURE 19 | EPS: Transport fuel mix (EJ)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

> Freight trucks are difficult to electrify, and R&D on alternative low carbon fuels would be needed to be able to deploy them as well as a shift from road to rail freight. Demand-side interventions such as enhancing public transport usage, shared mobility, urban design, and fuel efficiency can significantly contribute to reducing the energy required by the transport sector.

Takeaways for policy

Putting all the four models together, we find that on a least cost basis, as seen in GCAM and the EPS, a considerable shift to EVs already occurs in the reference scenario, primarily in the 2-wheeler, 3-wheeler 4-wheeler, and bus segments. This is already underway for the 2-wheeler and 3-wheeler segments, but the 4-wheeler and bus segments would require policy support and technological innovation as well as supporting infrastructure such as charging points to reach full electrification. More importantly, from 2030 onward, freight trucks will be responsible for most transport emissions. These vehicles are difficult to electrify, and R&D on alternative low carbon fuels (such as green hydrogen or biofuels) would be needed in the short to medium term to be able to deploy them in industry in the medium to long term as well as a mode shift from road to rail freight, for which rail connectivity, frequency, and conducive regulations would have to be developed. Finally, as seen in SAFARI and the EPS, demand-side interventions such as enhancing public transport usage, shared mobility, urban design, and fuel efficiency can significantly contribute to reducing the energy required by the transport sector. Table 27 summarizes the four models' outputs in each scenario for the share of electricity that should be reached in the transport sector in 2030, 2040, and 2050 to align with their corresponding carbon budgets. Table 28 summarizes the outputs of GCAM and the EPS in each scenario for the share of different vehicle modes that should be reached in the transport sector in 2030, 2040, and 2050 to align with their corresponding carbon budgets.

TABLE 27 | Transport sector: Percentage of electricity in fuel mix

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE (%)[a]	2030 MILESTONE (%)	2040 MILESTONE (%)	2050 MILESTONE (%)
Reference	2.8	2, 3, 3, 3	2, 6, 3, 5	2, 7, 3, 6
2°C ECPC		2, 3, 4, 3	2, 6, 5, 6	3, 7, 8, 10
2°C FI		3, 3, 4, 3	4, 6, 5, 7	4, 7, 9, 13
1.5°C ECPC		4, 3, 3, 4	7, 6, 5, 9	7, 8, 8, 19
1.5°C FI		5, 3, 4, 4	8, 6, 6, 10	8, 8, 8, 20
2°C PCC		6, 3, 4, 5	10, 6, 7, 15	12, 9, 10, 31
1.5°C PCC		6, 4, 3, 7	11, 46, 8, 24	14, 80, 14, 44

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
a. *2019 Historical Data Source:* (MoSPI 2022).

Sources: Authors; a. MoSPI 2022.

TABLE 28 | Transport sector: Share of EVs in total vehicle sales by vehicle segment (%)

🟥 GCAM 🟪 EPS

SCENARIO	2-WHEELERS			3-WHEELERS			4-WHEELERS			BUSES			TRUCKS		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	52, 18	80, 36	91, 38	26, 13	85, 28	93, 30	30, 17	58, 31	73, 33	4, 9	40, 20	58, 23	0, 1	0, 3	1, 4
2°C ECPC	52, 27	80, 53	92, 80	27, 27	84, 53	94, 80	30, 17	58, 33	74, 51	4, 10	40, 19	59, 25	0, 1	0, 3	1, 5
2°C FI	52, 30	80, 60	92, 90	27, 30	84, 60	95, 90	30, 16	58, 31	74, 52	4, 10	40, 19	60, 30	0, 2	0, 6	1, 10
1.5°C ECPC	53, 40	82, 80	92, 100	31, 40	90, 80	95, 100	30, 18	59, 43	74, 71	5, 10	43, 24	60, 40	0, 3	0, 9	1, 15
1.5°C FI	53, 40	82, 80	92, 100	31, 40	90, 80	96, 100	30, 18	59, 43	74, 71	5, 10	43, 27	62, 45	0, 3	0, 9	1, 15
2°C PCC	52, 40	80, 80	95, 100	27, 40	84, 80	98, 100	30, 22	58, 62	75, 82	4, 24	40, 48	69, 60	0, 5	0, 15	3, 20
1.5°C PCC	67, 50	99, 100	100, 100	74, 50	100, 100	100, 100	33, 50	74, 100	85, 100	8, 38	96, 75	98, 75	0, 12	100, 25	100, 25

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

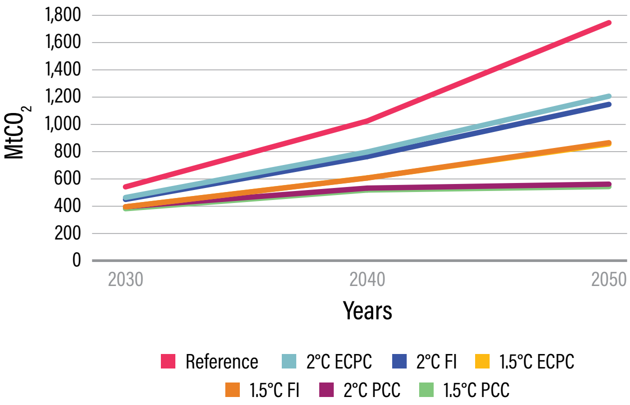
Source: Authors.

Transport sector emissions

Transport sector emissions grow 6.6, 2.9, 3, and 4.2 times from 2020–50 in CGE, GCAM, SAFARI, and the EPS, respectively. This aligns almost exactly with the increase in the total energy consumption of the transport sector from 2020 to 2050 in each model, showing that, similar to industry, decoupling of transport sector growth and emissions does not occur in the reference scenario. Once again, GCAM is the only exception, where the growth in emissions is lower than the growth in energy consumption, as a result of the comparatively higher level of electrification in the reference scenario. With transport sector emissions growing rapidly, there is a need to focus on lowering the cost of EVs, developing supporting infrastructure such as charging deployment, and exploring alternative solutions such as gas and hydrogen to decarbonize freight trucks, which will become the biggest source of transport emissions in the future.

In the low carbon scenarios, in CGE (Figure 20), transport sector emissions do not peak until 2050 in any scenario but fall compared to reference levels as electrification and fuel efficiency increase and the overall demand falls. The absolute value of transport emissions in CGE is the highest among all the four models, ranging between 550 and 1,200 $MtCO_2$. In GCAM (Figure 21), transport emissions peak by 2030 in 1.5°C PCC and by 2040 in 2°C PCC to reach net zero around mid-century, but do not peak in the other scenarios until 2050 and are approximately equal to the reference scenario levels due to low decarbonization of trucks. Absolute emissions of GCAM's transport sector are low, ranging between 680 and 820 $MtCO_2$. In SAFARI (Figure 22), transport emissions in all scenarios except 2°C ECPC peak between 2040 and 2050, although they plateau rather than decline in 1.5°C PCC. As a result of the strong demand reduction and efficiency interventions, absolute emissions range from 650 to 850 $MtCO_2$ in 2050 across all policy scenarios. Finally, in the EPS (Figure 23), transport emissions peak by 2030 in 1.5°C PCC, peak between 2040 and 2050 in 2°C PCC and the other 1.5°C scenarios, and do not peak until 2050 in the other two 2°C scenarios, although they fall considerably compared to the reference scenario due to demand-side and efficiency measures. Absolute emissions range between 200 and 960 $MtCO_2$ in 2050 across the various policy scenarios compared to 1,390 $MtCO_2$ in the reference scenario.

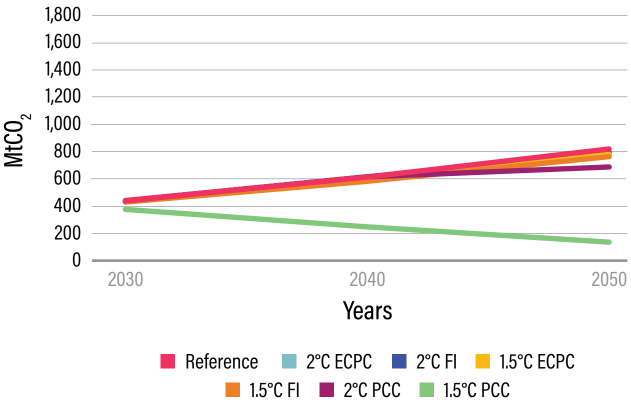
FIGURE 20 | CGE: Transport sector emissions ($MtCO_2$)



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

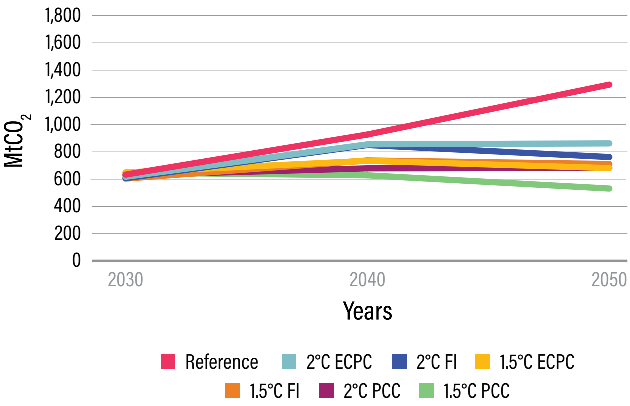
FIGURE 21 | GCAM: Transport sector emissions ($MtCO_2$)



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

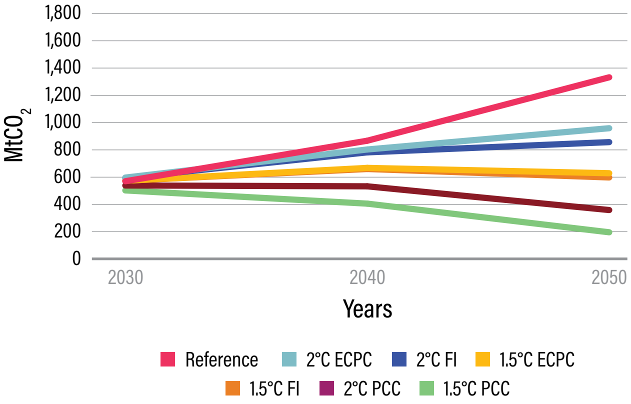
FIGURE 22 | SAFARI: Transport sector emissions ($MtCO_2$)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

FIGURE 23 | EPS: Transport sector emissions ($MtCO_2$)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

The power sector

In GCAM, SAFARI, and EPS, electricity demand by the end-use sectors of the economy (i.e., industry, transport, and buildings) drive the supply of electricity from the power sector. In the case of CGE, because it is a full equilibrium model, demand and supply act simultaneously to achieve equilibrium in the economy.

Sectoral demand for electricity

In the reference scenario of CGE, SAFARI, and the EPS, although industry has historically been the main driver of electricity demand, increasing urbanization and growing income levels drive an increased demand for cooling, lighting, appliance use, and so on, and so the buildings sector becomes the highest consumer of electricity by 2050. Consumption in the transport sector also rises marginally in the EPS due to some electrification. On the other hand, because GCAM sees a higher penetration of electrification than the other models in the industry and transport sectors in the reference scenario, these sectors maintain their share of the total electricity consumption over time. The "Others" category in SAFARI refers to public lighting, waterworks, bulk supply, and other miscellaneous demands. Agriculture is subsumed in industry.

In the low carbon scenarios, in all four models, industry is the highest consumer of electricity, followed by buildings and then transport, in the low carbon scenarios from before 2030 itself. In CGE and GCAM, the share of industry rises across scenarios as the scenarios become more stringent. Further, in GCAM, although the share of transport is below 5 percent in all scenarios, interestingly, in 1.5°C PCC, which is the only scenario to reach net zero emissions by 2050, the share of transport is higher by 20 percent and that of buildings is lower by the same value, indicating how the pressure on electricity demand from different sectors will change over time as they decarbonize at different timelines. Conversely, in SAFARI, industry is the highest consumer of electricity in all scenarios only up to 2030 as cement, steel, and other construction materials are in high demand to meet the development goals, which leads to more construction of houses, hospitals, and educational institutions. Beyond that, as the goals are met, the newly expanded buildings sector takes over as the highest consumer because thermal comfort (space cooling) and electric cooking are prioritized. However, interestingly, in the two PCC scenarios, to further reduce emissions, policies such as early penetration of efficient appliances, regulatory limits on the floor area of middle- and high-income housing, and passive cooling through improved construction materials and planning are introduced, which lowers electricity demand from the residential sector, making industry the highest consumer again. In the EPS, although industry is the highest consumer followed by buildings across all scenarios across time as well, their shares decline across time and scenarios (lowest to highest stringency) because the shares (i.e., the growth rate) of the transport and hydrogen sectors rise faster after 2030. Figures C-5 to C-8 in the Appendix represent the data on these trends in the four models.

Installed capacity and generation of electricity

As India strives to achieve its climate and development goals, electricity demand will rise due to increased income, urbanization, manufacturing, and so on, as well as the shift of end-use sectors such as transport, industries, and buildings toward electrification. Currently, the power sector is India's single largest source of CO_2 emissions at 40 percent (BUR 3); therefore, to limit emissions to the carbon budgets, it is important to ensure that the installed capacity built to meet this demand uses non-fossil fuels. This section discusses both the installed capacity and the electricity it actually generates from different energy sources to meet the total electricity demand. This comparison is important because the capacity utilization factor (CUF) of renewables, especially solar, has historically been much lower than that of coal (20–30 percent vs. 60–70 percent), and so shifting from thermal to solar would require a lot more capacity addition to meet the same electricity demand unless technologies such as battery storage for electricity are also simultaneously augmented.

Moreover, at COP26 in 2021, India announced its ambition of installing 500 GW of installed capacity of electricity from non-fossil fuel sources of energy by 2030. In its updated NDC submitted to the UNFCCC in 2022, India then made a conditional commitment that 50 percent of its cumulative installed capacity of electricity would come from non-fossil fuel sources by 2030. This section thus looks at the absolute value and share of the installed capacity from non-fossil fuel sources in 2030 and 2050 in the different low carbon scenarios, and how that relates to electricity generation in the country.

REFERENCE SCENARIO

In CGE, additional investments in coal, solar, wind, and so on, are fed exogenously and determine the future expansion of these sectors. Because reference scenario assumptions follow historical trends, there is low RE penetration at 31 percent in 2050, with the highest share going to coal until 2050 at 53 percent. In GCAM, SAFARI, and the EPS, the installed capacity of electricity is built to meet the total electricity demand from various end-use sectors (such as transport and industry). The technology mix of these power plants is based on a least cost basis, that is, from the lowest to the highest LCOE (which includes the cost of RE integration). If a resource is exhausted, it moves on to the next cheapest option. As a result, a much higher penetration of solar and wind is observed, reaching 66–68 percent in all three models in 2050. In the EPS, the least cost allocation means that no new coal power plants are built from 2028 onward in the reference scenario itself, as RE becomes cheaper than thermal power plants, leading to a fixed coal power plant capacity of 221 GW from 2028 onward. The share of natural gas power plants also rises over time to balance the variability in RE source (RES)-based plants, leading to a high share for the “Other Fossils” category. Although the share of coal falls over time, its absolute value still rises 1.5–1.9 times in all the models except the EPS. The EPS is the only model where new thermal power plants stop being installed in the reference scenario itself. Further, the growth of wind and solar installed capacity from 2030 to 2050 ranges widely at 1.95, 3.1, 4, and 4.2 times according to CGE, GCAM, SAFARI, and the EPS, respectively, driven by lower costs and improved CUFs.

> The technology mix of these power plants is based on a least cost basis. If a resource is exhausted, it moves on to the next cheapest option. As a result, a much higher penetration of solar and wind is observed, reaching 66–68 percent in all three models in 2050.

Generation of electricity by a particular energy source (coal, solar, etc.) depends on several factors such as the plant’s CUF (the amount of electricity it generates [TWh] per unit of installed capacity [GW]), technology to integrate RE into the grid, and battery storage for the hours where variable RESs (solar, wind) cannot generate electricity. In GCAM, the cost associated with accommodating this increasing share of RE in the grid including the costs of storage, backup, and so on, apart from the LCOE of wind and solar power generation, is called the variable RE (VRE) integration cost and has been estimated based on a literature review and stakeholder consultations in this paper (Chaturvedi et al. 2018).[13] In SAFARI, grid-based storage technology is assumed to improve in efficiency from 85 to 92 percent (2015–50). The model uses an upper bound of 250 GW grid storage to balance the variability from the penetration of renewables.[14] Solar CUFs are assumed to improve from 18 to 22 percent, and wind CUFs are assumed to improve from 19 to 26 percent. In the EPS, CEA’s 34 GW of grid battery storage target for 2030 is used followed by the India Energy Security Scenarios (IESS) Level 4 target of 65 GW until 2047 (NITI Aayog 2015).[15]

In CGE, electricity generation is dominated by coal at a fairly constant share of 70 percent from 2020 to 2050, followed by non-fossil fuel sources (solar, wind, nuclear, and hydro), which contribute about 25 percent. However, the efficiency of thermal power plants is assumed to rise up to 2050, leading to the peaking of absolute coal consumption in 2045 followed by a slight decline, although generation from coal continues to increase up to 2050. In GCAM, coal’s share, which falls but still dominates electricity generation up to 2050, reaches 50 percent in 2050 while the share of RES (wind and solar) rises to 35 percent in 2050. In SAFARI, although coal holds the dominant share up to 2040, it is then overtaken by RE by 2050 with shares of 38 percent for coal and 42 percent for solar and wind. Solar CUFs are assumed to improve from 18 percent to 22 percent, and wind CUFs are assumed to improve from 19 percent to 26 percent. In EPS, the share of thermal electricity generation falls by half to 23 percent in 2050 as RE rises to 61 percent.

Tables 29 and 30 give an overview of the total installed capacity and electricity generation of electricity required in 2030, 2040, and 2050 in the six policy scenarios and reference scenario by the four models.

TABLE 29 | Total electricity installed capacity (GW)

MODEL	CGE			GCAM			SAFARI			EPS		
SCENARIO	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Reference	640	907	1,229	669	1,209	1,636	684	1,141	1,762	755	1,465	2,129
2°C ECPC	911	1,240	1,432	685	1,292	2,035	698	1,464	2,425	687	1,204	1,858
2°C FI	944	1,503	1,758	685	1,292	2,173	714	1,521	2,494	690	1,255	2,060
1.5°C ECPC	973	1,653	2,180	784	1,781	2,928	687	1,205	1,979	679	1,367	2,022
1.5°C FI	1,002	1,775	2,724	784	1,862	3,182	680	1,210	2,141	679	1,427	2,147
2°C PCC	999	1,836	2,790	685	1,292	3,583	674	925	1,693	691	1,466	2,095
1.5°C PCC	1,108	2,028	3,136	1,610	4,753	6,835	675	1,094	2,302	949	1,817	2,365

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GW = gigawatts.

Source: Authors.

TABLE 30 | Electricity generation (TWh)

MODEL	CGE			GCAM			SAFARI			EPS		
SCENARIO	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Reference	2,791	3,924	5,000	2,693	4,290	5,757	2,445	3,824	5,638	2,516	4,056	5,592
2°C ECPC	2,945	4,016	4,558	2,705	4,346	6,251	2,526	4,029	6,154	2,370	3,960	6,531
2°C FI	2,995	4,532	5,280	2,705	4,346	6,405	2,566	4,081	6,249	2,365	4,083	7,196
1.5°C ECPC	3,015	4,809	6,118	2,853	4,897	6,974	2,429	3,700	5,260	2,309	4,332	7,058
1.5°C FI	3,017	4,889	6,735	2,853	4,969	7,212	2,413	3,726	5,517	2,302	4,472	7,467
2°C PCC	2,860	4,939	6,852	2,705	4,346	7,732	2,259	3,334	4,509	2,260	4,431	7,110
1.5°C PCC	2,909	4,951	7,501	3,429	9,081	13,890	2,314	3,603	5,181	2,802	5,447	8,374

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. TWh = terawatt-hour.

Source: Authors.

CARBON BUDGET SCENARIOS

CGE

In CGE, to meet the carbon budget constraints, investments are made in RE to shift away from the coal-dominated fleet. The total fleet and generation increase in the policy scenarios as their carbon stringency rises, to meet the increased demand for electricity from the other sectors undergoing electrification. Further, the fleet outgrows generation, with the difference between them rising across scenarios as their carbon constraint becomes more stringent, because the scenarios include higher shares of RE, which has a lower CUF and thus needs more capacity to meet the same demand.

Comparing CGE's outputs with India's 2030 targets, 287 GW of non-fossil capacity constituting 45 percent of the total fleet is from non-fossil fuels in the reference scenario, both of which are lower than India's targets (500 GW and 50 percent, respectively), indicating the need for additional policy support. In the low carbon scenarios, the non-fossil fleet rises to 587–599 GW constituting 59–64 percent of the fleet by 2030 (not considering 1.5°C PCC, which is an outlier), indicating that India's national targets are ambitious and need only a slight enhancement to align with the carbon budgets.

In 2050, the non-fossil fuel fleet would have to rise from a 45 percent share in the reference scenario to 67–95 percent across the policy scenarios, which would lead to a rise in generation from 29 percent in the reference scenario to 51–93 percent in the policy scenarios. Within this, the fleet from solar and wind would have to rise from 31 percent in the reference scenario to 54–82 percent in the policy scenarios, corresponding to a rise in generation from 16 percent in the reference scenario to 36–73 percent in the policy scenarios. Nuclear energy is used for the base load and hydro power for balancing, and so their share rises slightly over time as well. The share of coal falls from 53 percent capacity and 58 percent generation in the reference scenario to 4–29 percent capacity and 6–43 percent generation in the policy scenarios. Oil and gas (O&G) does not play a significant role in the high-ambition policy scenarios but rise slightly in the low ambition scenarios as a transition fuel. This shows the level of effort required to stay compliant with any of the carbon budgets under the temperature goals. No assumptions have been made regarding improvements in CUF, battery storage, or the grid. Table 31 gives the absolute values and shares of non-fossil fuel capacity and generation across time and scenarios. Figures C-9 and C-10 in Appendix C give details on the capacity and generation shares of four categories of fuel (coal, other fossil fuels, solar and wind, and other non-fossil fuels) across scenarios and time.

GCAM

In GCAM, the total electricity capacity is determined bottom-up to fulfill the electricity demand from the end-use sectors. Both these demands rise across scenarios as they become more stringent, to meet the rising electricity needs of end-use sectors. The fuel mix is then determined on a least cost basis under the constraint of the corresponding carbon budget. As a result, due to its low cost, the share of solar power rises dramatically. However, because its CUF is much lower than coal's (and the CUF of other RE sources), despite future improvements, a much higher magnitude of solar installed capacity is needed to meet the total demand for electricity in the economy. This is evident from the increasing difference between the growth rates of

TABLE 31 | CGE: Electricity growth, absolute value, and shares of capacity and generation from non-fossil fuels

CGE	GROWTH RATE: TOTAL CAPACITY (2020–2050)	GROWTH RATE: TOTAL GENERATION (2020–2050)	NON-FOSSIL FUEL CAPACITY (GW)			NON-FOSSIL FUEL CAPACITY SHARE (%)			NON-FOSSIL FUEL GENERATION (TWH)			NON-FOSSIL FUEL GENERATION SHARE (%)		
			2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	×2.7	×3.1	287	394	551	45	43	45	706	1,007	1,456	25	26	29
2°C ECPC	×3.2	×2.6	587	804	957	64	65	67	1,235	1,815	2,333	42	45	51
2°C FI	×3.9	×3.0	591	1,039	1,244	63	69	71	1,245	2,314	3,010	42	51	57
1.5°C ECPC	×4.9	×3.5	591	1,150	1,680	61	70	77	1,244	2,560	4,028	41	53	66
1.5°C FI	×6.1	×3.9	591	1,290	2,499	59	73	92	1,244	2,865	5,837	41	59	87
2°C PCC	×6.2	×4.0	599	1,322	2,570	60	72	92	1,263	2,949	6,002	44	60	88
1.5°C PCC	×7	×4.3	770	1,718	2,984	70	85	95	1,586	3,762	6,960	55	76	93

Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; GW = gigawatts; PCC = Per Capita Convergence. TWh = terawatt-hour.

Source: Authors.

the installed capacity and generation of electricity across scenarios as their carbon constraint becomes more stringent (and hence the scenarios include larger shares of RE), as seen in Table 32.

Comparing GCAM's outputs with India's 2030 targets, 435 GW of non-fossil capacity constituting 65 percent of the total fleet is from non-fossil fuels in the reference scenario itself, indicating that the NDC target can be met if investments in the power sector are made in a least cost manner, but would fall slightly short of the COP26 commitment without policy support. In the low carbon scenarios, the non-fossil fleet rises to 445–541 GW, constituting 65–69 percent of the fleet by 2030 (not considering 1.5°C PCC, which is an outlier), indicating that India's 500 GW target is ambitious, aligns with the 2°C budgets, and needs only a slight enhancement to align with the 1.5°C budgets.

In 2050, the non-fossil fuel fleet would have to rise from a 75 percent share in the reference scenario to 81–100 percent across the policy scenarios, which would lead to a rise in generation from 48 percent in the reference scenario to 57–100 percent in the policy scenarios. Within this, the fleet from solar and wind would have to rise from 66 percent in the reference scenario to 75–96 percent in the policy scenarios, corresponding to a rise in generation from 35 percent in the reference scenario to 46–88 percent in the policy scenarios. The other non-fossil fuels do not change relative to the reference scenario. The share of coal falls from 24 percent capacity and 50 percent generation in the reference scenario to 0–17 percent capacity and 0–41 percent generation in the policy scenarios. O&G does not play a significant role. This shows the level of effort required to stay compliant with any of the carbon budgets under the temperature goals. No additional assumptions have been made regarding improvements in the CUF, battery storage, or the grid beyond reference levels. Table 32 gives the absolute values and shares of non-fossil fuel capacity and generation across time and scenarios. Figures C-11 and C-12 in Appendix C show details of the capacity and generation shares of four categories of fuels (coal, other fossil fuels, solar and wind, and other non-fossil fuels) across scenarios and time.

TABLE 32 | GCAM: Electricity growth, absolute value, and shares of capacity and generation from non-fossil fuels

GCAM	GROWTH RATE: TOTAL CAPACITY (2020-2050)	GROWTH RATE: TOTAL GENERATION (2020-2050)	NON-FOSSIL FUEL CAPACITY (GW)			NON-FOSSIL FUEL CAPACITY SHARE (%)			NON-FOSSIL FUEL GENERATION (TWH)			NON-FOSSIL FUEL GENERATION SHARE (%)		
			2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	×4.4	×3.7	435	883	1,227	65	73	75	943	1,930	2,763	35	45	48
2°C ECPC	×5.5	×4.0	445	969	1,648	65	75	81	947	1,955	3,563	35	45	57
2°C FI	×5.9	×4.1	445	969	1,825	65	75	84	947	1,955	3,843	35	45	60
1.5°C ECPC	×7.9	×4.5	541	1,514	2,752	69	85	94	1,084	2,987	5,649	38	61	81
1.5°C FI	×8.6	×4.6	541	1,620	3,055	69	87	96	1,084	3,131	6,275	38	63	87
2°C PCC	×9.7	×5.0	445	969	3,547	65	75	99	947	1,955	7,345	35	45	95
1.5°C PCC	×18.4	×8.9	1,530	4,753	6,835	95	100	100	2,949	9,081	13,890	86	100	100

Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; GW = gigawatts; PCC = Per Capita Convergence. TWh = terawatt-hour.

Source: Authors.

SAFARI

In SAFARI, there are two competing forces in end-use sectors: a reduction in electricity demand because of demand-side interventions to improve energy and material efficiency and reduce consumption, and an increase in electricity demand due to electrification. As a result, the total electricity generation is higher than that in the reference scenario in the two least ambitious scenarios (2°C ECPC and 2°C FI) because of low demand-side interventions but a higher shift to RE (which increases the fleet size), but is lower than that in the reference scenario in the other four more ambitious scenarios because of stronger demand reduction measures.

Comparing SAFARI's outputs with India's 2030 targets, 427 GW of non-fossil capacity constituting 62 percent of the total fleet is from non-fossil fuels in the reference scenario itself, indicating that the NDC target can be met if investments in the power sector are made in a least cost manner, but would fall slightly short of the COP26 commitment without policy support. In the low carbon scenarios, the non-fossil fleet rises to 419–454 GW, constituting 62–64 percent of the fleet by 2030, indicating that the 500 GW target is ambitious and aligned with the carbon budgets but that the NDC target can be enhanced. In 2050, the non-fossil fuel fleet would have to rise from a 77 percent share in reference to 87–90 percent across the policy scenarios, which would lead to a rise in generation from 59 percent in the reference scenario to 76–85 percent in the policy scenarios. Within this, the fleet from solar and wind would have to rise from 64 percent in the reference scenario to 74–80 percent in the policy scenarios, corresponding to a rise in generation from 42 percent in the reference scenario to 58–74 percent in the policy scenarios. The share of generation from other non-fossil fuels remains similar to that in the reference scenario in 2050 but rises in intermediate years while infrastructure to accommodate RE is still being developed. The share of coal falls from 20 percent capacity and 38 percent generation in the reference scenario to 6–9 percent capacity and 11–17 percent generation in the policy scenarios because of the intervention "no new coal power plants from 2025 onward" that is applied across all policy scenarios. The share of generation from gas power plants is kept constant across time and scenarios by the model to meet the demand not met by RE due to its higher plant load factor. No additional assumptions have been made regarding the improvements in the CUF, battery storage, or the grid beyond the reference levels. Table 33 gives the absolute values and shares of non-fossil fuel capacity and generation across

TABLE 33 | SAFARI: Electricity growth, absolute value, and shares of capacity and generation from non-fossil fuels

SAFARI	GROWTH RATE: TOTAL CAPACITY (2020–2050)	GROWTH RATE: TOTAL GENERATION (2020–2050)	NON-FOSSIL FUEL CAPACITY (GW)			NON-FOSSIL FUEL CAPACITY SHARE (%)			NON-FOSSIL FUEL GENERATION (TWH)			NON-FOSSIL FUEL GENERATION SHARE (%)		
			2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	×4.6	×3.8	427	828	1,351	62	73	77	1,053	2,130	3,346	43	56	59
2°C ECPC	×6.3	×4.1	440	1,204	2,166	63	82	89	1,093	2,827	5,002	43	70	81
2°C FI	×6.4	×4.2	454	1,259	2,233	64	83	90	1,120	2,902	5,110	44	71	82
1.5°C ECPC	×5.1	×3.5	430	956	1,738	63	79	88	1,051	2,423	4,131	43	65	79
1.5°C FI	×5.5	×3.7	425	966	1,897	62	80	89	1,041	2,466	4,431	43	66	80
2°C PCC	×4.4	×3.0	419	691	1,466	62	75	87	984	1,902	3,411	44	57	76
1.5°C PCC	×5.9	×3.4	420	857	2,061	62	78	90	1,004	2,237	4,399	43	62	85

Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; GW = gigawatts; PCC = Per Capita Convergence. TWh = terawatt-hour.

Source: Authors.

time and scenarios. Figures C-13 and C-14 in Appendix C show details on the capacity and generation shares by four categories of fuels (coal, other fossil fuels, solar and wind, and other non-fossil fuels) across scenarios and time.

EPS

In the EPS, demand-side interventions have maximum impact in the early years, leading to a fall in demand and thus a corresponding fall in generation in the policy scenarios compared to the reference scenario in 2030 across all scenarios. However, in later years, electricity demand becomes higher in the policy scenarios than in the reference scenario because of higher electrification across the economy and the increasing use of electrolysis-generated hydrogen in transport and industry from 2030 to 2050 and across scenarios with increasing stringency. However, the fleet constructed to meet this demand is lower than that in the reference scenario, due to assumptions regarding improved demand response, battery storage, lower transmission and distribution (T&D) losses, and the higher CUFs of solar and wind (both onshore and offshore).

Comparing the EPS's outputs with India's 2030 targets, 475 GW of non-fossil capacity constituting 63 percent of the total fleet is from non-fossil fuels in the reference scenario itself, indicating that the NDC target can be met if investments in the power sector are made in a least cost manner, but would fall slightly short of the COP26 commitment without policy support. In the low carbon scenarios, the non-fossil fleet rises to 440–498 GW constituting 64–72 percent of the fleet by 2030 (not considering 1.5°C PCC, which is an outlier), indicating that India's 500 GW target is ambitious and aligns with the budget scenarios but that the NDC target can be enhanced.

In 2050, the non-fossil fuel fleet would have to rise from a 75 percent share in the reference scenario to 84–93 percent across the policy scenarios, which would lead to a rise in generation from 68 percent in the reference scenario to

TABLE 34 | EPS: Electricity growth, absolute value, and shares of capacity and generation from non-fossil fuels

EPS	GROWTH RATE: TOTAL CAPACITY (2020–2050)	GROWTH RATE: TOTAL GENERATION (2020–2050)	NON-FOSSIL FUEL CAPACITY (GW)			NON-FOSSIL FUEL CAPACITY SHARE (%)			NON-FOSSIL FUEL GENERATION (TWH)			NON-FOSSIL FUEL GENERATION SHARE (%)		
			2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Reference	×5.3	×4.1	475	1020	1598	63	70	75	992	2245	3796	39	55	68
2°C ECPC	×4.7	×4.7	440	865	1,560	64	72	84	1,181	2756	5,785	50	70	89
2°C FI	×5.2	×5.2	444	915	1,757	64	73	85	1,192	2916	6,517	50	71	91
1.5°C ECPC	×5.1	×5.1	463	1126	1,847	68	82	91	1,248	3598	6,776	54	83	96
1.5°C FI	×5.4	×5.4	466	1182	1,955	69	83	91	1,256	3777	7,164	55	84	96
2°C PCC	×5.3	×5.2	498	1297	1,929	72	88	92	1,332	4101	6,832	59	93	96
1.5°C PCC	×5.9	×6.1	775	1641	2,194	82	90	93	2,120	5106	8,087	76	94	97

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; GW = gigawatts; PCC = Per Capita Convergence. TWh = terawatt-hour.

Source: Authors.

89–97 percent in the policy scenarios. Within this, the fleet from solar and wind would have to rise from 68 percent in the reference scenario to 77–87 percent in the policy scenarios, corresponding to a rise in generation from 61 percent in the reference scenario to 82–95 percent in the policy scenarios. Other non-fossil fuels (nuclear, hydro, and biomass) decline slightly over time given their higher costs compared to solar and wind. The share of coal falls from 10 percent capacity and 25 percent generation in the reference scenario to 0–4 percent capacity and 0-6 percent generation in the policy scenarios. This is because no additional thermal capacity is added in the EPS after 2027 in the reference scenario due to its higher cost, and in the policy scenarios, the existing thermal power capacity is phased out with an early retirement policy. The shares of capacity and generation from natural gas power plants rise in intermediate years in the EPS in all scenarios to balance the variability of RE. However, relative to the reference scenario (where they keep rising until 2050), these shares are made to decline by 2050 through other policies such as higher storage and demand response to manage the variability of RE. Policy support has been used to improve the CUF, battery storage, and demand response and to reduce T&D losses compared to the reference levels. Table 34 gives the absolute value and share of non-fossil fuel capacity in generation across time and scenarios. Figures C-15 and C-16 in Appendix C show details on the capacity and generation shares by four categories of fuels (coal, other fossil fuels, solar and wind, and other non-fossil fuels) across scenarios and time.

Takeaways for policy

Putting all the four models together, we find from all the four models that electricity demand will rise considerably over the coming decades compared to the reference scenario as India grows its economy and strives to decarbonize (and electrify) different sectors. Although high levels of RE are projected to meet the development-induced demand in the reference scenario itself given their falling costs, even higher amounts of RE will be needed in the low carbon scenarios, which is most pronounced in GCAM. As discussed in the literature, RE imposes tremendous pressure on competing resources such as land, water, and finance (National Research Council 2010). Hence, an effort needs to be made to reduce the demand for electricity in end-use sectors through efficiency and demand reduction policies as seen in SAFARI and the EPS. Efficiency can also be improved in the power sector, such as by supporting R&D to increase the CUF of solar, and reducing T&D losses, as seen in the EPS. Lastly, for India to install the very large quantities of RE required to develop and decarbonize simultaneously, technical and technological efforts will have to be supported to improve the ability of the grid to manage RE and increase storage capacity so that natural-gas- or hydro-based power plants do not have to manage variability, as seen in the EPS.

In terms of India's announced target of installing 500 GW of electricity capacity from non-fossil fuel sources by 2030, we find that it is ambitious and almost met in the reference scenarios of the three models that build the fleet on a least cost basis (GCAM, SAFARI, and the EPS) at 427–475 GW. This indicates that least cost decision-making and a slight policy push (such as aligning India's RPOs with this goal) can help meet the target. Further, the models together recommend a range of 419–599 GW of non-fossil fuel capacity to align with all carbon budgets except 1.5°C PCC (which is very stringent and therefore an outlier), indicating that India's 500 GW target is ambitious and in the right range.

India's NDC commitment of achieving 50 percent electricity capacity from non-fossil fuel sources by 2030 is significantly exceeded by the three least cost models, which achieve 62–65 percent in the reference scenario itself. Further, the four models together recommend a range of 59–72 percent share of non-fossil fuel capacity to align with all carbon budgets except 1.5°C PCC (which is very stringent and therefore an outlier), indicating the scope for enhanced ambition. Table 35 summarizes the four models' outputs in each scenario for the cumulative installed capacity of electricity from non-fossil fuel sources that should be reached in the power sector in 2030, 2040, and 2050 to align with their corresponding carbon budgets.

Power sector milestones

Table 36 summarizes the four models' outputs in each scenario for the share of non-fossil fuels in the total installed capacity of electricity that should be reached in the power sector in 2030, 2040, and 2050 to align with their corresponding carbon budgets.

Table 37 summarizes the four models' outputs in each scenario for the share of electricity generation from non-fossil fuel sources that should be reached in the power sector in 2030, 2040, and 2050 to align with their corresponding carbon budgets.

TABLE 35 | Power sector: Cumulative installed capacity from non-fossil fuels (GW)

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2021 HISTORICAL VALUE	2030 MILESTONE	2040 MILESTONE	2050 MILESTONE
Reference	154[a]	287, 432, 427, 475	394, 887, 828, 1020	551, 1231, 1351, 1598
2°C ECPC		587, 447, 440, 440	804, 969, 1204, 865	957, 1663, 2166, 1560
2°C FI		591, 447, 454, 444	1039, 969, 1259, 915	1244, 1825, 2233, 1757
1.5°C ECPC		591, 543, 430, 463	1150, 1513, 956, 1126	1680, 2741, 1738, 1847
1.5°C FI		591, 543, 425, 466	1290, 1609, 966, 1182	2499, 3046, 1897, 1955
2°C PCC		599, 447, 419, 498	1322, 969, 691, 1297	2570, 3526, 1466, 1929
1.5°C PCC		770, 1536, 420, 775	1718, 4746, 857, 1641	2984, 6831, 2061, 2194

Notes: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GW = gigawatts. Non-fossil fuels include solar, wind, hydro, nuclear, biomass, municipal solid waste, and geothermal.
a. 2021 Historical Data Source: (CEA 2022).

Source: Authors.

TABLE 36 | Power sector: Share of non-fossil fuels in total installed capacity (%)

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	DECEMBER 2021 VALUE	2030 MILESTONE	2040 MILESTONE	2050 MILESTONE
Reference	38.4	45, 65, 62, 63	43, 73, 73, 70	45, 75, 77, 75
2°C ECPC		64, 65, 63, 64	65, 75, 82, 72	67, 81, 89, 84
2°C FI		63, 65, 64, 64	69, 75, 83, 73	71, 84, 90, 85
1.5°C ECPC		61, 69, 63, 68	70, 85, 79, 82	77, 94, 88, 91
1.5°C FI		59, 69, 62, 69	73, 87, 80, 83	92, 94, 89, 91
2°C PCC		60, 65, 62, 72	72, 75, 75, 88	92, 99, 87, 92
1.5°C PCC		70, 95, 62, 82	85, 100, 78, 90	95, 100, 90, 93

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

TABLE 37 | Power sector: Share of electricity generation from non-fossil fuel energy

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE[a]	2030 MILESTONE	2040 MILESTONE	2050 MILESTONE
Reference	24.62	25, 35, 43, 39	26, 45, 56, 55	29, 48, 59, 68
2°C ECPC		42, 35, 43, 50	45, 45, 70, 70	51, 57, 81, 89
2°C FI		42, 35, 44, 50	51, 45, 71, 71	57, 60, 82, 91
1.5°C ECPC		41, 38, 43, 54	53, 61, 65, 83	66, 81, 79, 96
1.5°C FI		41, 38, 43, 55	59, 63, 66, 84	87, 87, 80, 96
2°C PCC		44, 35, 44, 59	60, 45, 57, 93	88, 95, 76, 96
1.5°C PCC		55, 86, 43, 76	76, 100, 62, 94	93, 100, 85, 97

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. TWh = terawatt-hour.

a. 2019 Historical Data Source: (CEA 2020b).

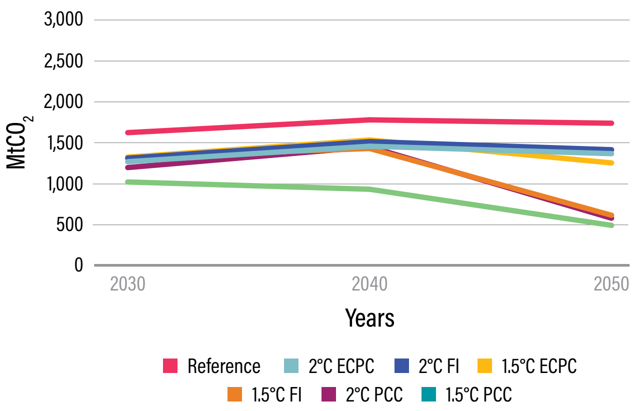
Source: Authors.

Power sector emissions

Although electricity generation grows 3.1–4.1 times from 2020–50 in the reference scenario, emissions only grow 1.4–2.1 times in the same period. This is because a certain level of decoupling of electricity generation and emissions has already begun in India as a result of the rise in RE consumption. However, power sector emissions rise up to 2050 in the reference scenario of the four models. CGE emissions peak in 2045 and begin to decline slightly thereafter because absolute coal consumption peaks in 2045, but power sector emissions in the other three models continue to rise up to 2050, although at different growth rates.

Because the transition of the power sector from fossil fuels to renewables has already begun in India, power sector emissions peak and begin to decline in most scenarios across models despite the rise in electricity generation in the policy scenarios, demonstrating the decoupling of emissions and growth in the power sector. In CGE (Figure 24) and SAFARI (Figure 26), power sector emissions across all scenarios remain under 2,000 MtCO$_2$ up to 2050, whereas in GCAM (Figure 25), the 1.5°C and 2°C PCC scenarios stay under it, but the other 2°C and reference scenarios exceed it from 2030 onward. In the EPS (Figure 27), power sector emissions are the lowest, staying under 1,500 MtCO$_2$ across all scenarios across time. In terms of power sector emissions peaking years, in CGE, 1.5°C PCC peaks by 2030, and all the other scenarios, including the reference scenario, peak by 2040. In GCAM, 1.5°C PCC power sector emissions peak by 2030 and reach 0 by 2040, the other 1.5°C scenarios and 2°C PCC peak by 2040 (the latter reaching 0 by 2050), and other 2°C scenarios (FI and ECPC) along with the reference scenario do not peak by 2050. In SAFARI and the EPS, all policy scenarios peak by 2030 compared to the reference scenario, which does not peak by 2050.

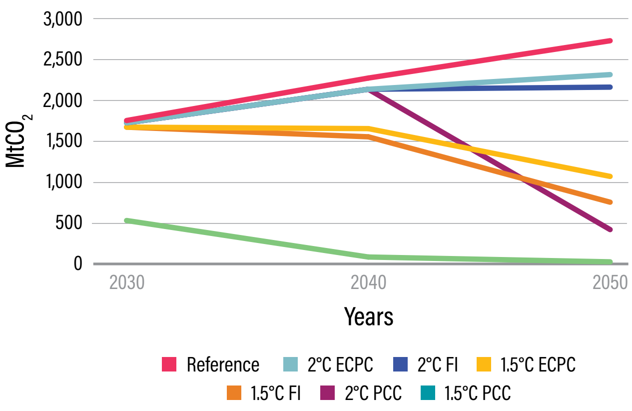
FIGURE 24 | CGE: Power sector emissions ($MtCO_2$)



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

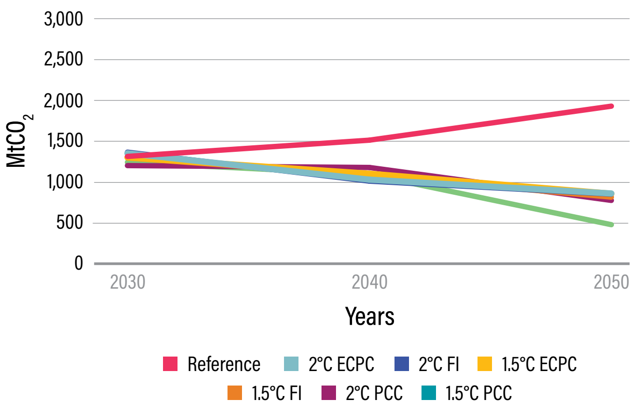
FIGURE 25 | GCAM: Power sector emissions ($MtCO_2$)



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

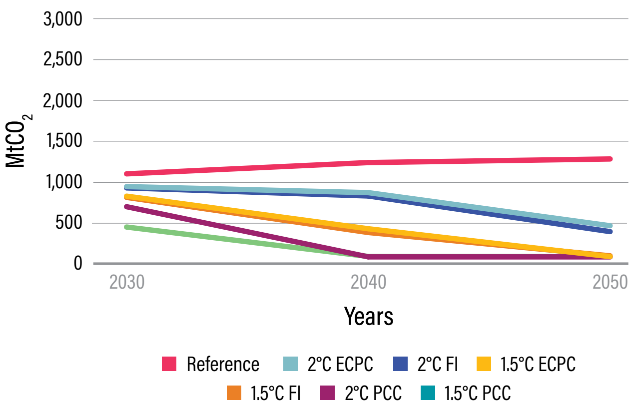
FIGURE 26 | SAFARI: Power sector emissions ($MtCO_2$)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

FIGURE 27 | EPS: Power sector emissions ($MtCO_2$)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. $MtCO_2$ = megatonnes of carbon dioxide.

Source: Authors.

The LULUCF sector

The modeling studies discussed above use only real emission reduction options while creating the low carbon pathways that limit cumulative emissions to the calculated carbon budgets for India. However, some carbon budgets—namely, PCC in both temperature scenarios—are so stringent that it may not be technologically feasible to decarbonize the economy fast enough and at the scale required to limit cumulative emissions to these prescribed budgets, as seen in CGE, SAFARI, and the EPS, which all exceed the PCC budgets. In this case, the LULUCF sector can be a source of carbon dioxide removals/sequestration that can neutralize the excess emissions beyond the prescribed budget. As all the models do not include the LULUCF sector in their framework (SAFARI and the EPS do to some extent, whereas CGE and GCAM do not include it), for the sake of comparability, we restricted the modeling analysis to the energy sector and conducted a separate external analysis to understand the scope for CDR in the LULUCF sector. This section gives an overview of the findings from this analysis.

Changes in land cover and land management influence the exchange of GHG fluxes between the terrestrial biosphere system and the atmosphere. Change in carbon stock in plant biomass and soil organic carbon (SOC) are an indicator of GHG removal from the vegetative/non-vegetative ecosystem. In India, the LULUCF sector has been acting as a net sink, and its mitigation potential has established its relevance. Based on the latest National GHG Inventory report (MoEFCC 2021), the LULUCF sector was responsible for abatement of 15 percent of the country's carbon dioxide emissions in 2016.

The incremental contributions of agriculture to GHG emission during the last five decades are well recognized (Smith et al. 2014). However, the fragmented nature of the sector and the complex interlinkage with nutritional need, food security, and the livelihood dependence of the major share of the rural population preclude adoption of critical emission reduction measures. Emission from the agriculture sector, such as methane and nitrous oxide, is broadly associated with enteric fermentation, manure management, rice cultivation, and application of synthetic fertilizers.

The current study is intended to assess the mitigation potential of the LULUCF sector in the medium-term and long-term scenarios.

Overview of different scenarios

Of the six GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) estimated and reported in the National GHG Inventory, LULUCF accounts for and reports on three: CO_2, CH_4, and N_2O.

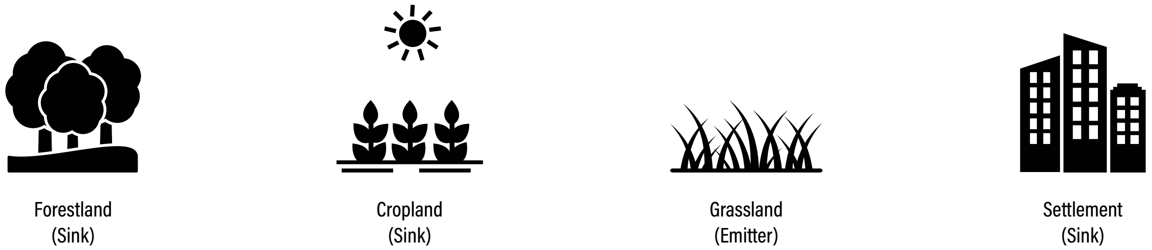
The key contributors to the LULUCF sector's GHG emission/removal (per the national inventory reporting) are Grassland (emitter) and Forestland, Cropland, and Settlement (sink) (Figure 28). Grassland was reported as a GHG sink per the GHG inventory for the year 2000. Settlement was reported as a GHG emission source per the GHG inventory for the year 2011.

Key policies, programs, and pledges are laid out by the Government of India as part of its national and international commitments and are likely to govern forestry sector growth and GHG abatement potential in the future. Further, acts and rules are in place to conserve forests and increase green cover. Although, the NDC pledge has clearly outlined the quantifiable target for achieving an additional carbon sink of 2.5 to 3 billion tCO_2eq by 2030 through additional forest and tree cover, it has not clarified the base year from which the carbon sink needs to be measured (FSI 2019).

The annualized CDR from the LULUCF sector during 2030, 2040, 2050, and 2100 is estimated based on the assumption of a carbon sink in line with the NDC pledge and the projected growth of the LULUCF sector up to 2100. Because the base year has not been specified in the NDC, we have assumed 2005 as the base year, in line with the base year of all the other NDC commitments. Table 38 summarizes the different scenarios considered in the LULUCF sector's analysis.

The detailed methodology of the analysis is given in Appendix D.

FIGURE 28 | Key contributors to the LULUCF sector's GHG emissions and removals



Notes: GHG = greenhouse gas; LULUCF = land use, land use change and forestry.

Sources: IPCC 2003, 2006; MoEFCC 2012, 2021.

TABLE 38 | AFOLU sector scenario descriptions

SCENARIO	TITLE	2030	2100
1	Business-as-usual (BAU)/reference pathway based forecasting	Estimation of long-term GHG emission/removal potential based on the growth of the carbon stock in forests and trees outside forests (ToF) between 2011 and 2017 and the increment in the area under different land categories based on the historical trajectory. The base year for the possibility of achieving the NDC commitment is 2005.	
2.1	NDC-pledge-compliant scenario without GHG emission/removal cap by 2100. (Highly Optimistic Scenario).	Achieving an additional carbon sink of 2.5 to 3.0 billion tCO_2eq above the GHG level projected for 2030 in the BAU scenario.	The scenario assumes that the increasing trend in carbon stock achieved up to 2030 toward compliance with the NDC target will be continued up to 2100 and the increment in the area will follow the growth trend.
2.2	NDC-pledge-compliant scenario without GHG emission/removal cap by 2100 and land expansion cap after 2030. (Highly Optimistic Scenario).	Achieving an additional carbon sink of 2.5 to 3.0 billion tCO_2eq above the GHG level projected for 2030 in the BAU scenario.	The scenario assumes that the increasing trend in carbon stock achieved up to 2030 toward compliance with the NDC target will be continued up to 2100 with caps on land expansion (for cropland, grassland, and settlement) after 2030.
3.1	NDC-and-NFP-pledge-compliant scenario with moderate emission cap. (Moderate Scenario).	Economy, energy, water, agriculture and land use, and climate	Achieving entire restoration of open forest and estimated restoration potential of impaired forest by 2100 (long-term emission capping).
3.2	NDC-and-NFP-pledge-compliant scenario with conservative emission cap (Conservative Scenario).	Population growth rate, GDP growth rate, technology characteristics, labor force participation and productivity, and emission constraints	Achieving the estimated restoration potential of open forest and estimated restoration potential of impaired forest by 2100 (long-term emission capping). The scenario also results in compliance with the forest policy requirement of a minimum geographical area under forest and tree cover (33%).

Notes: AFOLU = Agriculture, Forestry, and Other Land Use; GHG = greenhouse gas; NDC = nationally determined contributions; NFP = National Forest Policy; tCO_2eq = tonnes of carbon dioxide equivalent. The NFP requires 33 percent of the geographical area to be under forest and tree cover.

Source: Authors.

Results of analysis of different scenarios

Tables 39–44 summarize the annualized GHG emissions/removals from the LULUCF sector (both total and component-wise) in the milestone years 2030, 2040, 2050, and 2100 for the five scenarios described above.

TABLE 39 | Scenario 1: Net GHG emission/removal from LULUCF sector under BAU scenarios ($MtCO_2e$)

YEAR	ANNUALIZED GHG EMISSION/ REMOVAL: FORESTLAND	ANNUALIZED GHG EMISSION/ REMOVAL: CROPLAND	ANNUALIZED GHG EMISSION/ REMOVAL: GRASSLAND	ANNUALIZED GHG EMISSION/REMOVAL: SETTLEMENT	ANNUALIZED GHG EMISSION/REMOVAL: LULUCF SECTOR
2030	–103.68	–248.08	25.08	–3.20	–329.88
2040	–103.04	–253.17	27.23	–3.40	–332.38
2050	–102.40	–258.25	29.36	–3.61	–334.89
2100	–99.30	–283.61	39.94	–4.62	–347.59

Notes: GHG = greenhouse gas; LULUCF = land use, land use change, and forestry; NDC = nationally determined contributions; NFP = National Forest Policy; $MtCO_2eq$ = megatonnes of carbon dioxide equivalent.

Source: Authors.

TABLE 40 | Scenario 2.1: Net GHG emission/removal from LULUCF sector under NDC-pledge-compliant scenario without GHG emission/removal cap by 2100 ($MtCO_2e$)

YEAR	ANNUALIZED GHG EMISSION/ REMOVAL: FORESTLAND	ANNUALIZED GHG EMISSION/ REMOVAL: CROPLAND	ANNUALIZED GHG EMISSION/ REMOVAL: GRASSLAND	ANNUALIZED GHG EMISSION/REMOVAL: SETTLEMENT	ANNUALIZED GHG EMISSION/REMOVAL: LULUCF SECTOR
2030	–184.78 to –209.67	–300.39 to –321.24	19.54 to 16.48	–6.49 to –7.80	–472.12 to –522.24
2040	–183.52 to –208.25	–306.31 to –327.50	18.68 to 15.37	–6.90 to –8.29	–478.05 to –528.67
2050	–182.27 to –206.84	–312.22 to –333.73	17.83 to 14.29	–7.31 to –8.78	–483.96 to –535.07
2100	–176.18 to –199.99	–341.58 to –364.69	13.79 to 9.09	–9.28 to –11.13	–513.25 to –566.72

Notes: GHG = greenhouse gas; LULUCF = land use, land use change, and forestry; NDC = nationally determined contributions; NFP = National Forest Policy; $MtCO_2eq$ = megatonnes of carbon dioxide equivalent.

Source: Authors.

TABLE 41 | Scenario 2.2: Net GHG emission/removal from LULUCF sector under NDC-pledge-compliant scenario without GHG emission/removal cap by 2100 and land expansion cap after 2030 ($MtCO_2e$)

YEAR	ANNUALIZED GHG EMISSION/ REMOVAL: FORESTLAND	ANNUALIZED GHG EMISSION/ REMOVAL: CROPLAND	ANNUALIZED GHG EMISSION/ REMOVAL: GRASSLAND	ANNUALIZED GHG EMISSION/REMOVAL: SETTLEMENT	ANNUALIZED GHG EMISSION/REMOVAL: LULUCF SECTOR
2030	–184.78 to –209.67	–294.99 to –315.46	18.72 to 15.42	–6.00 to –7.22	–467.05 to –516.93
2040	–183.52 to –208.25	–294.63 to –315.01	18.77 to 15.49	–5.98 to –7.19	–465.36 to –514.96
2050	–182.27 to –206.84	–294.28 to –314.56	18.83 to 15.56	–5.96 to –7.16	–463.68 to –513.00
2100	–176.18 to –199.99	–292.58 to –312.38	19.10 to 15.91	–5.86 to –7.03	–455.52 to –503.48

Notes: GHG = greenhouse gas; LULUCF = land use, land use change, and forestry; NDC = nationally determined contributions; NFP = National Forest Policy; $MtCO_2eq$ = megatonnes of carbon dioxide equivalent.

Source: Authors.

TABLE 42 | Scenario 3.1: Net GHG emission/removal from LULUCF sector under NDC-and-NFP-pledge-compliant scenario with moderate emission cap by 2100 (MtCO$_2$e)

YEAR	ANNUALIZED GHG EMISSION/ REMOVAL: FORESTLAND	ANNUALIZED GHG EMISSION/ REMOVAL: CROPLAND	ANNUALIZED GHG EMISSION/ REMOVAL: GRASSLAND	ANNUALIZED GHG EMISSION/REMOVAL: SETTLEMENT	ANNUALIZED GHG EMISSION/REMOVAL: LULUCF SECTOR
2030	–160.68 to –155.44	–273.83 to –269.32	22.12 to 22.85	–4.75 to –4.48	–417.14 to –406.40
2040	–159.73 to –154.53	–273.59 to –269.10	22.16 to 22.89	–4.73 to –4.47	–415.88 to –405.21
2050	–158.78 to –153.62	–273.34 to –268.87	22.20 to 22.92	–4.72 to –4.45	–414.64 to –404.02
2100	–154.20 to –149.19	–272.14 to –267.78	22.39 to 23.10	–4.65 to –4.39	–408.59 to –398.26

Notes: GHG = greenhouse gas; LULUCF = land use, land use change, and forestry; NDC = nationally determined contributions; NFP = National Forest Policy; MtCO$_2$eq = megatonnes of carbon dioxide equivalent.

Source: Authors.

TABLE 43 | Scenario 3.2: Net GHG emission/removal from LULUCF sector under NDC-pledge-compliant scenario with conservative emission cap by 2100 (MtCO$_2$e)

YEAR	ANNUALIZED GHG EMISSION/ REMOVAL: FORESTLAND	ANNUALIZED GHG EMISSION/ REMOVAL: CROPLAND	ANNUALIZED GHG EMISSION/ REMOVAL: GRASSLAND	ANNUALIZED GHG EMISSION/REMOVAL: SETTLEMENT	ANNUALIZED GHG EMISSION/REMOVAL: LULUCF SECTOR
2030	–139.01 to –133.77	–256.95 to –252.44	24.84 to 25.57	–3.75 to –3.48	–374.90 to –364.12
2040	–138.16 to –132.96	–256.78 to –252.29	24.87 to 25.59	–3.74 to –3.47	–373.81 to –363.13
2050	–137.33 to –132.16	256.61 to –252.15	24.89 to 25.61	–3.73 to –3.46	–372.77 to –362.16
2100	–133.25 to –128.24	–255.81 to –251.45	25.02 to 25.72	–3.68 to –3.42	–367.72 to –357.40

Notes: GHG = greenhouse gas; LULUCF = land use, land use change, and forestry; NDC = nationally determined contributions; NFP = National Forest Policy; MtCO$_2$eq = megatonnes of carbon dioxide equivalent.

Source: Authors.

TABLE 44 | Cumulative of Net GHG emission/removal from LULUCF sector considering 2017 the baseline year (MtCO2e)

SECTOR	2030	2040	2050	2100
Forest	–2,100 to –2,150	–3,470 to –3,570	–4,830 to –4,990	–11,550 to –11,970
Cropland	–3,280 to 3,340	–5,800 to –5,910	–8,320 to –8,470	–20,870 to –21,230
Grassland	320 to 330	570 to 590	820 to 850	2,080 to 2,140
Settlements	–45 to –49	–80 to –86	–114 to –123	–284 to –305
Cumulative LULUCF	–5,105 to –5,209	–8,780 to –8,976	–12,444 to –12,733	–30,624 to –31,365

Notes: GHG = greenhouse gas; LULUCF = land use, land use change, and forestry; NDC = nationally determined contributions; NFP = National Forest Policy; MtCO$_2$eq = megatonnes of carbon dioxide equivalent.

Source: Authors.

India’s primary energy consumption will grow over time due to rising population growth, income, and urbanization with improvements in the energy intensity of production but higher per capita energy consumption.

Scenario 3.2 is the most likely conservative scenario because of its compliance with the long-term policies and programs of the national government that aim to enhance the forest-based carbon sink by integrating both the increased area under plantation and instituting sustainable forest management practices resulting in restoration of the forest ecosystem.

PRIMARY ENERGY CONSUMPTION

Primary energy consumption is the consumption of fossil fuels across the economy at their source, before they undergo transformation (e.g., coal to electricity or heat). The primary fuel mix broadly consists of coal, oil, gas, solar, wind, nuclear, and hydro in all models, plus biomass/ biofuels in all but CGE and geothermal in GCAM. India’s primary energy consumption will grow over time due to rising population growth, income, and urbanization with improvements in the energy intensity of production but higher per capita energy consumption.

Reference scenario

In the reference scenario, more than 75 percent of India’s energy needs up to 2050 are still met using fossil fuels in all the models. Coal continues to be the dominant fuel in all the three models (the EPS being the exception) but at a declining rate because the shares of solar and wind energy rise in the power sector due to falling costs and policy support. However, the shares of other fossil fuels such as O&G either remain constant or rises because according to CGE, SAFARI, and the EPS almost no decarbonization occurs in the reference scenario in the transport and industry sectors, where they are used most, and only to a limited extent in GCAM, which is progressive but not enough to bend the emissions curve. In terms of other non-fossil fuel sources such as nuclear, hydro, biomass, and geothermal, hydro and nuclear play an important role in CGE because hydro is used to balance the variability of RE and nuclear provides the base load, whereas in GCAM, biomass plays an important role (in industry). Nuclear and hydro play marginally increasing roles in SAFARI and the EPS, respectively. Table 45 gives a break-up of the primary energy mix of each model.

TABLE 45 | Reference scenario primary energy consumption across models (EJ)

	CGE			GCAM			SAFARI			EPS		
CGE	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Total	**48.77**	**67.00**	**87.42**	**45.48**	**64.53**	**83.55**	**39.70**	**54.70**	**73.93**	**59.42**	**89.85**	**121.10**
Coal	21.01	25.74	28.82	21.50	28.56	35.65	20.33	25.64	33.65	22.70	29.10	33.64
Oil	14.15	20.31	25.68	12.11	15.53	18.08	12.60	17.88	24.30	15.34	21.67	30.02
Gas	3.04	4.26	5.49	4.71	8.98	14.67				3.45	7.43	9.64
Solar	2.48	3.82	6.56	1.34	3.49	5.54	0.79	2.43	4.57	4.31	11.68	15.74
Wind	1.98	3.48	6.54	0.70	1.30	1.73	0.93	2.11	4.02	2.83	7.87	18.32
Nuclear	1.95	2.66	4.48	0.34	0.68	1.08	1.37	2.45	2.65	1.16	1.22	1.22
Hydro	4.16	6.73	9.86	0.56	0.65	0.78	1.24	1.80	1.92	2.55	3.12	3.70
Biomass				4.18	5.30	5.97	2.43	2.39	2.81	7.07	7.76	8.83
Geothermal				0.04	0.04	0.05						

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: FI = Fairness Index. EJ = exajoules.

Source: Authors.

Carbon budget scenarios

CGE

In CGE, unlike in the other models, the total primary energy consumption is much higher in the policy scenarios than in the reference scenario levels, with the additional consumption rising across scenarios as their carbon stringency rises. This is because CGE strives to achieve full equilibrium in the economy (unlike the other models), because of which industries manufacturing raw materials for renewables grow as the demand for renewables rises. The effect of this increased industrial growth then has a multiplier effect across the economy through direct, indirect, and induced impacts that increase the overall energy consumption in the economy. Energy demand is increasingly met by solar and wind energy across policy scenarios as their carbon stringency rises, which is enabled by higher investments and total factor productivity assumptions for renewables. The rise in variable RE such as solar and wind leads to an increase in nuclear and hydro, which are used for the base load and to balance variability, respectively. As a result, the shares of coal, oil, and natural gas decline in the policy scenarios relative to the reference scenario, with the decrease steepening with the carbon stringency of the scenarios, although they do not decline to zero by 2050 even in the most stringent scenarios because of the technological difficulty of fully decarbonizing the transport and industry sectors, the latter of which grows (and thus requires more fuel) in the policy scenarios as discussed above. Interestingly, in all the policy scenarios, the absolute demand for coal rises from 2030 and 2040 and then begins to fall after 2040, because in the initial years, a fall in coal consumption in the power sector is compensated by an increased demand in industry due to the price substitution

> In CGE the total primary energy consumption is much higher in the policy scenarios than in the reference scenario levels because it strives to achieve full equilibrium in the economy.

effect as explained in Box 1. Table 46 gives the share of non-fossil fuels, and Figure 29 gives the break-up of the total primary energy consumption by fuel source across time in all the scenarios.

GCAM

In GCAM, India's total primary energy consumption is lower in the policy scenarios than in the reference scenario, with the decrease steepening with the carbon stringency of the scenarios. This is because of their greater shift toward electrification in end-use sectors, which are inherently more energy efficient than their fossil fuel counterparts. Further, because of the late peaking of the high carbon budget scenarios in GCAM, the economy does not start

BOX 1 | CGE: Substitution effect between the power and industry sectors

As the power sector moves away from coal, its price falls due to lower demand and so the industry picks it up. However, after 2040, the high-electrification interventions in the industry sector kick in, and coal consumption falls again.

Notes: CGE = Computable General Equilibrium.

Source: Authors.

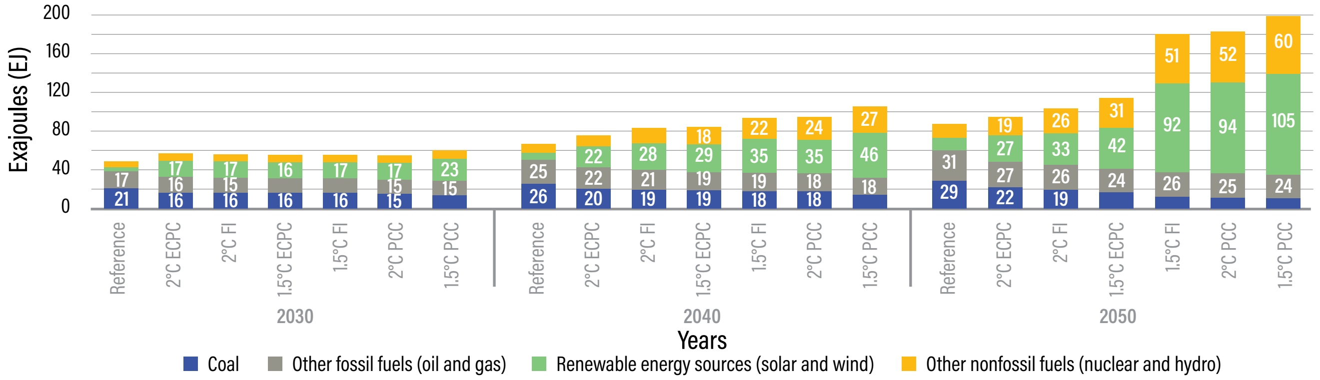
TABLE 46 | CGE: Primary energy consumption growth rate and share of non-fossil fuels

CGE	TOTAL ENERGY CONSUMPTION GROWTH RATE (2020-2050)	PERCENTAGE CUMULATIVE ANNUAL GROWTH RATE (2020-2050)	SHARE OF NON-FOSSIL FUELS (%)		
			2030	2040	2050
Reference	×2.7	3.4	22	25	31
2°C ECPC	×2.8	3.5	43	44	49
2°C FI	×3.1	3.8	43	52	56
1.5°C ECPC	×3.4	4.1	44	55	64
1.5°C FI	×5.3	5.7	44	61	79
2°C PCC	×5.4	5.8	45	62	80
1.5°C PCC	×5.9	6.1	53	70	83

Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE 29 | CGE: Primary energy consumption (EJ)



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

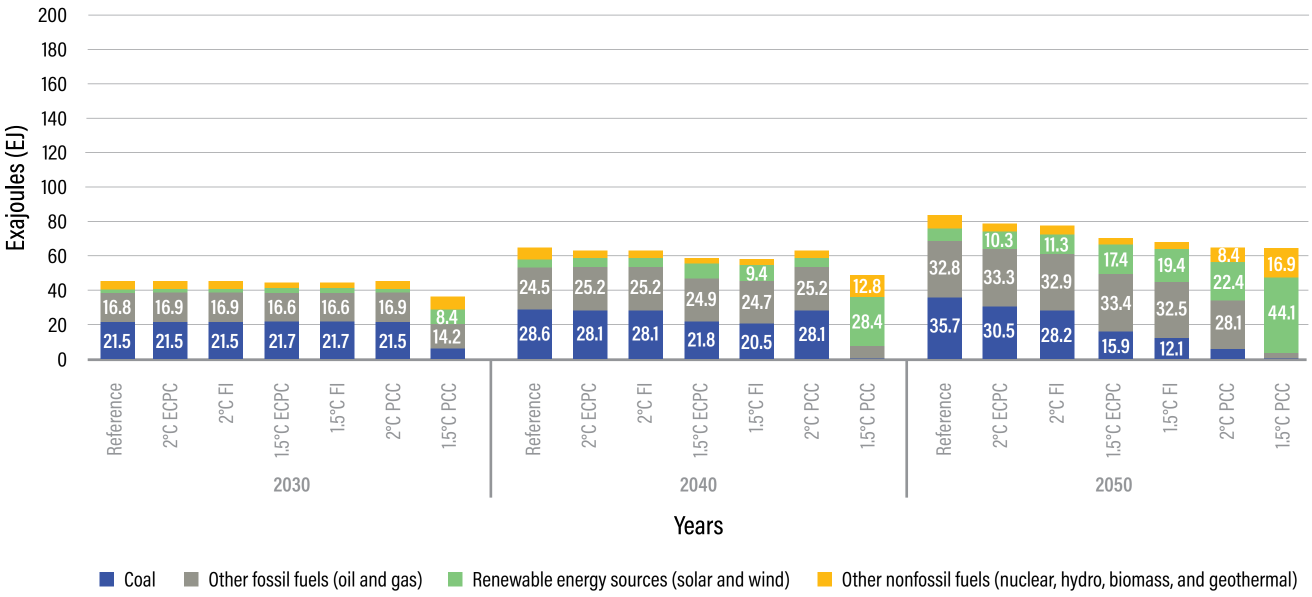
to decarbonize until then, as a result of which the share of non-fossil fuels in the total primary energy mix ranges from 19–48 percent in 2050 compared to 18 percent in the reference scenario. Although solar plays a key role in the non-fossil fuel mix, in both the PCC scenarios, the role of biomass becomes more important to achieve net zero by mid-century. The share of coal falls over time and scenarios but that of O&G rises as the truck segment of the transport sector is difficult to decarbonize, and in industry, gas is used as a transition fuel. Only in the two PCC scenarios do they decline to reach net zero by 2050–60. Table 47 gives the share of non-fossil fuels, and Figure 30 gives the break-up of the total primary energy consumption by fuel source across time in all the scenarios.

TABLE 47 | GCAM: Primary energy consumption growth rate and share of non-fossil fuels

GCAM	TOTAL ENERGY CONSUMPTION GROWTH RATE (2020-2050)	PERCENTAGE CUMULATIVE ANNUAL GROWTH RATE (2020-2050)	SHARE OF NON-FOSSIL FUELS (%)		
			2030	2040	2050
Reference	×2.7	3.4	16	18	18
2°C ECPC	×2.6	3.2	15	16	19
2°C FI	×2.5	3.1	15	16	21
1.5°C ECPC	×2.3	2.8	14	20	30
1.5°C FI	×2.2	2.7	14	22	34
2°C PCC	×2.1	2.5	15	16	48
1.5°C PCC	×2.1	2.5	44	85	95

Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

FIGURE 30 | GCAM: Primary energy consumption (EJ)



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

SAFARI

In SAFARI as well, the total primary energy consumption declines in the policy scenarios compared to the reference scenario, primarily due to demand reduction interventions and efficiency improvements in the economy. In terms of the fuel mix, the “no new coal” policy introduced in 2025 in the power sector reduces the absolute consumption of coal across time and scenarios (although it does not reach zero), but O&G persists in the economy at a rising trend across time (although lower than in the reference scenario) to meet the energy needs of the transport and industry sectors, which are difficult to decarbonize to a large extent by 2050 within SAFARI’s framework. The shares of solar and wind rise, but nuclear, biomass, and hydro do not play an important role in SAFARI’s scenarios. The share of non-fossil fuels across time thus ranges between 33 percent and 41 percent in 2050 across the scenarios. Although these shares are fairly low, the total energy consumption in SAFARI is lower than that in the other models. This is because although decarbonization technologies are still infeasible, the policy scenarios are made to align with the carbon budgets in the short to medium term through demand reduction interventions. Table 48 gives the share of non-fossil fuels, and Figure 31 gives the break-up of the total primary energy consumption by fuel source across time in all the scenarios.

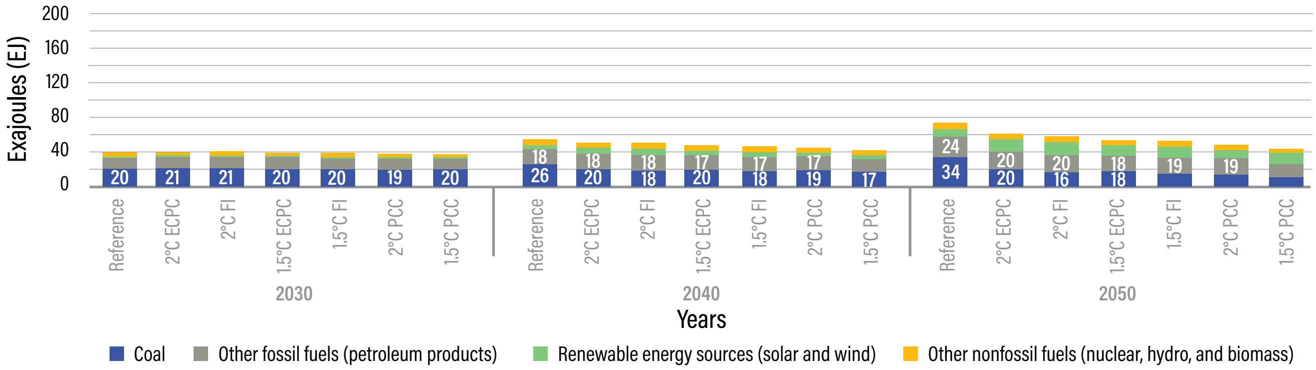
TABLE 48 | SAFARI: Primary energy consumption growth rate and share of non-fossil fuels

SAFARI	TOTAL ENERGY CONSUMPTION GROWTH RATE (2020–2050)	PERCENTAGE CUMULATIVE ANNUAL GROWTH RATE (2020–2050)	SHARE OF NON-FOSSIL FUELS (%)		
			2030	2040	2050
Reference	×2.5	3.1	17	20	22
2°C ECPC	×2	2.4	14	25	34
2°C FI	×1.9	2.2	18	28	38
1.5°C ECPC	×1.8	2	14	24	33
1.5°C FI	×1.8	1.9	18	27	37
2°C PCC	×1.6	1.6	15	22	32
1.5°C PCC	×1.5	1.3	14	25	41

Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE 31 | SAFARI: Primary energy consumption (EJ)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

EPS

In the EPS as well, primary energy consumption in the policy scenarios falls compared to the reference scenario due to interventions on energy and material efficiency in the end-use sectors. However, the total energy consumption is higher than that in GCAM and SAFARI, one of the reasons for which is the higher electricity demand owing to decarbonization of the industry sector using electrolysis-generated hydrogen, as well as higher energy consumption in industry than in other models (due to higher growth assumptions). However, a large share of the fuel mix gets decarbonized by 2050 across scenarios, with non-fossil-fuel-based energy (most of which is solar and wind) ranging from 60–85 percent, because the policy packages for each scenario were made to reach net zero emissions in the decades after 2050. Coal almost reaches zero by 2050 across most scenarios as it is completely phased out in the power sector and drops considerably in the industry sector. However, the share of O&G persists across scenarios owing to the difficulty of decarbonizing the freight truck segment of the transport sector (which is oil dependent) and the need for natural gas power plants to balance the variability of the rising share of variable RE (in the absence of sufficient battery storage). Table 49 gives the share of non-fossil fuels, and Figure 32 gives the break-up of the total primary energy consumption by fuel source across time in all the scenarios.

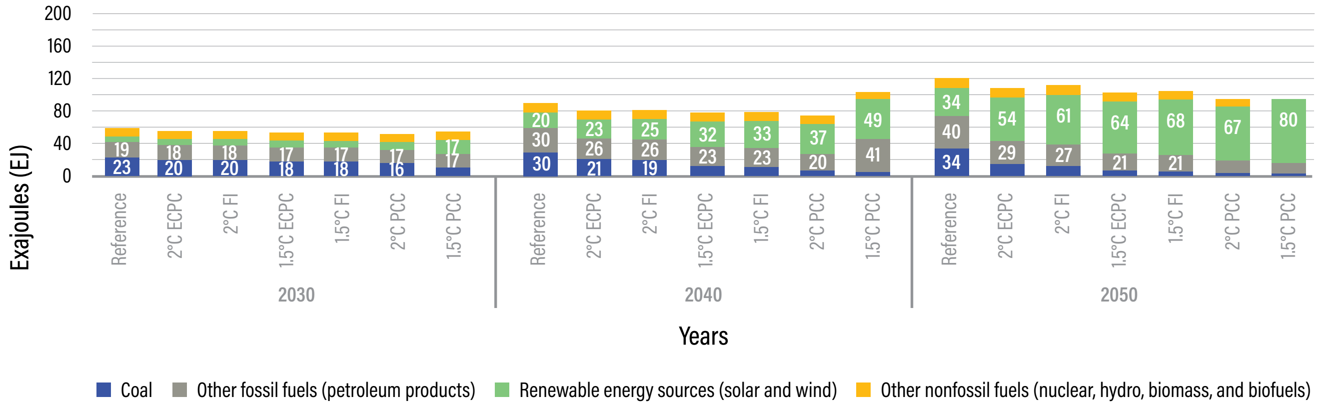
TABLE 49 | EPS: Primary energy consumption growth rate and share of non-fossil fuels

SAFARI	TOTAL ENERGY CONSUMPTION GROWTH RATE (2020–2050)	PERCENTAGE CUMULATIVE ANNUAL GROWTH RATE (2020–2050)	SHARE OF NON-FOSSIL FUELS (%)		
			2030	2040	2050
Reference	×3.2	4	29	35	39
2°C ECPC	×2.9	3.6	32	42	60
2°C FI	×3	3.7	32	44	65
1.5°C ECPC	×2.7	3.4	35	55	73
1.5°C FI	×2.8	3.5	35	56	75
2°C PCC	×2.5	3.1	38	64	80
1.5°C PCC	×2.8	3.5	50	71	85

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE 32 | EPS: Primary energy consumption (EJ)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

> CGE shows that reducing coal consumption in the power sector would reduce its market price, which would make industry pick it up instead.

Takeaways for policy

Putting all the four models together, CGE shows that the total primary energy consumption in the low carbon scenarios could exceed that in the reference scenario because the shift to RE boosts manufacturing in the industry sector. However, GCAM shows that the simultaneous shift to electrification of these processes could help improve their energy efficiency, and SAFARI and the EPS show that demand reduction and energy efficiency improvements can help reduce the total energy demand in the economy. In terms of the phasing down of coal, although it largely gets phased out of the power sector in the models (enabled by the availability of cheap RE), CGE shows that reducing coal consumption in the power sector would reduce its market price, which would make industry pick it up instead. This indicates the need for economy-wide rather than sectoral policies. Further, although the power sector becomes largely decarbonized, industry and freight trucks in the transport sector remain dependent on fossil fuels in all the models due to technological challenges, which sustains the presence of O&G in the economy, indicating the dire need for concerted R&D and policy support in the present decade to innovate mitigation options for them. In all the models, solar is the top RE choice given its lower costs, but supporting policies are imperative to improve its CUF, storage, T&D losses, and so on, to optimize the size of the constructed fleet. Lastly, the use of other fossil fuels such as hydro, nuclear, and biomass has largely been a policy choice in the models. CGE uses nuclear and hydro to provide the base load and manage variability in the power sector (the EPS achieves this using natural gas, and the other two models rely on the least cost basis to achieve this), whereas GCAM uses biomass to achieve net zero emissions in its two most ambitious scenarios, and the EPS uses electrolysis-generated hydrogen to decarbonize the industry sector.

Primary energy consumption milestones

Table 50 summarizes the four models' outputs in each scenario for the share of non-fossil fuel energy in India's total primary energy mix that should be reached in 2030, 2040, and 2050 to align with their corresponding carbon budgets.

TABLE 50 | Primary energy consumption: Share of non-fossil fuel sources (%)

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE	2030 MILESTONE	2040 MILESTONE	2050 MILESTONE
Reference	9.4	22, 16, 17, 29	25, 18, 20, 35	31, 18, 22, 39
2°C ECPC		43, 15, 14, 32	44, 16, 25, 42	49, 19, 34, 60
2°C FI		43, 15, 18, 32	52, 16, 28, 44	56, 21, 38, 65
1.5°C ECPC		44, 14, 14, 35	55, 20, 24, 55	64, 30, 33, 73
1.5°C FI		44, 14, 18, 35	61, 22, 27, 56	79, 34, 37, 75
2°C PCC		45, 15, 15, 38	62, 16, 22, 64	80, 48, 32, 80
1.5°C PCC		53, 44, 14, 50	70, 85, 25, 71	83, 95, 41, 85

Notes: Models: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

a. 2019 Historical Data Source: (MoSPI 2022).

Sources: Authors.

TABLE 51 | Primary energy consumption: Share of coal (%)

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE	2030 MILESTONE	2040 MILESTONE	2050 MILESTONE
Reference	44.5[a]	43, 47, 51, 27	38, 44, 47, 23	33, 43, 46, 20
2°C ECPC		29, 48, 53, 25	27, 45, 39, 18	23, 39, 33, 10
2°C FI		29, 48, 52, 25	23, 45, 36, 17	19, 36, 28, 8
1.5°C ECPC		29, 49, 51, 23	22, 37, 41, 11	15, 23, 33, 5
1.5°C FI		29, 49, 50, 23	19, 35, 38, 10	7, 18, 28, 4
2°C PCC		27, 48, 51, 21	19, 45, 41, 7	6, 9, 29, 3
1.5°C PCC		23, 17, 53, 14	13, 0, 40, 5	5, 0, 25, 2

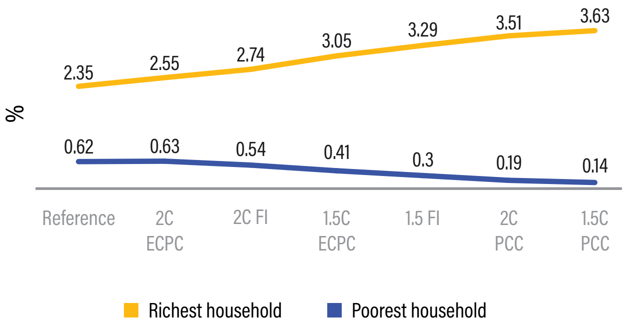
Notes: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

a. 2019 Historical Data Source: (IEA 2021).

Sources: Authors.

Table 51 summarizes the four models' outputs in each scenario for the share of coal in India's total primary energy mix that should be reached in 2030, 2040, and 2050 to align with their corresponding carbon budgets.

FIGURE 33 | CGE: Income inequality across scenarios



Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

SOCIOECONOMIC IMPACTS AND OTHER UNIQUE OUTCOMES OF THE MODELS

CGE

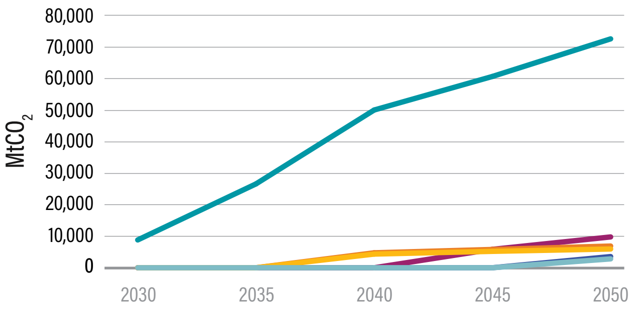
As the only full equilibrium and top-down model employed in this study, CGE's outcomes play a unique role in capturing the impact of the shift in investments from fossil fuels to renewables on the rest of the economy and the different actors within it. A key insight is the impact of the changing economy on private income and the resulting income inequality, because CGE treats different households as discrete agents in the economy who maximize profits individually. Households are differentiated based on rural and urban locations and type of employment. Thus, it can calibrate the relative income of different households over time. As seen in Figure 33, in the reference scenario, the poorest household earns 62 percent of the average household income. However, in the 1.5°C PCC scenario in 2050, the poorest household earns only 14 percent of the average household income, while the richest household earns 363 percent of the same value. The is because the new technologies (for RE generation and electrification) would be capital intensive and only the wealthy fraction of the population (who have access to more capital) would be able to invest in these sectors and hence would reap the benefits of their growth. On the other hand, the poor households (laborers, daily wage workers) currently employed in coal and other fossil sectors may become poorer if they become unemployed in the new technology landscape. Mitigative measures such as social inclusion, reskilling, capacity building, and other such initiatives are not captured by the CGE model, but they will be crucial to alleviate the negative impacts that the model does capture. This implies a widening of the income gap between the poor and rich in the carbon-constrained scenarios.

GCAM

In GCAM, the model solves for the carbon constraint in each time step in the least cost manner to the economy; that is, the sector that is the cheapest to mitigate is decarbonized first, followed by the next cheapest, and so on, until the quantum of mitigation required to meet the carbon constraint in that time step is fulfilled. The carbon price plays a crucial role in determining the price of each technology, which in turn determines the technology used to meet the demand in each sector and thus the type of fuel used and resultant emissions and reductions in the economy. In GCAM, the carbon price applied across the economy is an endogenous response estimated by the model to achieve the desired carbon constraint and thus reflects the magnitude of mitigation required in the economy. This is a unique outcome of great value, as this is the carbon price required over time to meet the desired emission target at the least cost to the economy.

No carbon price is applied in the reference scenario, but in all six policy scenarios, a carbon price is applied by the model, with only their magnitude and time lines varying. The carbon price in the economy is initiated in the peaking year and continues to rise until the year that net zero is achieved, after which it stabilizes. In other words, the carbon price is inversely proportional to the emissions in a carbon policy scenario: as emissions decline, the carbon price increases. As seen in Figure 34 and Table 52, in the two PCC scenarios, because net zero is achieved by 2050, the price in 2050 reflects the highest carbon price required by the scenario. In the other budget scenarios, the carbon price is negligible until the peaking year (2045 for 2°C ECPC and 2°C FI; 2040 for 1.5°C ECPC, 1.5°C FI, and 2°C PCC) and then begins to rise, corresponding to the decline in emissions required. However, the highest price is not reached until 2050, because net zero occurs after that. Moreover, the 1.5°C PCC scenario requires a substantially higher carbon price than the other scenarios because of the much higher mitigation efforts required to stay within its carbon budget of 46 $GtCO_2$.

FIGURE 34 | GCAM: Calculated carbon price



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

TABLE 52 | Carbon price estimated by GCAM (2018 INR/tCO_2)

SCENARIO	2025	2030	2035	2040	2045	2050
2°C ECPC						2,806
2°C FI						3,538
1.5°C ECPC				4,330	5,195	5,935
1.5°C FI				4,737	5,795	6,877
2°C PCC					5,831	9,766
1.5°C PCC		8,809	26,574	50,005	60,643	72,562

Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. tCO_2 = tonnes of CO_2.

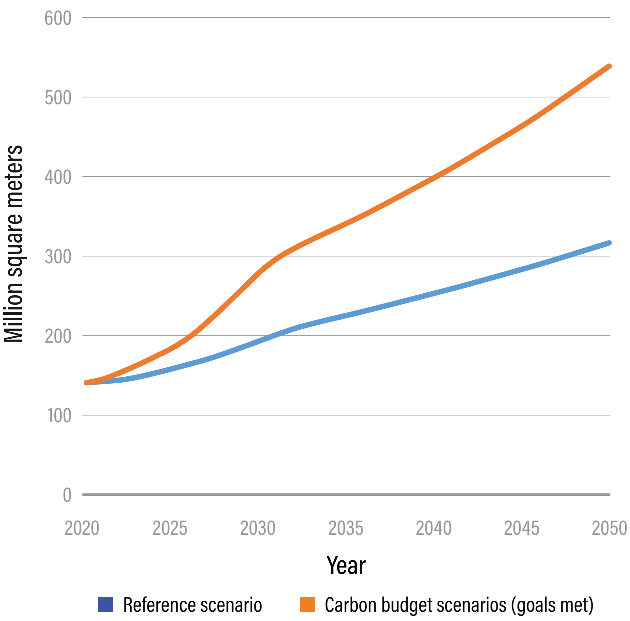
Source: Authors.

SAFARI

The SAFARI model focuses on the implications of achieving various development goals by 2030 and beyond. In the reference scenario, although some effort and progress has been made toward achieving the goals, they are not completely met. For instance, the affordable housing shortage in 2030 in the reference scenario would be about 26 million. Increased investments and prioritization of goals are thus required to be able to meet them.

In the policy scenarios, the development goals are met in 2050 by increasing the built area for healthcare units (Figure 35), educational institutions (Figure 36), and affordable housing (Figure 37) by 40 percent, 70 percent, and 25 percent, respectively, relative to the reference scenario (where the goals are not met). Regarding the other key goals, 100 percent of urban and rural households shift to clean cooking fuels by 2030, and food security is maintained up to 2050 through increased cropping intensity and better water-use efficiency. In terms of total electricity, energy, and emissions, the increase relative to the reference scenario is only marginal (5–10 percent).

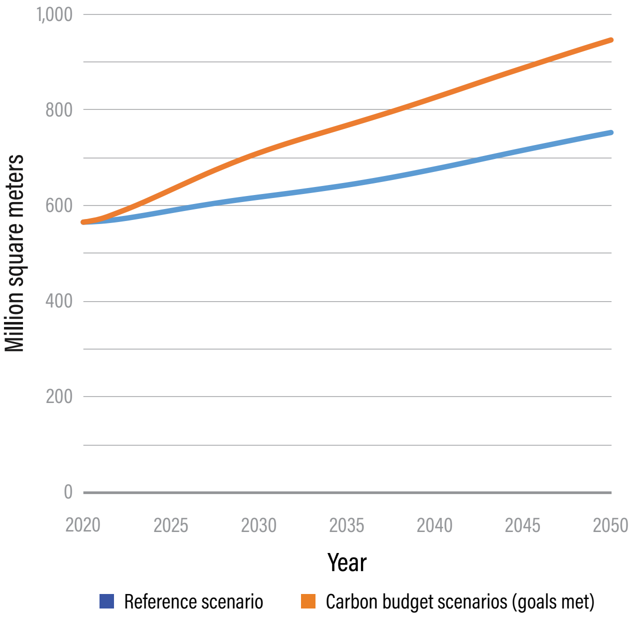
FIGURE 35 | SAFARI: Built area for healthcare units



Notes: SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

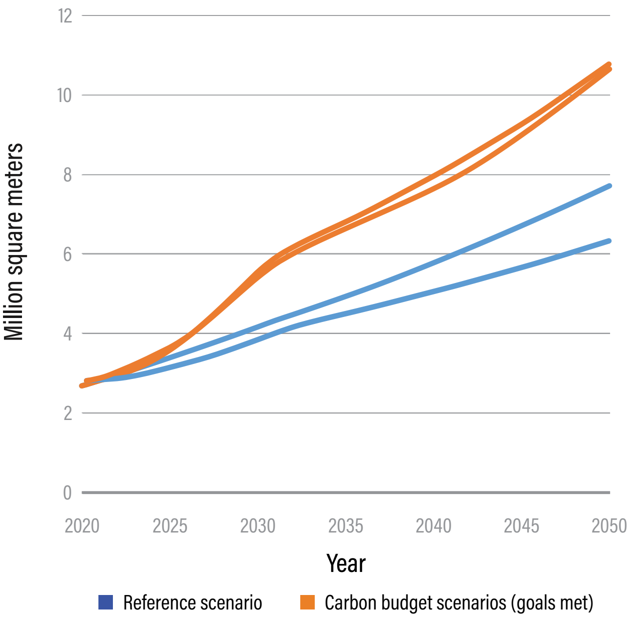
FIGURE 36 | SAFARI: Built area for schools and colleges



Notes: SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

FIGURE 37 | SAFARI: Built area for affordable housing



Notes: SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

EPS

The EPS calculates the impact of the chosen policy package on a variety of socioeconomic outcomes such as the impact on jobs, the GDP, cost savings, and health impacts with respect to the reference scenario. It also gives the marginal abatement cost curve of the policy package and the isolated impact of each chosen policy on the total achieved emissions reduction in terms of tCO_2 (this is possible given the systems dynamics framework of the EPS). A snapshot of the key outcomes is discussed below.

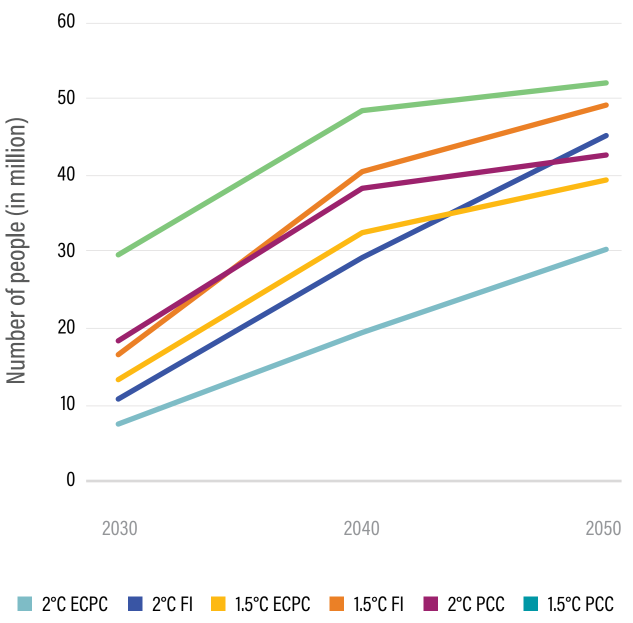
> A shift away from oil in low carbon scenarios significantly hits government cash flows, which in turn significantly impacts induced jobs and the GDP. One way to alleviate this is to impose a carbon tax, which brings in significant revenue in the short and medium term of the climate policy scenarios, thus compensating for the fall in oil revenues and preventing negative impacts on jobs and the GDP.

Change in jobs and GDP (with respect to the reference year = 0)

A unique outcome of the EPS is the impact of the chosen policy package on job creation and the GDP. Jobs impacted as a result of direct changes in a sector are categorized as *direct* (for example, workers in vehicle manufacturing). *Indirect* jobs are those impacted in the supply chains of the impacted sector (for example, workers in the steel industry, which supplies raw materials to the vehicle manufacturing sector). *Induced* jobs are those impacted as a result of a change in expenditure by the government/consumer because of a change in their income caused by the impact of the policy package on a sector/the economy. Higher private income due to increased direct/indirect job creation would raise private expenditure on goods consumption (for example, food), which would in turn have a multiplier effect on the rest of the economy (for example, agriculture) and their jobs, income, and thus the overall GDP. Higher income would also lead to higher tax revenue (income tax, sales tax, corporate tax, etc.) for the government, which would increase their expenditure in other sectors (such as public infrastructure, thus creating jobs and boosting income and the GDP there).

A few policy interventions significantly impact both job creation and the GDP. For one, policies on improved material efficiency in sectors such as iron and steel or cement through reuse, recycling, material longevity, and other efforts reduce the demand for these raw materials, significantly contributing to emissions reduction but at the cost of the growth of the sector, thus negatively impacting all three—direct, indirect, and induced jobs—which in turn impacts the GDP through reduced consumption. These policies are thus employed in moderation. Conversely, sectors currently in a nascent stage of development but with huge scope for government and private investment such as green hydrogen significantly boost all three: emissions reduction, the GDP, and job growth. Finally, as taxes on liquid fossil fuels (petrol and diesel) currently constitute a significant source of government revenue, a shift away from oil in low carbon scenarios significantly hits government cash flows, which in turn significantly impacts induced jobs and the GDP as described above. One way to alleviate this is to impose a carbon tax, which brings in significant revenue in the short and medium term of the climate policy scenarios, thus compensating for the fall in oil revenues and preventing negative impacts on jobs and the GDP. It also buys time to shift to other sources of revenue for the long run, when carbon emissions fall across the economy and tax revenues from a carbon tax also fall.

FIGURE 38 | EPS: Change in jobs (millions) over time (reference = 0)

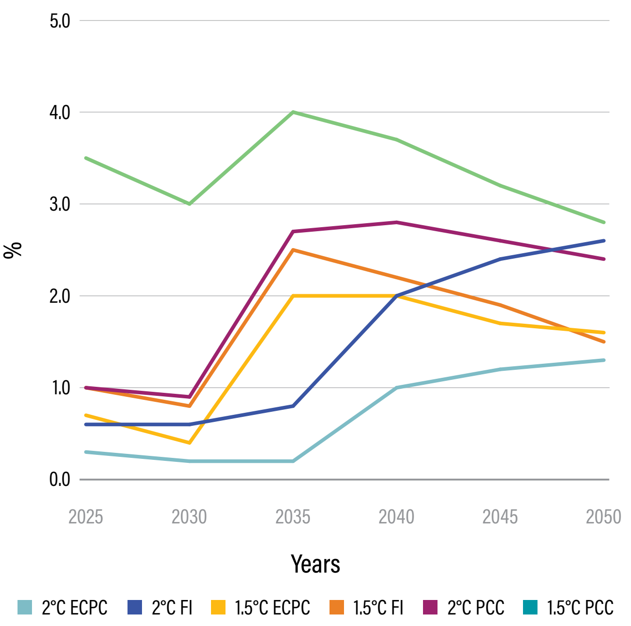


Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

The job numbers for each year are cumulative from 2020 until that year (for example, in 1.5°C PCC, approximately 52 million jobs were created from 2020 to 2050). Job losses are not factored in.

Source: Authors.

FIGURE 39 | EPS: Change in GDP (%) over time (reference = 0)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

Source: Authors.

Figures 38 and 39 show the changes in job creation and the GDP, respectively, relative to the reference scenario (i.e., reference = 0). The following trends can be observed:

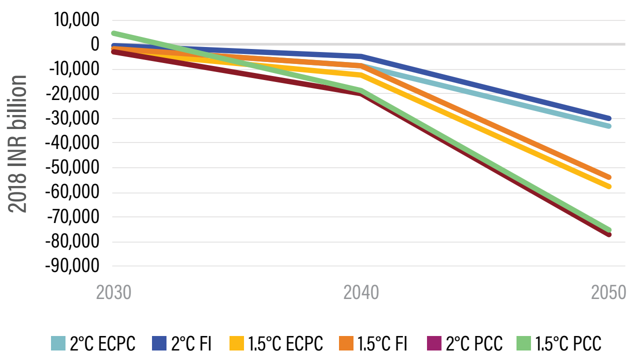
- The change in jobs relative to the reference scenario in all six policy scenarios is positive; that is, the chosen policy packages for all scenarios lead to the creation of additional jobs. Similarly, the percentage change in the GDP relative to the reference levels too is positive in all scenarios, implying a higher GDP in low carbon scenarios compared to the reference scenario.
- The quantum of jobs created and percentage GDP growth are both directly proportional to the stringency of the carbon budget; that is, the more ambitious the low carbon policy package, the higher are the job creation and GDP growth.
- However, the direction of change (rising or declining) of the GDP varies, with a continuous rise in the least ambitious scenarios but a rise followed by a fall in the most ambitious scenarios. This is because although the GDP growth in the 1.5°C PCC scenario is the highest among all scenarios up to 2050, it occurs with a declining trend because of falling government revenues from oil and carbon taxes as the scenario approaches net zero and the falling positive impact of increased investment in new technologies such as green hydrogen, as the technology becomes mature close to net zero. On the other hand, the GDP begins to rise after 2035 in 2°C ECPC (the least ambitious scenario) because that is when higher levels of green technologies such as hydrogen and EVs begin to get phased in, boosting the GDP. Thus, although a shift to a low carbon economy has a positive impact on jobs and the GDP in the short and medium term due to the investment boost in new technologies, decreasing individual costs from the reduced use of fossil fuels, and increasing government revenues from the imposition of a carbon tax, in the long term, as the economy approaches net zero, other sources of government tax revenue will have to be applied to sustain this positive impact.

Change in total costs to the economy (Opex + Capex with respect to the reference year = 0)

The EPS also calculates the impact of the chosen policy package on capital and operational costs (Opex and Capex) in the economy. Figure 40 shows a negative change in the total costs in all six policy scenarios, implying cost savings with respect to the reference scenario. Further, the extent of the cost savings is proportional to the ambition of the policy scenario; that is, the more stringent the carbon budget, the higher are the cost savings from the policy package chosen to meet it. These savings are a result of several shifts:

- The market-determined cost of clean technology options becoming competitive with or cheaper than fossil-fuel-based operations, such as a lower LCOE from RESs over thermal electricity or a lower TCO of EVs over ICEVs.
- Cost savings from reduced consumption of expensive fossil fuels, such as crude oil or petroleum gasoline and diesel, on which India is import dependent, which depend on global prices.
- An additional rise in the cost of fossil fuels if a strong carbon tax is imposed. This reduces fossil fuel consumption relative to the reference scenario in response to the higher price (because of the tax) to the extent that the total cost incurred in the policy scenario on the lower quantity of fuel consumed at a higher price is lower than that incurred on a higher quantity of fuel consumed at a lower price in the reference scenario, leading to net savings. In the case of these six policy scenarios, an exogenously determined carbon tax that is inversely proportional to the carbon budget of the scenario has been applied; that is, the lower the carbon budget, the higher the carbon tax. The carbon taxes applied are shown in Table 53.

FIGURE 40 | Change in costs (2018 INR million) to the economy from the policy package over time (reference = 0)



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

Source: Authors.

TABLE 53 | EPS: Carbon tax applied in the scenarios

SCENARIO	CARBON TAX (2018 INR) (FOR POWER AND INDUSTRY SECTORS)
2°C ECPC	INR 2,000, linearly phased in from 2020 to 2050
2°C FI	INR 3,000, linearly phased in from 2020 to 2050
1.5°C ECPC	INR 4,000, linearly phased in from 2020 to 2050
1.5°C FI	INR 5,000, linearly phased in from 2020 to 2050
2°C PCC	INR 6,000, linearly phased in from 2020 to 2050
1.5°C PCC	INR 8,000, linearly phased in from 2020 to 2050

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

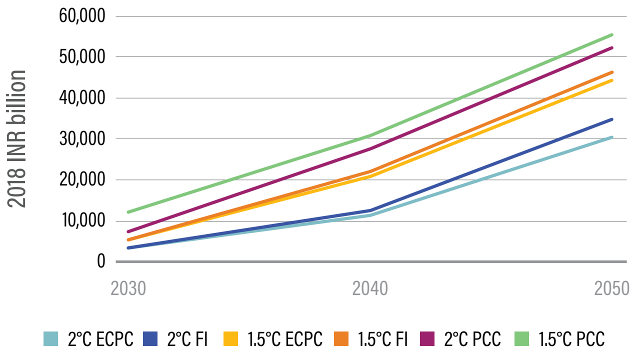
Source: Authors.

Note that the EPS does not recommend the most cost-optimal pathways for a scenario; thus, these trends represent the cost savings from the set of policies chosen to meet the carbon budget of a scenario, rather than the most cost-optimal pathway to meet the budget.

Health outcomes: Monetized avoided deaths and climate benefits

Apart from economic benefits such as cost savings and job creation, emissions reduction also significantly impacts social and ecological aspects such as health and water consumption. Although this study focuses on the reduction of CO_2 emissions, a shift to CO_2-free technology would lead to the induced reduction of other pollutants and particulate matter as well, such as PM 2.5, PM 10, sulfur oxides (Sox), and nitrous oxides (Nox), which directly impact premature mortality, respiratory symptoms, and cardiac diseases. The EPS calculates the impact of the chosen policy package on health impacts in different forms (Energy Policy Solutions n.d.). Figure 41 compares the monetized benefits from deaths avoided. Evidently, the monetized benefits are directly proportional to the stringency of the policy scenarios; that is, the lower the carbon budget, the greater the monetized health benefits.

FIGURE 41 | EPS: Monetized health benefits



Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. GDP = gross domestic product.

"Monetized" refers to avoided deaths and climate benefits from the chosen policy package in monetary terms with respect to the reference scenario (INR millions).

Source: Authors.

Note that these outcomes are a result of policies regulating CO_2 emissions alone. Inclusion of a few other policies such as regulations on fluorinated gases (F-gases) and methane in the industry sector and pollution standards in the transport sector can yield even more enhanced health co-benefits.

Abatement cost of various policies

The abatement cost curve gives the net present value (NPV) of the costs associated with the reduction of each tonne of CO_2e by a particular policy (calculated as the ratio of the NPV of the total cost and the total emissions abated up to a chosen point of time). This cost can be either positive or negative, that is, a cost savings. Some of the key policy interventions that resulted in negative abatement costs per tonne of CO_2e abated (i.e., cost gains) were efficiency measures across sectors, such as Industry Energy Efficiency Standards, Vehicle Fuel Economy Standards and Building Energy Efficiency Standards; a shift toward public transport through the "Mode Shifting of Vehicles policy"; and an EV sales mandate.

> Apart from economic benefits such as cost savings and job creation, emissions reduction also significantly impacts social and ecological aspects such as health and water consumption.

The imposition of a carbon tax has the highest impact on cumulative emission reduction from 2020 to 2050. This is because the carbon tax is introduced and fully phased in between 2020 and 2035 in all scenarios. It not only contributes greatly to government tax revenues, it also incentivizes a quick shift away from fossil-fuel-based operations because of their change in relative price.

Top policies contributing to 80 percent of total emission abatement

Table 54 gives a snapshot of the top 11 interventions that make the maximum contribution (percentage share) to cumulative emissions reduction from 2020 to 2050 in each of the EPS policy scenarios.

The imposition of a carbon tax has the highest impact on cumulative emission reduction from 2020 to 2050. This is because the carbon tax is introduced and fully phased in between 2020 and 2035 in all scenarios. This not only contributes greatly to government tax revenues, which in turn has a positive impact on jobs, the GDP, and public investment in technologies that are not yet market competitive such as green hydrogen, but also incentivizes a quick shift away from fossil-fuel-based operations because of their change in relative price.

Next, in the industry sector, two policies, that is, those on energy efficiency and electrification + hydrogen,[16] have the highest impact on emissions reduction. They are followed by material efficiency interventions, which have a very high potential for emissions reduction but have been applied in moderation due to their negative impact on jobs and the GDP. It was also observed that to prevent the displacement of emissions from industry to hydrogen production, the "electrification + hydrogen" policy must be supplemented with a policy on the production of hydrogen using electrolysis, instead of the current fossil-fuel-based practices.

In the power sector, the early retirement of thermal power plants has the highest impact on emissions reduction. This is because when thermal power plants are retired, the cost-optimizing mechanism in the EPS automatically replaces them with RE (solar and wind) plants to meet demand, due to their lower and falling costs. As a result, other policies incentivizing RE do not necessarily contribute more to emissions reduction by themselves.

In the transport sector, fuel efficiency standards and mode shifting make a higher impact in the low-ambitious scenarios where EV sales mandates are kept relatively lower. However, in the high-ambition scenarios, the EV sales mandate plays a more important role because it helps transform the fleet from ICEVs to EVs.

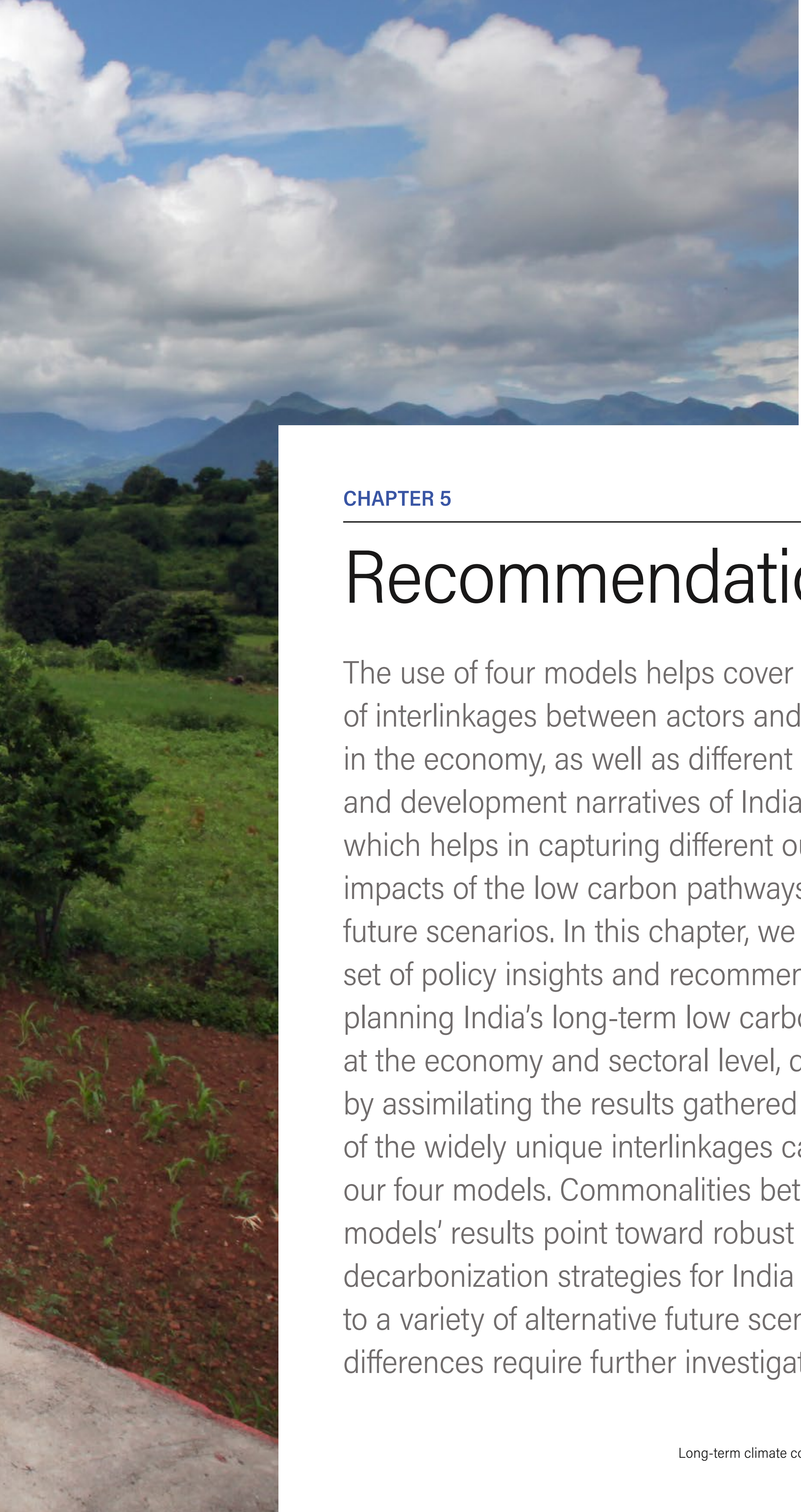
Note that the contributions of policies to total emissions reduction reported here are a result of the policy package chosen for each scenario, their implementation schedule, and the chosen stringency of the policy. The contributions will therefore change if these settings and choices are changed.

TABLE 54 | EPS: Policies with the highest impact on emission abatement (% contribution)

NATURE OF POLICY	POLICY INTERVENTION	2°C ECPC	2°C FI	1.5°C ECPC	1.5°C FI	2°C PCC	1.5°C PCC
Carbon pricing	Carbon tax	20	24	20	21	16	15
Energy efficiency	▪ Industry energy efficiency standards	15	13	11	10	11	9
	▪ Vehicle fuel economy standards	3	2	2	2	3	2
Demand reduction	▪ Mode shifting	3	3	2	2	2	2
	▪ Material efficiency, longevity, and reuse	7	6	8	8	11	10
Early retirement of power plants	Early retirement of thermal power plants	9	8	15	14	14	7
Electrification	▪ Electrification + hydrogen	10	12	12	13	12	19
	▪ EV sales mandate	2	3	4	4	5	9
	▪ Hydrogen vehicle sales mandate	1	1	2	2	2	2
	▪ Hydrogen electrolysis	6	7	7	8	8	11
Forest restoration		6	5	5	4	5	5
	Total contribution to cumulative emissions reduction from 2020 to 2050	**82**	**85**	**89**	**88**	**89**	**90**

Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. EV = electric vehicle; GDP = gross domestic product.

Source: Authors.



CHAPTER 5

Recommendations

The use of four models helps cover a variety of interlinkages between actors and sectors in the economy, as well as different economic and development narratives of India's future, which helps in capturing different outcomes and impacts of the low carbon pathways in different future scenarios. In this chapter, we discuss a set of policy insights and recommendations for planning India's long-term low carbon pathways at the economy and sectoral level, developed by assimilating the results gathered because of the widely unique interlinkages captured by our four models. Commonalities between the models' results point toward robust outcomes and decarbonization strategies for India applicable to a variety of alternative future scenarios, while differences require further investigation.

The purpose of employing four models as widely different as CGE, GCAM, SAFARI, and the EPS is to capture the differences and similarities in how they treat the same low carbon constraints so that Indian policymakers can become aware of the key pressure points and low-hanging fruit. In the earlier section titled "Modeling India's carbon budget scenarios," this was evident; the different approaches they employ (full equilibrium, cost optimization, prioritizing development, and what-if simulations) helped us gain rich insight into how the same low carbon scenario plays out when different interlinkages between the sectors and actors of the economy are captured, when different objectives are prioritized, and different kinds of interventions are used. This section aims to assimilate these learnings and formulate recommendations on India's climate policies for Indian policymakers.

The different sectors and actors of the economy are interlinked, so a systemic approach to decarbonization is necessary to identify and manage trade-offs and maximize impact. For this, a comprehensive strategy comprising cross-cutting policies and actions is needed. Various sectors of the economy demonstrate interlinkages and dependencies, and a narrow strategy that focuses only on a few sectors will not deliver the policy's maximum mitigation and development potential. We observe this in different forms in the models employed in this study. For example, the CGE model shows that a policy-driven incentive away from thermal power leads to a fall in coal prices (due to reduced demand), which then makes it cheaper for industry to use coal (this is known as the substitution effect), thus leading to a shift in emissions from one sector to another rather than overall mitigation. Similarly, the EPS shows that in the absence of a decarbonizing power sector, the increased consumption of electrolysis-generated hydrogen in industry (in place of fossil fuels) or a shift to EVs only displaces emissions to the power sector. Thus, a comprehensive policy that discourages the use of fossil fuels across all sectors may be more effective in containing emissions than one focused more narrowly on one sector or on a few sectors.

Policies that counterbalance socioeconomic trade-offs must be part of the mix. A well-designed and well-implemented carbon tax could play an important role in this. The contrasting impacts of the low carbon scenarios on the GDP across the four models reflect the core differences in their underlying modeling paradigms and economic assumptions. For example, because the CGE model starts with the assumption that the economy operates in equilibrium, the pursuit of climate objectives has a negative impact on economic growth as the economy shifts from labor-intensive fossil fuel sectors to more efficient, capital-intensive low carbon technologies. These negative impacts highlight the need for reskilling programs and good financial planning to ensure a just transition for the affected people and communities (this is discussed further in Recommendation 3). On the one hand, in the EPS, a similar negative impact on the GDP occurs, but unlike in the CGE scenarios, the EPS introduces a carbon tax, which is seen to be highly effective in offsetting this loss.[17] This is because the tax compensates for the fall in government revenue from the excise duty on oil, gas, and petroleum products (as their consumption gets phased out in low carbon scenarios). This revenue is then funneled back into the economy through increased government spending (made possible by another policy lever in the model), which boosts jobs and income across the economy (induced impacts), raising the GDP to even higher levels than in the reference scenario. In terms of what the carbon price should be, because each model builds scenarios in distinctive and non-comparable ways, different models may recommend different carbon prices. The GCAM model uniquely provides the minimum carbon price required across the economy to meet the desired emission constraint in that time step. On the other hand, the value of the carbon tax in the EPS is determined subjectively by the user, based on its ability to sufficiently counter negative impacts on the GDP and jobs in the economy. We notice a convergence in the carbon prices of both models in the 1.5°C FI and 1.5°C ECPC scenarios in 2050 at INR 4,000–5,000/tCO_2 in the EPS and ~INR 6,000/tCO_2 in GCAM, both at 2018 prices. Lastly, we also observe in the EPS that investment in new low carbon technologies boosts GDP and jobs, leading to cost savings (primarily in the private sector from lower fuel costs) and reduced health impacts across the economy. The following caveats should be noted:

- In the real world, there will be other socioeconomic impacts as well that are not captured by the models, including those caused by existing inefficiencies/socioeconomic structures. Policies considering these uncaptured impacts must therefore be designed and implemented to be able to alleviate these issues to the extent possible.

- In the short run, in the absence of cheaper low carbon alternatives, the carbon-tax-induced higher fossil fuel prices may lead to distributional and inflationary impacts on the economy. Therefore, countermeasures such as subsidizing the use of alternative fuels, for example, hydrogen, biofuels, and storage systems (where feasible), would be necessary.
- A separate analysis of the political economy of carbon taxes would be useful for understanding the feasibility of these assumptions.

We need to design an equitable low carbon transition that is just and does not disproportionately impact low-income households. As witnessed during the COVID-19 lockdowns, the impacts of climate change will hit socioeconomically vulnerable people first and the hardest. This makes climate action key to equitable development in India. However, the low carbon transition will cause a disruptive transformation of the economy, creating both winners and losers. Although we see above that counteractive policies such as a carbon tax can lead to net positive impacts associated with the low carbon transition, the CGE model captures the impact of the changing economy on private income and the resulting income inequality. It finds that given the predominantly capital-intensive nature of low carbon technologies (in contrast to fossil fuel technologies, which are both labor and capital intensive), private income of the impacted labor force falls whereas that of the owners of capital rises, leading to a widening income gap between the poor and rich as the carbon constraint becomes more stringent across scenarios. It will thus be necessary to identify the potential affected parties, understand the direction and extent to which they would be impacted within various sectors, and address their needs adequately. National models capture this information to varying extents. Whereas the CGE sees a decline in the GDP due to the decreasing private income of the low-income work force employed in the fossil fuel industry and the indirect and induced jobs resulting from this decrease, the EPS sees a net positive impact on the GDP and jobs as a whole (because of the inclusion of a carbon tax, unlike CGE) but does not disaggregate their distribution among income classes or regions. Upskilling/reskilling, enhanced creation of jobs by incentivizing local manufacturing of new clean technologies, improved worker safeguards, and direct benefit transfer schemes could be some other policies to address the negative impacts, but more modeling studies and qualitative socioeconomic analyses are needed to capture the different socioeconomic impacts of the low carbon transition and devise interventions to alleviate them.

A strong yet small set of decarbonization policies holds the key. Although every emitting sector will have to decarbonize substantially to align with the temperature targets, the different policies differ in their levels of impact on emissions reduction. Although the SAFARI model is goal oriented and the EPS model is policy oriented, both provide insights into which policies have the greatest impact on emissions. The EPS scenarios demonstrate that the same set of 8–10 policies contribute to 80–90 percent of the cumulative emissions abatement from 2020–50 in all scenarios. Table 55 lists these policy levers by sector

TABLE 55 | Top 10 highest impact emission reduction policies in the EPS scenarios

	ENERGY EFFICIENCY	DEMAND REDUCTION	DEEP DECARBONIZATION	CARBON PRICING
Power	n/a	n/a	Early retirement of thermal power plants (7–15%)	Carbon tax (15–20%)
Industry	Industry energy efficiency standards (10–15%)	Material efficiency, longevity, and reuse (6–11%)	Electrification + Hydrogen (10–19%)	
Transport	Vehicle fuel economy (2–3%)	Mode shifting (2–3%)	Electric and hydrogen vehicles sales mandate (2–9%)	n/a
Hydrogen	n/a	n/a	Hydrogen electrolysis (6–11%)	n/a
AFOLU	Forest restoration: 5%			

Notes: AFOLU = Agriculture, Forestry, and Other Land Use; n/a=not applicable.
Source: Authors.

and type of intervention along with their share of the total cumulative emissions reduction from 2020–50 across scenarios. The post-COVID-19 recovery offers an opportunity for India to integrate inclusiveness with climate concerns by accommodating such high mitigation policies within stimulus packages and processes.

Industry becomes the largest source of annual emissions by the 2030s, and decarbonization of the industry sector will need to be the key focus of government policies. This sector includes several hard-to-abate emission sources that use fuels to generate high-temperature heat and that produce process emissions that cannot be mitigated without changing the product itself. Thus, transformative industrial decarbonization is a significant technical and financial challenge for India. As a result, in the reference scenario, industry emissions and energy consumption do not decouple and grow 2.4–3.3 times from 2020–50. Moreover, as CGE achieves full equilibrium in the economy, it finds that industry grows faster in the low carbon scenarios than in the reference scenario because of the shift to renewables and new technologies in other sectors (assuming that they are domestically manufactured). This would further enhance the production of materials that are both energy and emissions intensive. To decouple the growth of the industry sector from emissions and ensure that the low carbon transition in other sectors does not lead to a rise in industrial emissions, a technology switch from fossil fuels to electricity and green fuels to meet the electricity, heat, and feedstock needs of industrial subsectors is vital. Compared to the reference scenario, electrification of the industry sector would need to more than triple across all the 1.5°C-compliant scenarios per the CGE by 2050, and to a lesser extent in the EPS and GCAM as well. The EPS (which is the only model that includes hydrogen as an alternative fuel in the industry sector) estimates that 18–28 percent of the industry energy consumption needs to come from hydrogen in 2050 to be compliant with the three 1.5^{0}C scenarios.[18] GCAM and SAFARI also use natural gas as a transition fuel, but given its risk of stranded assets, along with the current higher cost of electricity-based technologies, and the nascent stage of the development of hydrogen-based technologies in the Indian industry, a threefold policy approach must be taken in the short to medium term:

- Mandate high energy efficiency; material efficiency, longevity, and reuse standards; and encourage better urban design, which the EPS and SAFARI find reduce energy demand and thus have a high mitigation impact.
- Adopt policies that can incentivize the achievement of economies of scale and consequent cost reductions in existing technologies that are currently financially unviable. Development of ancillary infrastructure by the government is also needed to support the large-scale adoption of these technologies, such as storage and grid infrastructure for RE and charging points for EVs.
- Promote and finance R&D into new or nascent technologies such as green hydrogen, CCUS, and other alternatives that have been theoretically proved to be capable of replacing fossil use, such as in steel manufacturing. This would put India on the path of industrial decarbonization in the medium to long term.

Transport is the fastest-growing source of emissions and needs a multidimensional approach. Energy use and emissions from the transport sector roughly triple between 2020 and 2050 in the CGE reference scenario, and double in the other reference scenarios. By 2050, taking into account current trends and technological feasibility, 90–100 percent of 2-wheeler and 3-wheeler sales, 70–80 percent of 4-wheeler sales (passenger and freight), 40–60 percent of passenger HDVs (buses), and 10–15 percent of freight HDV (trucks) sales will have to come from EVs to align with the 1.5°C scenarios per GCAM and the EPS. However, in both models, in 2050, almost 70 percent of transport emissions will come from freight trucks alone, which is the hardest segment to abate in both models and whose electrification levels are very low in their reference scenarios. Therefore, the transport sector policy effort should focus on decarbonizing this hard-to-abate segment. This can be achieved by mandating fuel efficiency targets, incentivizing a mode shift to freight rail, and financing R&D into new technologies (alternative fuels such as hydrogen and biofuels) in the short to medium term, so as to be able to start phasing in the new technologies and meet the abovementioned targets in the medium to long term. In SAFARI, the decarbonization potential of demand-side interventions such as mode shifting, better urban planning, shared mobility, and fuel efficiency, along with some level of electrification, leads to a 40–50 percent fall in energy consumption in the 1.5°C-aligned scenarios. This requires an integrated approach involving urban planners, consumer behavior interventions, and so on. Further inquiry by other models into the potential for a shift from road to rail freight is necessary to address the challenge of freight decarbonization.

A least cost approach to capacity installment in the power sector leads to considerable decarbonization of the sector, but given the rising demand for electricity in an electrifying economy, a comprehensive strategy on RE is required. According to the three models in this study that take a least cost approach to building power plants in their reference scenario (GCAM, SAFARI, and the EPS), 66–68 percent of the installed capacity comes from solar and wind energy by 2050. In the EPS, no new coal is added beyond 2028 in the reference scenario itself (leading to a constant coal fleet of 221 GW until 2050). In the low carbon scenarios, not only would this share have to rise to 80–90 percent, but in absolute terms, it would mean an even higher rise because electricity demand in all four models in the low carbon scenarios rises compared to that in the reference scenario as other end-use sectors such as industry, transport, and buildings electrify to decarbonize their operations. As discussed in the literature, the installation of RE imposes tremendous pressure on resources such as land and water, which have other competing development demands such as urbanization and agriculture (National Research Council 2010). Hence, special attention is needed to reduce the demand for energy in end-use sectors through efficiency measures and demand reduction policies as seen in SAFARI and the EPS. Efficiency in the power sector must also be raised by supporting improvements in the CUF of solar energy through innovation and R&D, improving the ability of the grid to manage RE, reducing T&D losses, and increasing the storage capacity to prevent the need for natural-gas- or hydro-based power plants to manage variability.

India's NDC and COP26 targets are a mixed bag (as summarized in Table 56):

- **India's commitment to install 500 GW of electricity capacity from non-fossil-fuel sources by 2030, announced at COP26**: We find from our analysis that this target is ambitious and almost met in the reference scenario of the three models that build the fleet on a least cost basis (GCAM, SAFARI, and

> Industry becomes the largest source of annual emissions by the 2030s, and decarbonization of the industry sector will need to be the key focus of government policies. This sector includes several hard-to-abate emission sources that use fuels to generate high-temperature heat and that produce process emissions that cannot be mitigated without changing the product itself. Thus, transformative industrial decarbonization is a significant technical and financial challenge for India.

the EPS) at 427–475 GW but not in CGE, which is based on historical trends. This indicates that least cost decision-making and a slight policy push (such as aligning India's RPOs with this goal) can help meet this target. Further, the models together recommend a range of 419–599 GW of non-fossil fuel capacity to align with all carbon budgets except 1.5°C PCC (which is very stringent and therefore an outlier), indicating that India's 500 GW target is ambitious and in the right range.

- **India's NDC commitment of achieving 50 percent electricity capacity from non-fossil fuel sources by 2030**: This target is significantly exceeded in the reference scenario itself by the three least cost models, which achieve 62–65 percent by 2030. Further, the four models together recommend a 59–72 percent share of non-fossil fuel capacity to align with all carbon budgets except 1.5°C PCC (which is very stringent and therefore an outlier), indicating the scope for enhanced ambition.
- **India's NDC commitment of reducing its emissions intensity of GDP by 45 percent by 2030 with respect to 2005 levels**: We find that this target is higher than the reference scenario levels in three models (GCAM being the exception), and so enhanced policy support would be needed to meet it. Further, to comply with the calculated carbon budgets, India's CO_2 emissions intensity of GDP in 2030 should be 51–56 percent per CGE, 55 percent per GCAM, 39–41 percent per SAFARI, and 39–49 percent per the EPS across all scenarios except 1.5°C PCC,[19] indicating that the target's ambition is reasonable. Note that the NDC target is in CO_2e terms whereas the model outputs are in CO_2 terms, so these numbers are only indicative. According to BUR 3, 78.5 percent of India's total national GHG emissions were from CO_2 in 2016 (MoEFCC 2021).
- **The reduction of 1 billion tonnes of CO_2e from 2021–30 with respect to the reference scenario announced at COP26**: This target is overachieved per CGE and the EPS at –2 to –5.4 $GtCO_2$ across the low carbon scenarios. GCAM's annual emissions do not peak until 2030 in any scenario except 1.5°C PCC, indicating no decline, and SAFARI's cumulative emissions rise compared to the reference scenario because development goals are prioritized to be met until 2030.[20] Note that we consider only CO_2 whereas the target is in CO_2e, indicating that the overachievement of this target is underestimated.
- **India's NDC commitment of achieving net zero emissions by 2070**: The scenarios that align with net zero emissions around 2070 are 2°C PCC, 1.5°C FI, and 1.5°C ECPC according to the maximum number of models. The other two 2°C scenarios (2^{0}C ECPC and 2^{0}C FI) reach NZ emissions after 2070, and 1.5°C PCC must reach NZ by 2050 along with CDR given an overshoot in cumulative emissions per three models (CGE, SAFARI, and the EPS). SAFARI requires CDR in all scenarios to reach net zero emissions.

Note that 1.5°C PCC indicators are excluded from the ranges because it is extremely stringent and therefore an outlier.

TABLE 56 | Assessment of India's targets announced in its NDC 2022 and COP26 updates

TARGET	TARGET TYPE		CGE	GCAM	SAFARI	EPS
–45% of CO_2e emissions intensity of GDP by 2030 with respect to 2005 (model outputs refer to CO_2 emissions intensity of GDP)	NDC	Reference	–40%	–55%	–37%	–32%
		Budgets (excluding 1.5°C PCC)	–51% to –56%	–55%	–39% to –41%	–39% to –49%
50% of electricity capacity from non–fossil fuels by 2030	NDC	Reference	45%	65%	62%	63%
		Budgets (excluding 1.5°C PCC)	59%–64%	65%–69%	62%–64%	64%–72%
500 GW of electricity capacity from non-fossil fuels by 2030	COP26	Reference	287 GW	432 GW	427 GW	475 GW
		Budgets (excluding 1.5°C PCC)	587–599 GW	447–543 GW	419–454 WG	440–498 GW
Reduction of 1 billion tonnes of CO_2e from 2021–30 with respect to the reference scenario (model outputs refer to CO_2)	COP26	Reference	No	No	No	No
		Budgets (excluding 1.5°C PCC)	–4 to –5.4 $GtCO_2$	0	0.6 to –0.2 $GtCO_2$	–2 to –4 $GtCO_2$
Net zero emissions by 2070	COP26	Reference	No	No	No	No
		Budgets	2°C PCC 1.5°C FI 1.5°C ECPC	2°C PCC	Requires CDR for NZ	1.5°C FI 1.5°C ECPC

Notes: Models: CGE = Computable General Equilibrium; GCAM = Global Change Analysis Model; EPS = Energy Policy Simulator; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. COP26 = 2021 United Nations Climate Change Conference; GW = gigawatts; $GtCO_2$ = gigatonnes of carbon dioxide; MSW = municipal solid waste; NDC = nationally determined contributions.

Source: Authors.

India will underconsume its fair share of the global carbon budget in its pursuit of low carbon development and thus should be supported with international finance and technology to ensure that the low carbon transition is just for all and builds resilience to climate impacts. India is especially vulnerable to the impacts of climate change, owing to both geographical reasons and the presence of existing socioeconomic vulnerabilities that are inequitably exacerbated by catastrophes such as climate change (as witnessed during the COVID-19 pandemic). Further, as observed in the CGE and EPS models and discussed above, in the absence of compensatory employment and public revenue generation measures, the low carbon transition will lead to a fall in the private income and consumption of those currently employed in fossil fuel industries (who are typically already vulnerable), leading to a socioeconomic decline across the economy. Moreover, our models (as summarized in Table 57) find that in the low carbon pathways that approximately align with India's commitment to achieve net zero emissions in 2070, only 30–40 percent of the carbon budget allocated to India by the FI and ECPC approaches in a 1.5°C-compatible scenario gets consumed by 2050 (and even less per GDR, whose budget allocation to India exceeds the reference emission levels). This is also observed in the 2°C scenarios, and only 1.5°C PCC is exceeded, given its infeasibly stringent budget allocation (for which we conduct a separate analysis to assess the scope for natural CDR from the LULUCF sector; see Table 58). Given that India will underconsume its fair share of the carbon budget in the shift to a low carbon economy, it must be supported with international finance and technology. This support is not only for mitigation but also to ensure that the people impacted by the low carbon transition are fairly compensated and re-employed in other sectors, and that the loss and damage from the climate change that has already occurred (of which India is historically responsible for only 3 percent) is fairly compensated, resilience to future impacts is built, and development priorities such as health and education are not lost sight of in the trade-off.

TABLE 57 | Share of carbon budgets consumed by 2050 across all models and scenarios

🟦 CGE 🟥 GCAM 🟩 SAFARI 🟪 EPS

SCENARIO	2019 HISTORICAL VALUE	2030 MILESTONE	2040 MILESTONE	2050 MILESTONE
Reference		127, 116, 113, 133		
2°C ECPC	408	103, 111, 99, 104	24–27	After 2075
2°C FI	327	99, 110, 96, 101	29–34	After 2075
1.5°C ECPC	289	91, 94, 96, 84	29–33	2065–75
1.5°C FI	226	86, 91, 92, 81	36–40	2065–75
2°C PCC	132	81, 97, 92, 70	53–73	2060–70
1.5°C PCC	46	72, 39, 88, 60	–91 to 84	2050–60 (with CDR)

Notes: Models: CGE = Computable General Equilibrium; GCAM = Global Change Analysis Model; EPS = Energy Policy Simulator; SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence. CDR = carbon dioxide removals; EV = electric vehicle; $GtCO_2$ = gigatonnes of carbon dioxide.

Sources: Authors.

TABLE 58 | Annualized GHG removal from LULUCF sector under five scenarios

SECTOR	UNIT	2030	2040	2050	2100
Forest	$MtCO_2e$	–2,100 to –2,150	–3,470 to –3,570	–4,830 to –4,990	–11,550 to –11,970
Cropland	$MtCO_2e$	–3,280 to 3340	–5,800 to –5,910	–8320 to –8470	–20,870 to –21,230
Grassland	$MtCO_2e$	320 to 330	570 to 590	820 to 850	2,080 to 2,140
Settlements	$MtCO_2e$	–45 to –49	–80 to –86	–114 to –123	–284 to –305
Cumulative LULUCF	$MtCO_2e$	**–5,105 to –5209**	**–8,780 to –8,976**	**–12,444 to –12,733**	**–30,624 to –31,365**

Notes: GHG = greenhouse gas; LULUCF = land use, land use change, and forestry; MtCO2e = megatonnes of carbon dioxide equivalent.

Source: Authors.

To support strategizing on India's emissions intensity target, further clarity is needed on the emissions intensity in the base year (2005) as well as the scope and coverage of the target. There is no official published estimate of India's 2005 emissions inventory except for a bar graph in BUR 2 with a "time series" of CO_2e emissions from 2005 to 2014 disaggregated by sector (but not by subsector or gases), and the method of estimation is not specified. Independent studies exist such as the World Resources Institute Climate Analysis Indicators Tool (WRI CAIT), GHG Platform India, and so on, but their estimates are 22 percent higher than the country-reported data (Jain 2020). Further, the emissions intensity estimates of 2005 and 2010 in BUR 2 and 2016 in BUR 3 do not include emissions from the agriculture sector (as they are considered to be "survival emissions" for India), but the NDC does not clearly specify whether agriculture emissions are to be included within the goal boundary, as was clearly specified in the Copenhagen voluntary pledge. The gases covered within the scope of the goal are also not clear. The BUR includes CO_2, CH_4, N_2O, HFC-134a, HFC-23, CF_4, C_2F_6, and SF_6 emissions, but it is unclear whether the base year emissions include these gases. Without this information on the sectoral scope, gas coverage, or the publication of an estimation of CO_2e emissions in 2005, it is challenging for modeling studies such as this paper to discuss milestones relating to India's NDC pertaining to the emissions intensity of GDP with respect to 2005 as the base year. These issues should be addressed by Indian policymakers for more transparent and robust studies and planning around the reduction of India's emissions intensity.

CHAPTER 6

Conclusion

Large scale decarbonization implies a disruptive transformation in the way economic growth and development is pursued in India, and would require detailed, scientific, and integrated planning supported by large infusions of technology and finance. While these are currently massive challenges for India, the pursuit of immediate action could avoid the lock-in of high-emissions technologies and risk of stranded assets in the future, send early and consistent policy intent signals to all actors within the economy, allow for the planning for the low carbon transitions to be just and equitable for all, and prevent climate change from exacerbating poverty, inequality and the living conditions of India's vulnerable population. It is thus, a crucial endeavour to pursue.

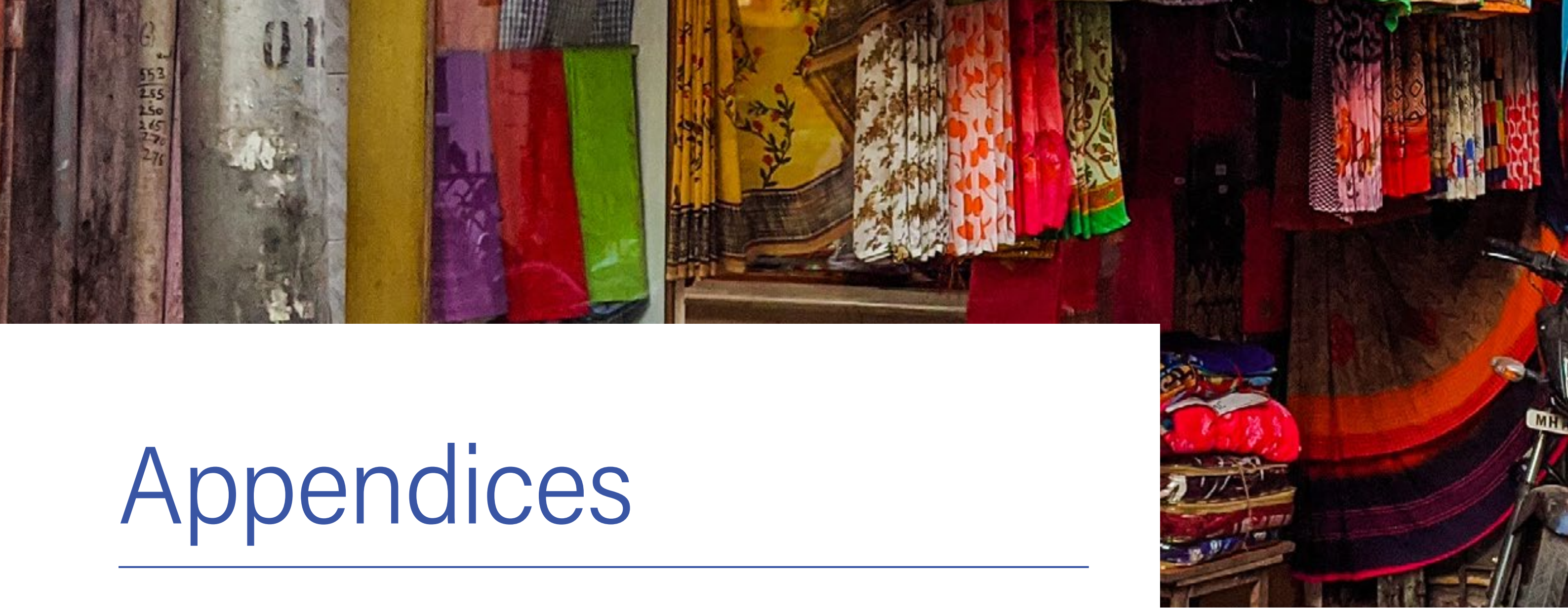
The scenario modeling undertaken in this study, which was steered by these carbon budget approaches, highlights the need to align near-term action with long-term goals instead of deferring ambition to later years, to avoid a lock-in to high-emissions technologies, plan for just and equitable transitions, bolster technological innovation and public finances, build more resilient infrastructure, and send early and consistent policy intent signals to all actors within the economy.

Restricting global temperature rise to below 1.5°C or well below 2°C necessitates coordinated global action at an unprecedented pace. The magnitude of the challenge demands that efforts be ramped up, not just globally, but also at the country level across key sectors of the economy at a transformational scale. Thus, despite India's low annual per capita emissions and the fact that it contributed only 3 percent of global cumulative CO_2 emissions from 1751 to 2017 (Ritchie 2019), India plays an important role in global climate action given its projected growth of future emissions, which our models estimate to grow (cumulatively) 46–60 times from 2020 to 2050 in the reference scenario. Although this would involve a disruptive transformation in the economy requiring large infusions of finance and new technology, it also simultaneously provides an opportunity to tap into new economic opportunities, as some of the models show. It is also crucial to contribute to India's development goals, as climate change would exacerbate poverty and inequality and worsen the lives of India's vulnerable population.

The scale of ambition needed at the country level for India to align with the temperature targets can be determined in several ways, and approaches grounded in the concept of carbon budgets can serve as important directional guides. The scenario modeling undertaken in this study, which was steered by these carbon budget approaches, highlights the need to align near-term action with long-term goals instead of deferring ambition to later years, to avoid a lock-in to high-emissions technologies, plan for just and equitable transitions, bolster technological innovation and public finances, build more resilient infrastructure, and send early and consistent policy intent signals to all actors within the economy. It also highlights the interlinkages and causal relationships between different sectors and actors of the economy, allowing us to identify key short- and long-term milestones and the policy packages needed to meet them. Our study shows that although certain sectors such as the power sector are already on temperature-compliant pathways, supporting infrastructure and higher efficiency are needed to meet future demands and targets. Efforts across other sectors such as industry and transport need to be significantly ramped up. A small package of 8–10 cross-cutting and sectoral policies that reduce energy consumption through efficiency and physical demand reduction and also support the adoption of alternative low carbon fuels and electricity can be extremely effective in meeting the targets. Further, R&D and policies to achieve economies of scale are also crucial, as they will help support the uptake of those policies.

Some high-impact policies are the use of green hydrogen as an alternative fuel in industry and transport, a shift to EVs, and a carbon price across the economy. The National Hydrogen Mission; the FAME initiative, which provides subsidies for EVs; and the Energy Conservation Amendment Act, 2022, which provides the legal basis for implementing a carbon market in India, are the first steps toward achieving these policies. However, challenges regarding lack of finance, technology, capacity, and supporting infrastructure, as well as the negative impacts on the current labor force of fossil fuel industries, are some of the key challenges that need to be addressed. Because we find that India would underconsume its fair share of the global carbon budget to achieve net zero emissions by 2070, an international transfer of finance and technology is imperative to support the costs and technological capability of mitigation, facilitate a just transition, build resilience among vulnerable actors in India to the impacts of the climate change that has already occurred and for which India has very limited responsibility, compensate for the losses and damage due to current climate impacts, and ensure that other development priorities such as health and education will not be jeopardized in the competition for public finance.

Finally, some aspects that the models employed in this study do not capture but that would play an important role in India's long-term decarbonization strategies and should be explored in further analyses are the investments required to achieve these low carbon pathways and the role of the removal of fossil fuel subsidies within them; the impact of the Carbon Border Adjustment Mechanism (CBAM) imposed by the EU on industrial competitiveness in India; the cost of inaction on socioeconomic outputs, which is not captured in the reference scenarios of the models; the employment opportunities and associated costs of LULUCF sector interventions; and the political economy of imposing a tax on carbon emissions.



Appendices

APPENDIX A

Approaches to global carbon budget allocation

The available atmospheric space is constrained by ambitions limiting temperature increase to 1.5°C or 2°C, and the scarce resources thus remaining are split among countries. The mitigation effort required to bring down the emissions may be estimated through bottom-up or top-down approaches. Bottom-up approaches are typically those in which the mitigation efforts by individual countries are summed up to understand the total global emissions reductions targets. Another set of approaches uses the top-down lens. Because these approaches typically allocate the limited carbon space among countries based on certain principles, they are often collectively termed resource-sharing approaches. The following section dives deep into the various such approaches developed over time to understand how the global carbon budget may be distributed fairly among nations such that overall global temperature increase is limited to 1.5°C or 2°C, as the case may be, with a certain probability.

Effort-sharing approaches

As a part of the literature review, several approaches were identified that focused on bottom-up analysis of countries' mitigation potential. The starting point for such approaches may be the sectoral emission allowances of an individual country, which are then summed up to obtain a national budget (the global Triptych approach). On a larger scale, countries may be grouped into developed and developing or Annex I countries and Annex II countries to clearly differentiate the mitigation commitments and highlight the financial and/or technological support that certain countries would require to fulfill their commitments (South-North proposal). Another approach, the Greenhouse Development Rights (GDR) approach, is an effort-sharing approach, categorized as responsibility-capability-need, that incorporates the right to development by allocating mitigation requirements, although the link between the objective right to development and the selected implementation criteria is subjective. These are further divided into two categories (van den Berg et al. 2020): emissions pathway approaches and carbon budget approaches. Emissions pathway approaches are based on dynamic, scenario-dependent allocation factors. Under these approaches, allocations can be derived by calculating the integral of emissions over time. Approaches in this category can be applied to all greenhouse gases (GHGs). Carbon budget approaches are based on static allocation factors. Under these approaches, the budgets can be derived by using regional modeling. These are time independent, allow for decisions within regions, and are best applicable to long-lived GHGs.

Qualitative and complex approaches

The introduction of the concept of a carbon budget inevitably raises the question of what constitutes a "fair" allocation of the finite carbon space among nations. Several researchers have attempted to resolve the fairness question through qualitative approaches. Although these approaches are not accompanied by a set of mathematical equations that determine the distribution of the pie, they offer "welfare"-based solutions to the question at hand.

One such approach is to distribute the budget in such a way that the net welfare changes for all countries are equalized (horizontal equity). A more progressive distribution is advocated by the vertical equity approach, which

requires distribution of the budget such that welfare losses vary directly with the gross domestic product (GDP) of the countries. In a nod to the significance of political dialogue in arriving at a fair and acceptable solution, the "consensus" approach advocates international negotiations to ensure stability. These approaches are further detailed in Table A-1. Further, we also include here any approaches that are either too complex due to the numerous variables involved or that use a model based on a certain modeling platform. This is typically true for one of the approaches identified during the literature review: the Tata Institute of Social Sciences–Delhi Science Forum (TISS-DSF) model. This model is based on the General Algebraic Modeling System (GAMS)-based emissions model, and although the exact inputs to the model remain uncertain, a general idea of the model is presented in Table A-1.

TABLE A-1 | Approaches to global carbon budget allocation

SCENARIO NUMBER	APPROACH	KEY PRINCIPLE[a]	METHODOLOGY/ CATEGORY[b]	SALIENT FEATURES
1	Global Triptych	Capability	Emissions pathway approach	▪ Emission allowances are allocated among countries on the basis of national indicators and circumstances relevant to the level of emissions and emissions reduction potential. ▪ Sectoral emission allowances are calculated and then summed up to obtain a national target (Höhne et al. 2014; Höhne and Moltmann 2009).
2	South-North Proposal	Responsibility, Capability	Emissions pathway approach	▪ Outlines emissions reduction pathways for equitable mitigation effort, considering appropriate funding and institutional mechanisms. ▪ Developed countries are required to initiate immediate action with deep reduction in emissions, followed by delayed action from developing countries (Höhne 2005).
3	Multistage	Capability, Right to development	Emissions pathway approach	▪ Countries participate in several stages with differentiated types and levels of commitment at each stage. ▪ Once a certain threshold is met (GDP per capita/ emissions per capita), countries are graduated to the higher stage (Höhne 2005).

TABLE A-1 | Approaches to global carbon budget allocation, continued

SCENARIO NUMBER	APPROACH	KEY PRINCIPLE[a]	METHODOLOGY/ CATEGORY[b]	SALIENT FEATURES
4	Contraction and Convergence	Equality	Emissions pathway approach	▪ Based on the long-term stabilization target, all countries collectively agree on a future emissions reduction pathway (van den Berg et al. 2020). ▪ Targets for individual countries are set in such a way that per capita emission allowances converge from the countries' current levels to a level equal for all countries within a given period (Höhne et al. 2014).
5	Contraction but Differentiated Convergence	Equality, Right to development	Emissions pathway approach	▪ Similar to contraction and convergence, this approach, however, allows the developing countries' emissions to peak until a certain percentage threshold of the global average is reached (van den Berg 2020).
6	Contraction and Convergence with Historical Debt	Equality, Responsibility	Emissions pathway approach	▪ Similar to contraction and convergence, this approach also considers the historical emissions debt (or credit). ▪ The historical debt may be monetized or traded in the open market as carbon credits or through any other mechanism negotiated in policy discussions (Gignac and Matthews 2015).
7	Common but Differentiated Responsibility of Individuals	Responsibility	Emissions pathway approach	▪ The approach centers on emissions of individuals, and not of nations. ▪ Future emission goals are converted to national reduction targets, determined by business-as-usual (BAU) scenarios and in-country income distributions. ▪ Income distribution is used to distribute fossil fuel emissions among citizens.
8	Cost-Optimal	Cost-effectiveness	Emissions pathway approach (emission allowances based on mitigation potentials)	▪ Allocations of emission allowances based on mitigation potentials. ▪ The emissions could be reduced in each country to the extent that the marginal costs of further reductions are the same across all countries. The allocation depends greatly on the assumed marginal abatement cost (MAC) curves (van den Berg 2020).
9	Tata Institute of Social Sciences–Delhi Science Forum (TISS-DSF) Model	Responsibility, Right to development, Equality	Carbon budget approach	▪ The model dynamically reallocates the carbon space, constrained by the overall remaining carbon budget among countries. ▪ Assuming a maximum allowable emissions growth rate and emissions reduction rate, a constrained nonlinear optimizer is used to achieve the objectives of keeping global emissions within the given carbon budget while dynamically reallocating the carbon space (Kanitkar et al., 2010).
10	Horizontal Equity	Equity	Qualitative approach	▪ Advocates budget distribution such that the net welfare change (the net loss as a proportion of the GDP) for all countries is equalized. ▪ Also understood as equalization of the burdens of the abatement cost across nations, or an equal percentage reduction in welfare.

TABLE A-1 | Approaches to global carbon budget allocation, continued

SCENARIO NUMBER	APPROACH	KEY PRINCIPLE[a]	METHODOLOGY/ CATEGORY[b]	SALIENT FEATURES
11	Vertical equity	Equity	Qualitative approach	▪ Advocates progressively distributing budgets such that welfare losses vary directly with the GDP (the greater economic burden is borne by the richer countries).
12	Compensation	Equity	Qualitative approach	▪ Advocates budget allocation such that no nation is made worse off and the net losing nations are compensated.
13	Rawls's Maximin	Equity	Qualitative approach	▪ This approach suggests the distribution of the largest proportion of the net welfare gain to the poorest nations.
14	Consensus	Equity	Qualitative approach	▪ This approach advocates that the international negotiation process should be fair and a political solution promoting stability should be sought. The distribution of permits/budgets should satisfy the majority of nations.
15	Market Justice	Equity	Qualitative approach	▪ This approach advocates that the market is fair, and emission permits should be distributed to the highest bidder.
16	Inertia Sharing	Sovereignty	Emissions pathway approach	▪ Countries should be allocated future emissions based on their historical emissions trajectories. ▪ Similar to the grandparenting approach (discussed in detail in Appendix B) (Sahu and Saizen 2019).
17	Equity Sharing	Equality	Carbon budget approach	▪ Each person on Earth has an equal right over emissions, and hence, future emissions should be allocated based on the population share of countries (Sahu and Saizen 2019).
18	Blended Sharing	Sovereignty, Equality	Carbon budget approach	▪ Similar to the per capita convergence approach, it uses a sharing index to maintain a balance between equity and inertia (Sonam Sahu, 2018).
19	Inclusion Sharing	Responsibility, Equality	Carbon budget approach	▪ Similar to ECPC, the approach introduces a factor of "historical accountability" in the equity sharing (Sahu and Saizen 2019).
20	Egalitarian Method	Equality	Carbon budget approach	▪ Similar to IEPC, the global carbon resource is distributed across regions in proportion to their population (Böhringer and Welsch 2006).
21	Grandparenting (GP)	Sovereignty	Emissions pathway and carbon budget approach	▪ Emissions pathway: Allocations of emission allowances are proportional to the current emission shares. ▪ Carbon budget: Allocations of carbon budgets are based on the current emission shares (van den Berg 2020).
22	Immediate Emissions Per Capita (IEPC)	Equality	Emissions pathway and carbon budget approach	▪ Emissions pathway: Allocations of emissions allowances are proportional to the population shares. ▪ Carbon budget: Allocation of national carbon budgets is based entirely on the average (projected) population shares in the period 2018–2100 (van den Berg 2020).

TABLE A-1 | Approaches to global carbon budget allocation, continued

SCENARIO NUMBER	APPROACH	KEY PRINCIPLE[a]	METHODOLOGY/ CATEGORY[b]	SALIENT FEATURES
23	Per Capita Convergence (PCC)	Sovereignty, Equality	Emission pathways and carbon budget approach	▪ Emissions pathway: Per capita emissions allowances across countries converge linearly over time from current levels toward equal per capita levels by a convergence date, after which allowances are allocated based on an equal per capita basis. ▪ Carbon budget: Allocation of national carbon budgets is based on both current emission shares and population shares (i.e., a combination of the grandparenting and IEPC approaches). ▪ This approach is a combination of the grandparenting and IEPC approaches (van den Berg 2020).
24	Equal Cumulative Per Capita Convergence (ECPC)	Responsibility, Equality	Carbon budget approach	▪ Allocation of national carbon budgets based on cumulative emissions per capita in a certain period that is equal across countries. ▪ Incorporates historical cumulative emissions (responsibility) and based on the share of the population (equality) (van den Berg 2020).
25	Ability to Pay	Capability	Emissions pathway and carbon budget approach	▪ Based on the ability to bear the burden. ▪ Carbon budget reduction targets from the baseline are allocated based on GDP per capita over the period 2010–2100, considering increasing marginal costs with steeper reductions (van den Berg 2020).
26	Greenhouse Development Rights (GDR)	Responsibility, Capability	Emissions pathway and carbon budget approach	▪ Global carbon budgets from the baseline are allocated based on a Responsibility and Capacity Index (RCI) that includes GDP per capita and measures of income distribution. ▪ Based on the Brazilian proposal, the underlying idea is to safeguard people's right to "reach a dignified level of sustainable human development" (van den Berg 2020).
27	Economic Equity	Equity	Carbon budget approach	▪ All nations should be allowed to maintain their standard of living. ▪ Advocates distributing emission permits in proportion
28	Uniform Carbon Price	Cost-effectiveness	Emissions pathway and carbon budget approach	▪ The global carbon budget is assessed against the BAU scenario, after which the required abatement effort is obtained (Bretschger and Molle, 2015).
29	Fairness Index	Capability, cost-effectiveness	Carbon budget approach	▪ Budgets for each country are calculated using several equity principles, using four main variables: The ability to pay principle, the cost sharing principle, technological contributions, and technological developments. ▪ These are used to calculate the Fairness Index. The higher the Fairness Index, the higher the budget allocated (Bretschger and Molle, 2015).

Notes:

a: Certain approaches are based on more than one principle. The key principle discussed in the approach is listed in the table.

b. Certain approaches are based on more than one methodology (of the three types: carbon budget approach, emissions pathway approach and qualitative approach).

Source: Authors.

Evaluation of shortlisted approaches with respect to equity principles

Using the equity principles of carbon budget allocation, comprehensive criteria were developed to evaluate and assess all the nine approaches that were shortlisted. Further, equal weights were assigned to them given the relative significance of their principles.

Table A-2 presents the results of the assessment of approaches against the criterion, and a brief explanation of a parameter is included in the approach under consideration.

TABLE A-2 | Evaluation of shortlisted approaches with respect to equity principles

SCENARIO NUMBER / EQUITY PRINCIPLE	WEIGHTAGE (%)	GRANDPARENTING (GP)	IMMEDIATE EMISSIONS PER CAPITA (IEPC)	PER CAPITA CONVERGENCE (PCC)	EQUAL CUMULATIVE PER CAPITA EMISSIONS (ECPC)	ABILITY TO PAY (AP)	GREENHOUSE DEVELOPMENT RIGHTS (GDR)	UNIFORM CARBON PRICE	FAIRNESS INDEX (FI)	ECONOMIC EQUITY
1 Capability	20	n/a	n/a	n/a	n/a	Considers GDP per capita	Responsibility and Capacity Index (RCI) considers development threshold (income levels)	n/a	Indirectly accounted for in income per capita	n/a (only looks at the overall GDP)
2 Equality	20	n/a	Based on present and projected population shares	Based on the projected population for the target year	Considers the projected population share	n/a	n/a	n/a	Emissions per capita are accounted for	n/a
3 Responsibility-Capability-need	20	n/a	n/a	n/a	n/a	n/a	Considers Responsibility and Capacity need as the basis for distributing emissions	n/a	n/a	n/a
4 Equal Cumulative Per Capita	20	n/a	n/a	n/a	Considers that cumulative emissions per capita reach the same level when emissions are reduced	n/a	n/a	n/a	n/a	n/a
5 Sovereignty	20	Based on current emission shares	n/a	Based on current emission shares	n/a	n/a	n/a	n/a	n/a	n/a
Total (absolute score based on weightages)	**100**	**20**	**20**	**40**	**40**	**20**	**40**	**0**	**40**	**20**

Note: n/a = not applicable

Source: Authors.

After assessing the approaches, the four approaches with the highest scores—GDR, Equal Cumulative Per Capita Emissions (ECPC), Fairness Index (FI), and Per Capita Convergence (PCC)—were selected, also implying that these approaches consider several principles of budget sharing and are hence more inclusive than the other approaches. These approaches are likely to be more acceptable to countries because they consider various viewpoints on budget sharing highlighted in the scientific literature and expressed by countries.

Data inputs, assumptions considered, and sensitivity analysis

Greenhouse Development Rights (GDR)

A. The formula used for calculating the budget using the GDR approach was

where:

$$b_i GDR = \sum_{t=1850}^{2100} bau_{i,t} - \left(\sum_{t=1850}^{2100} BAU_t - B\right).\left(\sum_{t=1850}^{2100} rci_i / (2100 - 1850)\right)$$

- $b_i GDR$ is the regional budget allowance based on the GDR approach
- $bau_{i,t}$ is the regional baseline emissions based on business as usual (BAU)
- BAU_t is the global baseline emissions based on BAU
- B is the total global carbon budget (1850–2100)
- rci_i is the Responsibility and Capacity Index (RCI)

B. The following data inputs were used for the analysis:

- BAU for India and the world ($bau_{i,t}$, BAU_t, B): The CD-LINKS Scenario Explorer hosted by the International Institute for Applied Systems Analysis.

Responsibility and Capacity Indices for India (rci_i): The Climate Equity Reference Calculator hosted by the Climate Equity Reference Project. The RCI combines the Responsibility and Capability measures (using a user-specified weighting) into a combined indicator of national obligation. The RCI is then used to straightforwardly calculate each country's fair share of the global climate effort—a country's fair share of the global effort (say, in total tonnes of mitigation required) is proportional to its RCI. A country's RCI is affected by its income distribution, because both Responsibility and Capability are calculated in terms of a user-specified development threshold. The RCI for India is assumed to be 0.5.

C. The following assumptions were made during the analysis and calculation of the carbon budget:

- Historical responsibility was calculated using the cumulative emissions since 1850 (the start of the Industrial Revolution). For developing countries such as India, past emissions have been low. Hence, taking into consideration the principle of responsibility, 1850 was chosen as the baseline scenario.
- In the BAU scenario, no climate policies are assumed to be implemented after 2010.
- Capability to reduce emissions is a component of the RCI Index that is embedded in the formula for the GDR approach. A development threshold of $7,500 purchasing power parity (PPP) per person per year, which is slightly above a reasonably defined global poverty line based on empirical observations, is the standard setting presented to the user.
- Sensitivity analysis.

We also conducted a sensitivity analysis on an approach that allocates different weights to Responsibility and Capability in the RCI Index. As indicated in Table A-3, the variation in the budget for India was observed to be between −0.3 percent and 0.4 percent. Hence, we can conclude that the sensitivity of the budgets to different values of Responsibility and Capability is low.

TABLE A-3 | Sensitivity analysis for India's remaining carbon budget until 2050 according to the GDR approach

TEMPERATURE THRESHOLDS		1.5°C		2°C	
Probability (%)		**50**	**66**	**50**	**66**
Percentage change based on India's GDR budget (%)	**R=0.7; C=0.3**	−0.3	−0.3	−0.4	−0.6
	R=0.3; C=0.7	0.3	0.4	−0.1	−0.3

Notes: GDR = Greenhouse Development Rights.

Source: Authors.

Equal Per Capita Emissions (ECPC)

A. The calculation of budget with the help of the ECPC approach involves two major aspects:

$$b_i ECPC = b_i IEPC + Debt$$

- where $b_i IEPC$ = carbon budget using the Immediate Emissions Per Capita (IEPC) approach
- This can be calculated as

$$b_i IEPC = \sum_{t=2018}^{2100} \frac{Regional\ population}{Global\ population} \times Global\ Carbon\ Budget$$

- Debt can be calculated as

$$Debt = \sum_{t=1850}^{2017} \Big[\Big(\frac{Regional\ population}{Global\ population} \Big) \times (Global\ emission \times Discounting\ Factor) - (Regional\ emission \times Discounting\ Factor) \Big]$$

B. The following datasets are required to implement the ECPC methodology:

- The historical total CO_2 emissions of countries (1850–2017): The Climate Equity Reference Calculator hosted by the Climate Equity Reference Project. Carbon dioxide data for the period 1850–2015 comes from the PRIMAP-hist database, which is a well-documented, well-constructed, and well-maintained composite dataset compiled by the Potsdam Institute for Climate Impact Research (PIK). PRIMAP-hist, in turn, is based on various authoritative data sources such as the United Nations Framework Convention on Climate Change (UNFCCC), the Carbon Dioxide Information and Analysis Center (CDIAC), the Electronic Data Gathering, Analysis, and Retrieval (EDGAR) database, and others.
- Discounting factor = 100 percent = 1.
- Historical and future projections of populations (1850–2100): UN Population Database (medium variant). In projecting future levels of fertility and mortality, probabilistic methods were used to reflect the uncertainty of the projections using the historical variability of changes in each variable.

C. The following assumptions were made:

- For the historical emissions, different start years can be chosen: 1850, as it represents the start of the Industrial Revolution; 1970, as it represents the beginning of the decade in which several research scholars and scientists began to increasingly publish about global warming; and 1990, as the first IPCC Scientific Assessment Report was published that year. In the analysis, 1850 was taken as the base year because it would represent the highest level of accuracy in accounting for the emissions that have already occurred, and also best satisfy the principle of Responsibility.
- A discounting factor of 100 percent = a discounting rate of 0 percent. In our analysis, we have considered the discounting rate to be 0 percent. Because the United Nations Framework Convention on Climate Change (UNFCCC) does not have any specific provision regarding this, no discounting was applied in the base case.

D. Sensitivity analysis

In the ECPC approach, the sensitivity analysis is based on different values of the discounting factor (DF). As highlighted in Table A-4, the percentage change is between 9 percent and 36 percent for various DFs. Hence, the sensitivity of the budget to the DF is in the low-to-medium range.

TABLE A-4 | Sensitivity analysis for India's remaining carbon budget until 2100 according to the ECPC approach

GLOBAL CARBON BUDGET (IN GTCO$_2$)		**500**	**400**	**1,350**	**1,150**
Percentage change based on India's ECPC budget (%)	**DF = 0.50%**	12	13	9	9
	DF = 0.8%	18	19	13	19
	DF = 1%	22	23	15	16
	DF= 1.5%	29	30	20	21
	DF = 2%	34	36	24	18

Notes: DF = discounting factor; ECPC = Equal Cumulative Per Capita Emissions; $GtCO_2$ = gigatonnes of carbon dioxide.

Source: Authors.

Fairness Index (FI)

A. Formula:

- A fairness index (FI) *F* was developed using the above principles.
    - A higher value of *F* indicates a higher budget. *F* depends on four variables:
    - A: Inverse of the Ability to Pay (income Y per capita L)
    - C: Abatement Cost parameter (emissions E per capita L)
    - x: Individual or Country Technology Contribution (output Y per emission E)
    - X: General Technology Development (emissions E per capita L)
    - An individual I is taken as a unit for calculating the parameter at the beginning of the considered time period. The exponential weighted average F_i is used to establish the mathematical relation between these parameters:

$$F_i = A_i^{\alpha} C_i^{\beta} x_i^{\gamma} X_i^{\partial}$$
$$\text{where } 0 < \alpha, \beta, \gamma, \partial < 1$$

- Further, considering economies to be inherently dynamic and potentially driven by technical progress (i.e., δ > 0) and assigning equal exponential weights (α = β = Υ = δ), we obtain the simplification:

$$F_i = (Ei / Li)^{\alpha}$$

- For the country-level allocation, the population share of a specific country j is defined as

$$m_j(t) = L_j(t) / L(t)$$

- The emission budget is calculated as

$$Q_j = \frac{(m_j . F_j)}{\sum_j^M m_j . F_j} .Z$$

B. The assumptions shown in Table A-5 were made while calculating the budget using this approach.

C. Sensitivity analysis

For the FI approach, the sensitivity analysis is conducted by changing the value of theta, that is, the historical responsibility of all countries together that contribute to cumulative emissions from 1850 to 2017. Whereas the actual analysis uses 100 percent, the sensitivity analysis is conducted using 80 percent and 50 percent, which lead to a percentage change between 10 percent and 38 percent as highlighted in Table A-6. Hence, the sensitivity of the budget to historical responsibility is low to medium.

TABLE A-5 | The Fairness Index: Data inputs and assumptions

PARAMETER	ASSUMED VALUE	JUSTIFICATION
Start period	1850	It was considered the baseline year for historical emissions as it marked the start of the Industrial Revolution.
Population size	1850 values	It was considered the baseline year for population as it marked the start of the Industrial Revolution.
α, β, Υ, δ	α = β = Υ = δ = 0.25	Economies are considered to be inherently dynamic and driven mainly by technical progress. Equal exponential weights have been assigned, leading to α = β = Υ = δ; Fi = 1, which is the perfect egalitarian solution. The nonlinearity is high owing to the obvious restriction α = β = Υ = δ = 1.
Historical responsibility (θ)	θ=1 (full responsibility)	Complete historical responsibility (100%); that is, historical emissions from 1850 to 2017 are considered in the analysis.

Source: Authors.

TABLE A-6 | Sensitivity analysis for India's remaining carbon budget until 2100 according to the ECPC approach

GLOBAL BUDGET (IN GTCO$_2$)		500	400	1,350	1,150
Percentage change based on India's ECPC budget (%)	**Budget left with 80% historical responsibility**	14	15	10	11
	Budget left with 50% historical responsibility	36	38	24	26

Notes: FI = Fairness Index; GtCO$_2$ = gigatonnes of carbon dioxide.

Source: Authors.

Per Capita Convergence (PCC)

A. The calculation of the carbon budget with the help of the PCC approach is based on two aspects:

$$b_i PCC = (1-w) b_i GP + w b_i IEPC$$

- Where
  - $b_i GP$ = the carbon budget using the grandparenting (GP) approach;
  - $b_i IEPC$ = the carbon budget using the IEPC approach;
  - w = the weighting factor used for the carbon budgets to determine the relative importance the approach assigns to GP (current emissions) and IEPC (population).
- The carbon budget using the GP approach can be calculated as

$$b_i GP = \left(\frac{\text{Regional emission for the year 2018}}{\text{Global emission for the year 2018}}\right) \times \text{Global Carbon Budget available (2018–2100)}$$

- The carbon budget using the IEPC approach can be calculated as

$$b_i IEPC = \sum_{t=2018}^{2100} \frac{(\text{Regional population})}{(\text{Global population})} \times \text{Global Carbon Budget available (2018–2100)}$$

B. The following datasets were used to implement the PCC methodology:

- Current total CO$_2$ emissions of countries (2020): The Climate Equity Reference Calculator hosted by the Climate Equity Reference Project; CO$_2$ data for the period 1850–2015 comes from the PRIMAP-hist database, which is a well-documented, well-constructed, and well-maintained composite dataset compiled by the Potsdam Institute for Climate Impact Research (PIK). PRIMAP-hist, in turn, is based on various authoritative data sources such as the UNFCCC, the CDIAC, the EDGAR database, and others.
- Population (2020–2100): The UN Population Database, medium-variant projection. In projecting future levels of fertility and mortality, probabilistic methods were used to reflect the uncertainty of the projections based on the historical variability of changes in each variable.

C. The following assumptions were made:

- For uniformity, equal weightages (50 percent) have been allocated under the approach while calculating the budget.

D. Sensitivity analysis

For the PCC approach, the sensitivity analysis is based on different weightages between current emissions and population shares. As highlighted in Table A-7, the percentage change is between –13 percent and 16 percent considering both scenarios. Hence, the sensitivity of the budget to historical responsibility is low.

TABLE A-7 | Sensitivity analysis of India's remaining carbon budget until 2100 according to the PCC approach

GLOBAL BUDGET (IN GTCO$_2$)		500	400	1,350	1,150
Percentage change based on India's PCC budget (%)	**w = 0.7**	16	15	15	15
	w = 0.3	–14	–15	–13	–13

Notes: GtCO$_2$ = gigatonnes of carbon dioxide.; PCC = Per Capita Convergence.

Source: Authors.

APPENDIX B

Macroeconomic assumptions of the models

Impact of COVID-19 on the reference scenario's GDP

In the aftermath of the COVID-19-induced lockdown and the resulting lull in economic activity, India witnessed muted consumption and lower productivity during 2020–21. In the Computable General Equilibrium (CGE) framework, investment and productivity growth rates are adjusted to reflect a 5.3 percent contraction in the GDP in 2020 relative to 2019 to account for this impact. The Global Change Analysis Model (GCAM) assumes an economic contraction of –7.7 percent in 2020, which takes the 2015–20 compound annual growth rate (CAGR) to a low of 3.4 percent. Thereafter, a fast recovery is assumed, taking the GDP growth rate in the next time step (2020–25) to 8.2 percent. In Sustainable Alternative Futures for India (SAFARI), the investment and productivity parameters were adjusted for 2020 and 2021 to indicate near-zero growth in the two years. The EPS assumes a –7.7 percent contraction in the GDP of 2020 with respect to the counterfactual (GDP growth rate for 2020 in the absence of the pandemic), after which a V-shaped recovery is assumed, taking growth rates to counterfactual levels by 2026. The assumption of a fast post-COVID-19 recovery is consistent across CGE, GCAM, and the EPS. On the other hand, SAFARI assumes the effect of COVID-19 to persist longer, but with continued rising growth until 2050 due to sustained investments in the future. In contrast to this, the other models assume the GDP to grow at a decreasing rate in the future.

Other drivers

In the case of CGE, because GDP growth is endogenously calculated, assumptions regarding government consumption and capital formation are crucial. The government consumption growth rate has been set per trends from the Economist Intelligence Unit Database (The Economist Intelligence Unit n.d.) and is 7 percent (average growth rate for 10 years) from 2014 to 2030, 5 percent from 2031 to 2040, and 3.5 percent from 2040 to 2050. The gross capital formation growth rate has also been set per trends sourced from the Economic Intelligence Unit database. The average growth rate is 8 percent from 2014 to 2030, 5 percent from 2031 to 2040, and 3.5 percent from 2040 to 2050.

In the case of SAFARI, the investment assumptions in the reference scenario are aligned with historical sectoral trends (2010–15), albeit at lower levels of investment growth across the overall economy (6 percent per annum, compared with a historical investment growth of 7–8 percent per annum). Capital stock assumption is another vital factor. The investment and productivity parameters were adjusted in 2020 and 2021 to indicate near-zero growth due to the impacts of COVID-19. Growth projections begin from 2023, where a moderate level of investment is introduced, and growth is mainly driven by the services sector. Growth in the agriculture and construction sectors (and allied manufacturing sectors) is relatively slower than long-term historical trends and more in line with post-2010 trends, meaning that even as service sector investments are assumed to grow at about 6.5 percent per annum, primary agriculture sector investment growth is limited to about 3 percent per annum (in line with historical trends), and manufacturing sector investment grows at about 5 percent per annum (instead of the historical highs of 8–9 percent per annum). An overall factor productivity growth of about 1 percent has been considered in the economy. A 3 percent increase in government transfers to lower-income households is also assumed in SAFARI.

In the case of the EPS and GCAM, no other demand drivers are applicable. In the EPS, this is because the demand trajectories of each end-use sector are based on trends taken from the India Energy Security Scenarios (IESS) level 2 High Growth Trajectory, which are used to scale base year data to project trajectories for the future. These IESS demand trajectories are driven by the GDP, population, and urbanization. In GCAM, the key growth drivers are the exogenous variables population and GDP. Sectoral growth in the model is projected based on these two variables along with endogenously estimated per capita income using sectoral income elasticities.

CGE

The targets assumed for the interventions in each scenario are listed in Table B-1.

TABLE B-1 | CGE model assumptions

SCENARIO	TOTAL INVESTMENT IN NON-FOSSIL-BASED POWER AND RESULTING INSTALLED CAPACITY OF NON-FOSSIL-FUEL-BASED POWER, 2018–2050[a] (BILLION INR)[a]	TRANSPORT ELECTRIFICATION IN 2050 (%)[b]	INDUSTRIAL ELECTRIFICATION IN 2050 (%)[c]
Reference	44,218 (288 GW by 2030, 531 GW by 2050)	3	17
2°C ECPC	52,349 (369 GW by 2030, 658 GW by 2050)	4	30
2°C FI	62,960 (369 GW by 2030, 755 GW by 2050)	6	43
1.5°C ECPC	69,966 (369 GW by 2030, 827 GW by 2050)	8	52
1.5°C FI	86,508 (369 GW by 2030, 981 GW by 2050)	8	60
2°C PCC	88,263 (369 GW by 2030, 997 GW by 2050)	12	64
1.5°C PCC	120,492 (454 GW by 2030, 1256 GW by 2050)	14	66

Notes: ECPC = Equal Cumulative Per Capita Emissions; EPS = Energy Policy Simulator; GW = gigawatts; FI = Fairness Index; PCC = Per Capita Convergence.

a. Investment at current 2020–21 prices.

b. Transport electrification refers to the share of electricity in the transport sector's overall energy consumption.

c. Industrial electrification refers to the share of electricity in the industrial sector's overall energy consumption.

Electrification is mainly introduced in the land transport sector and in industrial sectors such as cement, iron and steel, machinery, textile, paper, and mineral industries (iron ore, bauxite ore, etc.)

Source: Authors.

The reference scenario targets were chosen in such a way that the resulting future trends are an extrapolation of the performance of the economy from 2013 to 2018. It takes into account all government and climate policies that came into effect before 2018. The impact of these policies is implicitly covered up to 2018 because the reference scenario model results are calibrated to the broad macroeconomic trends in the economy from 2013 to 2018.[21] Also, the study considers the impact of the COVID-19 pandemic and related lockdowns on the overall economy; however, all scenarios assume that economic recovery is achieved by 2021. Apart from the interventions in transport, power, and industry, all scenarios assume that production technologies, household preferences, government expenditure, and existing policies evolve in line with the trends prevailing between 2013 and 2018.

The following is a set of common assumptions for all the scenarios:

- A carbon tax equivalent to the past clean environment cess rates and existing GST compensation cess is levied on coal consumption. All scenarios assume that for 2014–15 a cess of INR 100/tonne is levied, which increases to INR 200/tonne in 2015 and further to INR 400/tonne in 2016 and onward. In all the scenarios, the cess is redistributed to the various sectors of the economy and apportioned according to the investments flowing into each sector.
- The government consumption growth rate has been set per the trends sourced from the Economic Intelligence Unit database. It ranges from 7 percent (the average growth rate for 10 years) from 2014 to 2030, 5 percent from 2031 to 2040 and 3.5 percent from 2040 onward in all the scenarios.
- The gross capital formation growth rate has also been set per the trends sourced from the Economic Intelligence Unit database. It ranges from 8 percent (the average growth rate for 10 years) from 2014 to 2030, 5 percent from 2031 to 2040, and 3.5 percent from 2040 onward in all the scenarios.
- Population is assumed to grow at a compound annual growth rate (CAGR) of 0.06 percent between 2018 and 2050 in all the three scenarios. In 2050, India's population is assumed to grow to 1.6 billion. This matches the World Bank's projections for India's population growth.
- The labor force in the economy grows at a CAGR of 1.14 percent between 2018 and 2050 in all the three scenarios. This has been set per the data from the Economic Intelligence Unit database.

- Wages grow at a CAGR of 7.5 percent between 2018 and 2050 in all the scenarios, per trends sourced from the Economic Intelligence Unit database.
- The total factor productivity grows at an average rate of 1.5 percent per year. The growth rate is changed in some sectors for which a more rapid increase or decline is expected.

GCAM

Table B-2 summarizes the key macroeconomic assumptions made in the GCAM model.

SAFARI

Table B-3 (on the next page) summarizes the key macroeconomic assumptions made in SAFARI and its linked CGE model.

EPS

Tables B-4 and B-5 summarize the key macroeconomic assumptions made in the EPS model.

TABLE B-2 | GCAM assumptions

GCAM (CEEW)	REFERENCES	UNITS	OVERALL, 2015–2050 (%)	2015	2020	2025	2030	2035	2040	2045	2050
GDP growth rate	MoSPI for historical years up to 2020.[a]	CAGR % (over 5 years)	6.16	6.8	3.4	8.2	7.7	7.1	6.5	5.6	4.7
Population growth rate	UN Population projections (medium rate)	Million	0.64	1,310	1,380	1,445	1,504	1,554	1,593	1,621	1,639
Urbanization rate	For the historical years up to 2020, World Bank data are considered	Share of urban population in total population (%)	50.7 (by 2050)	32.7	34.5	37.2	39.9	42.6	45.3	48.0	50.7

Notes: CAGR = compound annual growth rate; CEEW = Council on Energy, Environment and Water; GCAM = Global Change Analysis Model; GDP = gross domestic product; MoSPI = Ministry of Statistics and Programme Implementation.

a. Considers the COVID-19-related GDP contraction and post-pandemic recovery. Aligned with Shared Socio-Economic Pathway 5 (SSP5).

Source: Authors.

TABLE B-3 | SAFARI assumptions

SAFARI (CSTEP)	GDP ANNUAL GROWTH RATE (%)	GDP, CSTEP'S CGE MODEL (INR TRILLION)	POPULATION (BILLION)	URBANIZATION RATE (%) [53% OVERALL BY 2050]
2018		126	1.3	33.8
2019	6	133	1.4	34.2
2020	6	141	1.4	34.7
2021	0	142	1.4	35.2
2022	0	142	1.4	35.6
2023	0	143	1.4	36.1
2024	5	150	1.4	36.6
2025	5	157	1.4	37.1
2026	5	165	1.5	37.6
2027	5	173	1.5	38.2
2028	5	182	1.5	38.7
2029	5	192	1.5	39.3
2030	5	202	1.5	39.8
2031	5	213	1.5	40.4
2032	6	225	1.5	41
2033	6	238	1.5	41.6
2034	6	251	1.6	42.2
2035	6	266	1.6	42.9
2036	6	281	1.6	43.5
2037	6	298	1.6	44.1
2038	6	316	1.6	44.8
2039	6	335	1.6	45.4
2040	6	355	1.6	46
2041	6	377	1.6	46.7
2042	6	401	1.6	47.3
2043	6	426	1.6	48
2044	6	454	1.6	48.6
2045	6	483	1.6	49.3
2046	7	515	1.6	49.9
2047	7	549	1.6	50.6
2048	7	585	1.6	51.2
2049	7	624	1.7	51.9
2050	7	667	1.7	52.5

Notes: CGE = Computable General Equilibrium; CSTEP = Center for Study of Science, Technology and Policy; GDP = gross domestic product; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

TABLE B-4 | EPS assumptions 1

EPS (WRII)	UNITS	2012	2017	2022	2027	2032	2037	2042	2047
Share of manufacturing	%	16	19	21	24	26	29	31	34
Population	Billion	1.22	1.29	1.38	1.45	1.53	1.59	1.66	1.7
Urbanization	%	30	33	36	39	42	45	48	51
Household size	People/household	4.9	4.8	4.6	4.4	4.3	4.1	4	3.81
Urban population	Million	365	427	498	567	644	716	797	869
Rural population	Million	851	867	885	887	890	876	863	835
Urban households	Million	74	90	108	128	150	174	201	228
Rural households	Million	173	182	193	200	208	212	218	219

Notes: EPS = Energy Policy Simulator; WRII = Word Resources Institute India.

Source: Authors.

TABLE B-5 | EPS assumptions 2

	GDP 2018 INR TRILLION	PERCENT ANNUAL GROWTH RATE
2020	209	
2021	225	7
2022	240	7
2023	256	7
2024	272	6
2025	289	6
2026	306	6
2027	323	6
2028	341	6
2029	360	5
2030	379	5
2031	399	5
2032	419	5
2033	439	5
2034	460	5
2035	482	5

	GDP 2018 INR TRILLION	PERCENT ANNUAL GROWTH RATE
2036	504	5
2037	526	4
2038	549	4
2039	572	4
2040	596	4
2041	621	4
2042	645	4
2043	671	4
2044	696	4
2045	723	4
2046	749	4
2047	777	4
2048	804	4
2049	832	3
2050	861	3

Notes: CGE = Computable General Equilibrium; CSTEP = Center for Study of Science, Technology and Policy; GDP = gross domestic product; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

Reference scenario: Industry assumptions

Demand growth

In CGE, investment and productivity, which are exogenous inputs, determine the industry demand trajectory. Under the assumption that India is shifting away from agriculture to manufacturing and the service sectors, the demand for cement in the reference scenario is thus 6.8 percent, 5.6 percent, and 4.3 percent from 2020–30, 2030–40, and 2040–50, respectively, and the demand for steel is 6.8 percent, 5.5 percent, and 4.2 percent in the same time frame.

In GCAM, socioeconomic indicators such as the GDP set the scale of economic activity and the associated demand trajectories of end-use sectors. Given the assumption of a fast-growing and predominantly industrialized economy in the future, the demand trajectory of the industry sector, which is represented at an aggregate level in GCAM, showcases a high CAGR of 5.1 percent from 2020 to 2030, 4.1 percent from 2030 to 2040, and 2.6 percent from 2040 to 2050.

In SAFARI, a large portion of the energy demand from meeting development goals such as housing for all, healthcare infrastructure, and so on, arises from industrial production of materials such as cement and steel. The rest comes from the operational energy requirements of these goals. In the reference scenario, these goals are only partially met, and the construction activity required in the residential and commercial sectors drives industrial demand. As a result, the demand for cement grows at a CAGR of 4.3 percent, 3.8 percent, and 3.1 percent in 2020–30, 2030–40, and 2040–50, respectively, while the demand for steel grows at a CAGR of 3.4 percent, 4.3 percent, and 3.6 percent in the same time frame. Further, the annual food grain demand to ensure food security drives a higher demand for fertilizers.

In the EPS, the demand growth trajectories driving industry fuel consumption are taken from the IESS 2047 v2.0 (NITI Aayog 2015),[22] which in turn are based on their assumptions regarding socioeconomic indicators such as the GDP. The demand growth rates assumed for cement are 4.1 percent, 2.2 percent, and 0.8 percent from 2020–30, 2030–40, and 2040–50, whereas the demand growth rates for steel are 6.9 percent, 4.1 percent, and 1.8 percent in the same time frame.

Energy efficiency

As demand for industrial production rises, so does the energy demand by industry.

The government has increasingly focused on industry energy efficiency measures such as Perform, Achieve and Trade (PAT) and other such industrial efforts.

Table B-6 summarizes the assumptions made regarding energy efficiency in the industry sector in the four models.

TABLE B-6 | Reference scenario energy efficiency assumption

MODEL	TIMELINE	ASSUMPTION REGARDING ENERGY EFFICIENCY
CGE	▪ Annually until 2040 ▪ Annually from 2040–2050	▪ 2.1% ▪ 2.4%
GCAM	▪ 2020–30 ▪ 2030–40 ▪ 2040–50	▪ 1.4% ▪ 0.5% ▪ 0.2%
SAFARI	▪ Until 2030 ▪ 2030–50	▪ Energy efficiency under PAT ▪ Plateaus thereafter; uses historical trends
EPS		▪ Trajectory 1 of the IESS: Cement, Iron, and Steel ▪ Trajectory 2: Other subsectors

Notes: CGE = Computable General Equilibrium; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; IESS = India Energy Security Scenarios; PAT = Perform, Achieve and Trade; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

Reference scenario: Transport assumptions

Demand growth

CGE models transport through its linkages with other sectors of the economy. The transport sector is split into land, railways, and other transport (air, water, and auxiliary transport services). The demand for and supply of transportation services are determined endogenously in the equilibrium state of the economy. The growth in transport services drives its increasing energy demand.

GCAM includes a detailed bottom-up modeling of the sector. In the reference scenario, passenger demand (defined as the number of passenger kilometers [pkm]) increases nearly 1.32 times between 2020 and 2030 and 1.44 times between 2030 and 2050, whereas freight demand increases significantly—1.84 times—between 2020 and 2030 and 2.5 times between 2030 and 2050. These long-term projections highlight a shift from public to private services in the passenger sector, induced by growing income levels that increase the affordability of and preference for private vehicles. The share of public transport in full passenger service declines from 25 percent in 2020 to 9 percent by 2050. Moreover, the freight sector is likely to dominate in the future, with its share reaching 66 percent of the total transport sector energy consumption in 2050. This is because the railways are not sufficiently well connected or logistically well planned enough to support freight demand; also, the increasing demand for home deliveries leads to a rise in demand for freight trucks.

In SAFARI, the annual passenger transport demand, in terms of per capita pkm for India, is assumed to follow an S-shaped curve that saturates at 22,000 km. This is split into intercity and urban travel. Urban passenger transport is driven by the rate of urbanization, and growth in trip rates and trip lengths is based on the literature, while the remaining pkms are assumed to be intercity. The growth rate for freight transport, in tonne-kilometers (tkms), is calculated from the CGE model soft-linked to the SAFARI model. Most road-based freight is assumed to use diesel as fuel (and the rest is assumed to use compressed natural gas [CNG]); 100 percent electrification of railways (passenger and freight) is assumed to be completed by 2030; and aviation fuel and bunker fuel are assumed to be used in air and water freight, respectively.

In the case of the EPS, travel demand by passenger and freight transport in the base year (2018) is estimated by interpolating the total cargo distance traveled between 2012 and 2022 under the BAU trajectory (Level 1) of the IESS. Thereafter, future demand for passenger and freight transport by mode share and public/private share is projected from the base year using the growth rates of cargo distance traveled underlying the International Council on Clean Transportation's Roadmap model results for India. These growth rates are based on the growing per capita intercity and intra-city travel resulting from increasing economic activity and improved access to transport infrastructure in the passenger transport segment, and increased demand for the movement of goods and materials due to growing industrial activity in the freight segment.

Tables B-7 and B-8 give the annual CAGR of decadal passenger and freight transport assumed by each model.

Cost assumptions for transport sector in GCAM

Table B-9 summarizes the cost assumptions per vehicle type made in the GCAM model.

TABLE B-7 | Transport demand projections in CGE, CAGR (reference scenario)

CGE[a]	2020–2030	2030–2040	2040–2050
Land transport (%)	5.5	5.5	5.0

Notes: CAGR = compound annual growth rate; CGE = Computable General Equilibrium.

a. CGE disaggregates transport by land, rail, and air and not by passenger and freight. Thus, the associated CGE numbers in the table refer to the growth rate of all land-based transport, including both passenger and freight.

Source: Authors.

TABLE B-8 | Transport demand projections in GCAM, SAFARI, and EPS, CAGR (reference scenario)

	PASSENGER TRANSPORT			FREIGHT TRANSPORT		
	2020–2030 (%)	2030–2040 (%)	2040–2050 (%)	2020–2030 (%)	2030–2040 (%)	2040–2050 (%)
GCAM	2.8	2.1	1.6	6.3	5.3	3.9
SAFARI	4.2	2.8	1.7	3.6	5.1	5.3
EPS	6.0	6.4	6.1	6.0	6.0	5.4

Notes: CAGR = compound annual growth rate; EPS = Energy Policy Simulator; GCAM = Global Change Analysis Model; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

TABLE B-9 | GCAM transport cost assumptions (reference scenario)

SECTOR	CONSUMER	TECHNOLOGY	FUEL	2020	2030	2050	2100
Transport	International aviation		Liquids	9.70	9.02	8.69	8.79
	Freight	Freight rail	Coal	0.30	0.31	0.32	0.34
		Freight rail	Electric	1.73	1.72	1.69	1.65
		Freight rail	Liquids	2.82	2.83	2.87	2.89
		Domestic shipping	Liquids	0.69	0.69	0.73	0.73
		Truck	Electric	6.16	5.28	4.54	3.57
		Truck	FCEV	15.45	15.42	15.72	14.49
		Truck	Liquids	3.20	3.25	3.54	3.46
		Truck	NG	2.85	2.77	3.06	3.26
	Passenger	Domestic aviation	Liquids	14.26	13.25	12.76	12.92
		High-speed rail	Electric	0.93	0.92	0.90	0.87
		Passenger rail	Electric	0.45	0.45	0.44	0.41
		Passenger rail	Liquids	0.61	0.61	0.62	0.63
		Bus	Electric	0.85	0.64	0.52	0.40
		Bus	Liquids	0.82	0.79	0.77	0.63
		Bus	NG	0.76	0.71	0.70	0.67
		Three-wheeler	Electric	1.23	1.05	0.92	0.82
		Three-wheeler	Liquids	1.83	1.76	1.75	1.73
		Three-wheeler	NG	1.57	1.42	1.54	1.59
		Two-wheeler	Electric	6.31	5.25	4.94	4.86
		Two-wheeler	Liquids	5.70	5.94	6.54	6.42
		Four-wheeler	Electric	55.13	36.08	31.61	29.68
		Four-wheeler	FCEV	121.50	125.18	133.49	127.84
		Four-wheeler	Liquids	36.85	38.74	43.13	43.09
		Four-wheeler	NG	41.55	35.86	40.35	40.53
			Liquids	0.30	0.30	0.31	0.31

Notes: FCEV = fuel cell electric vehicles; NG = natural gas. The unit is 2015 INR per vehicle-kilometer (2015 INR/vkm).

Source: Authors.

Reference scenario: Power sector assumptions

Levelized cost of electricity

In GCAM, SAFARI, and the EPS, the total electricity demand from various end-use sectors (such as transport and industry) is met by constructing power plants using different sources of energy such as coal, gas, solar, wind, hydro, and nuclear. The choice of energy source is determined endogenously by the model on a least cost basis. In CGE, additional investments in coal, solar, wind, and so on, are fed exogenously, which determine the future expansion of these sectors. The quantum of investment is decided based on either various government policy targets or historical trends of past capacity additions. The actual generation mix as well as the cost of electricity (fuel-wise), is, however, determined endogenously by the model using demand-supply equilibrium. Similar to all other models, the cost of non-fossil-based power in CGE declines over time (a decrease of about 11 percent from 2030 to 2050).

In the case of GCAM, the capital costs of each technology are decided on the basis of discussions with sectoral experts from solar and wind power developers, the Ministry of New and Renewable Energy (MNRE), the NTPC, and so on. The model considers two coal technologies, supercritical and ultra-supercritical, an assumption that is in line with the announcement by the Government of India that the country will phase out conventional subcritical power plants and only have these two advanced technologies for coal power generation. However, currently, ultra-supercritical is very expensive, and hence, it is assumed that this technology will be economically feasible only by 2030. On the other hand, the cost of electricity generation from renewable technologies plays a crucial role in the diversification of the grid generation mix by competing with deep-rooted and cheaper options such as coal. In the past two decades, the cost of solar panels has significantly fallen, and policy support for them and ambitious targets have increased in the Indian ecosystem. However, a certain cost will be associated with accommodating this increasing share of RE in the grid including the costs of storage, backup, and so on, apart from the levelized cost of electricity (LCOE) of wind and solar power generation. This is called the variable renewable energy (VRE) integration cost and has been estimated based on a literature review and stakeholder consultations (U.S. Energy Information Administration n.d.).[23] Table B-10 gives the LCOE for the different technologies as considered in GCAM. It is evident that generation for renewable technologies is likely to see a further decline in the future, especially in solar.

TABLE B-10 | GCAM: Levelized cost of electricity (in 2015 INR/kWh)

GENERATION TECHNOLOGY	2030	2040	2050
Coal ultra-supercritical	3.68	3.71	3.76
Coal supercritical	3.55	3.57	3.6
Gas	5.08	5.17	5.4
Nuclear	3.87	3.92	3.99
CSP	6.86	6.78	6.9
PV	2.32	2.06	1.85
Wind	3.23	3.14	3.04
VRE integration cost	0.75	0.9	1.1

Notes: CSP = concentrating solar-thermal power; kWh = kilowatt-hour; PV = photovoltaic; VRE = variable renewable energy.
This includes the cost of integrating VRE while considering the renewable energy sources because additional systems for integrating renewable energy in the grid would increase the levelized cost of generation from solar and wind.

Source: Authors.

In SAFARI, the electricity supply module is designed to respond to demand and aims to meet the overall and peak demand for all demand scenarios. It captures interactions between electricity demand, electricity supply, and constraints in fuel resources and in natural resources such as water and land. The supply sources considered in SAFARI are coal, nuclear, natural gas, large hydro, solar PV, wind, biomass, micro-hydro, and grid storage-integrated solar PV. The module has four balancing loops to help plan decisions in the long term. The loops are adding future capacity to meet the changing future demand, managing the plant load factors of the existing capacity to maintain the demand-supply equilibrium, and future planning (constraints) based on the peak load and dynamic supply mix changes based on a discounted LCOE.

The LCOE of SAFARI is based on the following assumptions (as summarized in Table B-11): Coal's LCOE increases but not by much after 2040 because although the capital costs of new supercritical and ultra-supercritical plants increase, so does the average thermal efficiency (from 33 percent to 44 percent). A 50 percent decline in module costs of solar PV technologies is assumed by 2050, from INR 21 billion/GW in 2015 (determined from industry estimates). Similarly, the decrease in wind technology's LCOE is on account of a 15 percent fall in Capex from INR 66 billion/GW in 2015 to 57 billion/GW in 2050. The upper bound for nuclear capacity, which is capped at about 40 GW by 2050, was estimated from India's current planning and deployment of pressurized heavy-water reactor and the additional capacity of fast breeder reactors. The efficiency of grid-based storage technology is assumed to improve from 85 percent to 92 percent (2015–50). The model uses an upper bound of 250 GW grid storage to balance the variability from renewables penetration.[24] All technology cost calculations account for a discount rate of 8 percent.

In the EPS, the technology share of new power plants that are built each year to meet the increasing electricity demand is calculated by the model, first based on policies on the general type of capacity construction, followed by a cost-prioritizing mechanism of the model that selects a generation technology starting from the lowest LCOE within the type. The policies that the EPS considers for capacity construction include conventional sources (including large hydro) until 2027 from the National Electricity Plan and a target of 104 GW RE by 2022 based on Credit Rating Information Services of India Limited's (CRISIL's) assessment of the achievement of the target of 175 GW RE by 2022.

The levelized costs of electricity in the EPS (as summarized in Table B-12) are calculated within the model using a combination of exogenous capital costs, as well as other factors impacted by policies such as fuel prices, and endogenous learning impacts on capital costs as more capacity is deployed.[25] For coal, existing costs are used in the base year and are then scaled for the future using assumptions by the U.S. Energy Information Agency (U.S. Energy Information Administration n.d.). Further, cost projections for solar energy are taken from the National Renewable Energy Laboratory's (NREL's) cost reduction projections (Fu et al. 2017), for onshore wind from projections from the U.S. Department of Energy (U.S. Department of Energy 2015), and for natural gas and offshore wind from the IESS v2.0 (NITI Aayog 2015).

TABLE B-11 | SAFARI: Levelized cost (in 2015 INR/kWh)

GENERATION SOURCES	2030	2040	2050
Coal	3.04	3.11	3.11
Solar	2.13	1.68	1.48
Wind	3.87	2.98	2.77
Nuclear	3.52	3.68	3.53
Capex in 2015 INR billion/GW			
Grid storage	30.23	21.05	11

Notes: GW = gigawatts; kWh = kilowatt-hour; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

TABLE B-12 | EPS: Levelized cost of electricity (2018 INR/kWh)

EPS LCOE (2018INR/KWH)	2030	2040	2050
Utility solar PV	2.44	2.17	2.09
Onshore wind	2.71	2.22	1.83
Nuclear	2.99	3.77	3.19
Hard coal	3.18	3.43	4.06
Hydro	3.87	3.70	3.47
Offshore wind	4.59	3.70	3.20

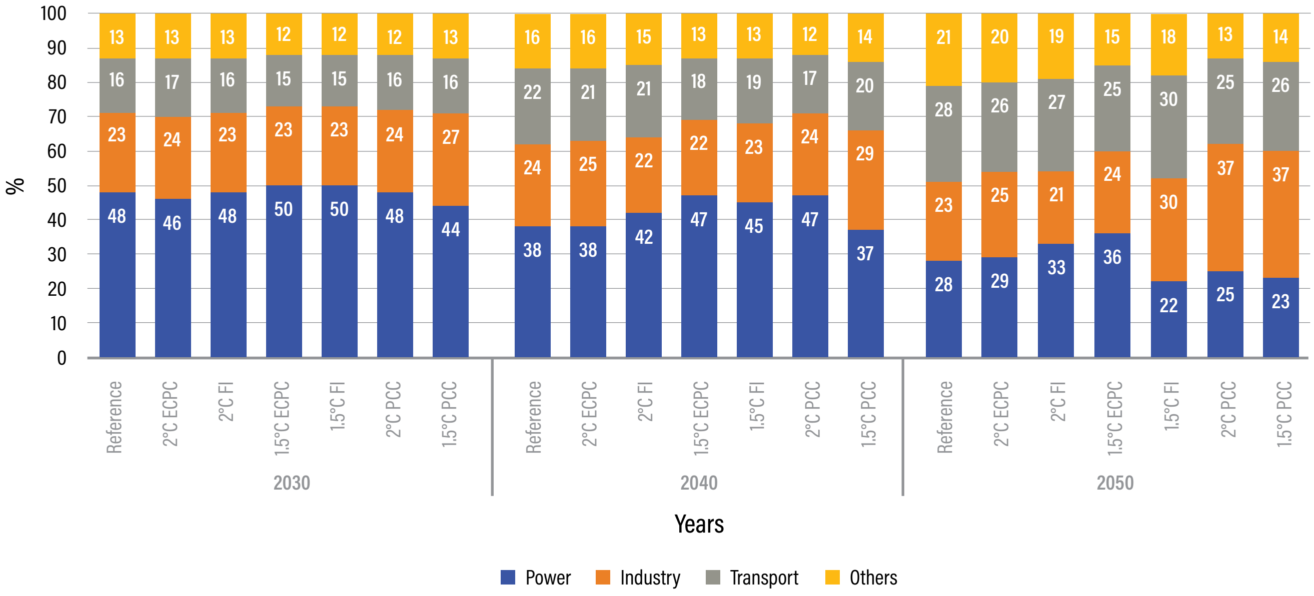
Notes: EPS = Energy Policy Simulator; kWh = kilowatt-hour; LCOE = levelized cost of electricity.

Source: Authors.

APPENDIX C

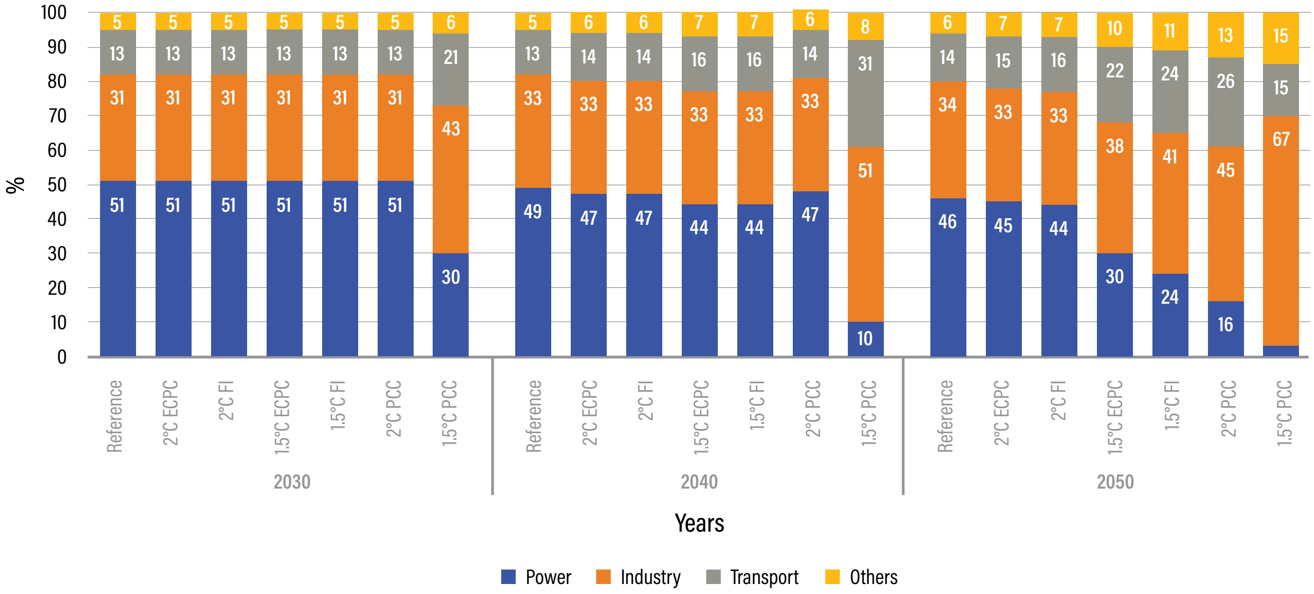
Sectoral distribution of total annual emissions

FIGURE C-1 | CGE: Sectoral distribution of total annual emissions (%)



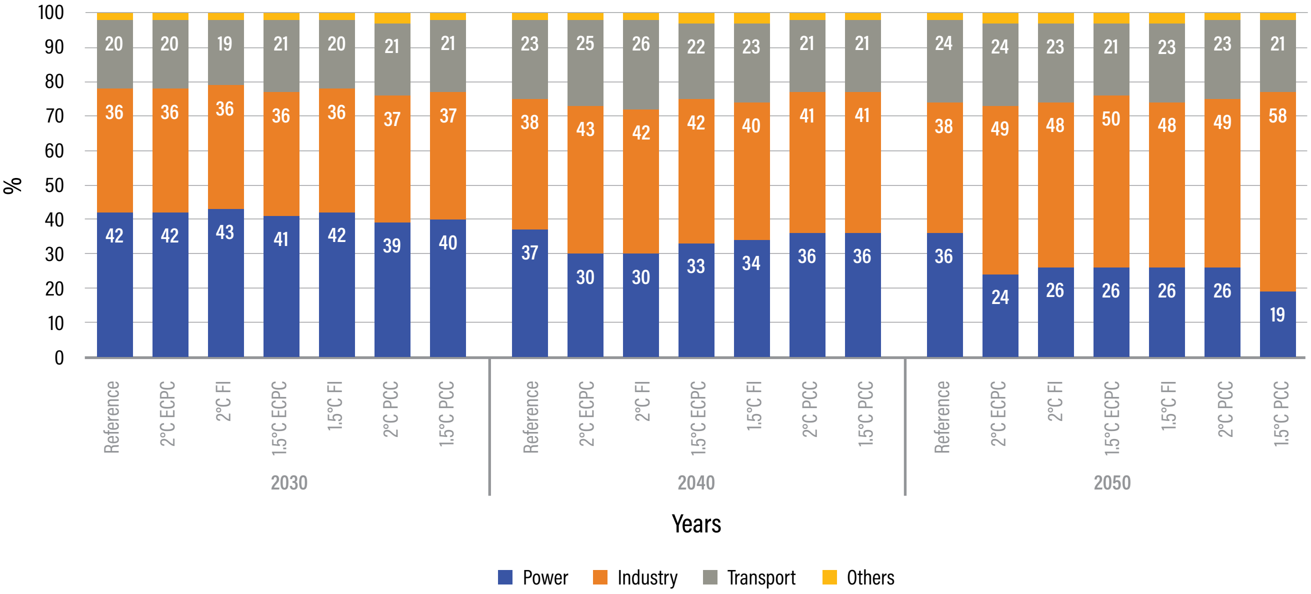
Notes: Models: CGE = Computable General Equilibrium. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

FIGURE C-2 | GCAM: Sectoral distribution of total annual emissions (%)



Notes: Models: GCAM = Global Change Analysis Model. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.
Source: Authors.

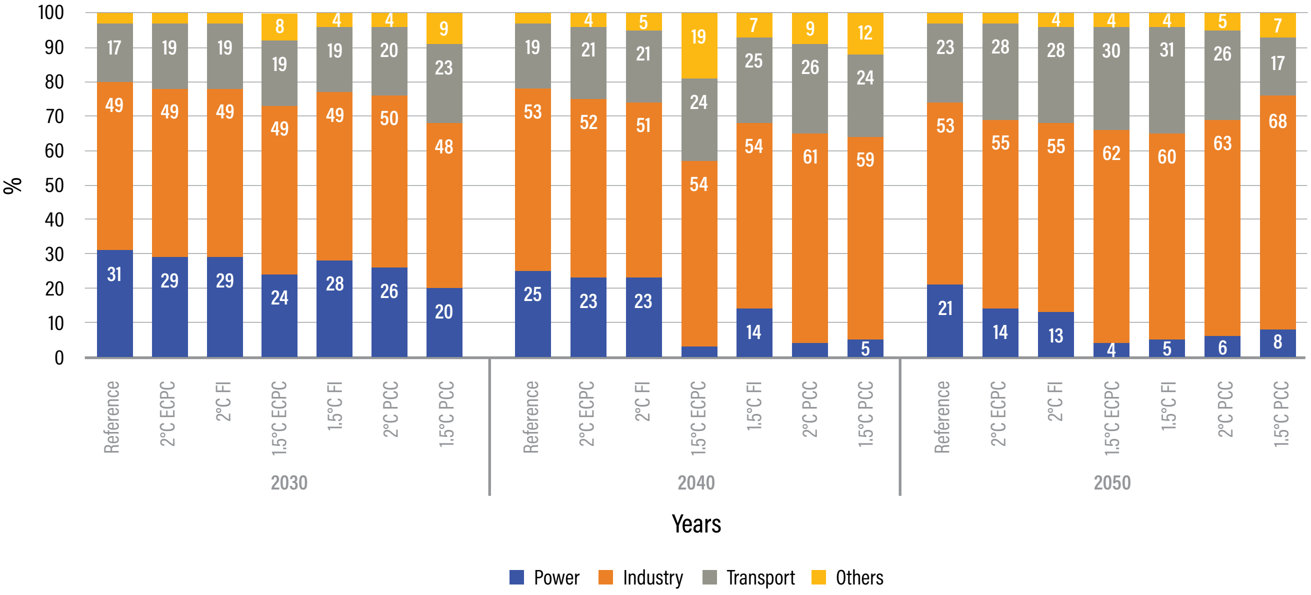
FIGURE C-3 | SAFARI: Sectoral distribution of total annual emissions (%)



Notes: Models: SAFARI = Sustainable Alternative Futures for India. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE C-4 | EPS: Sectoral distribution of total annual emissions (%)

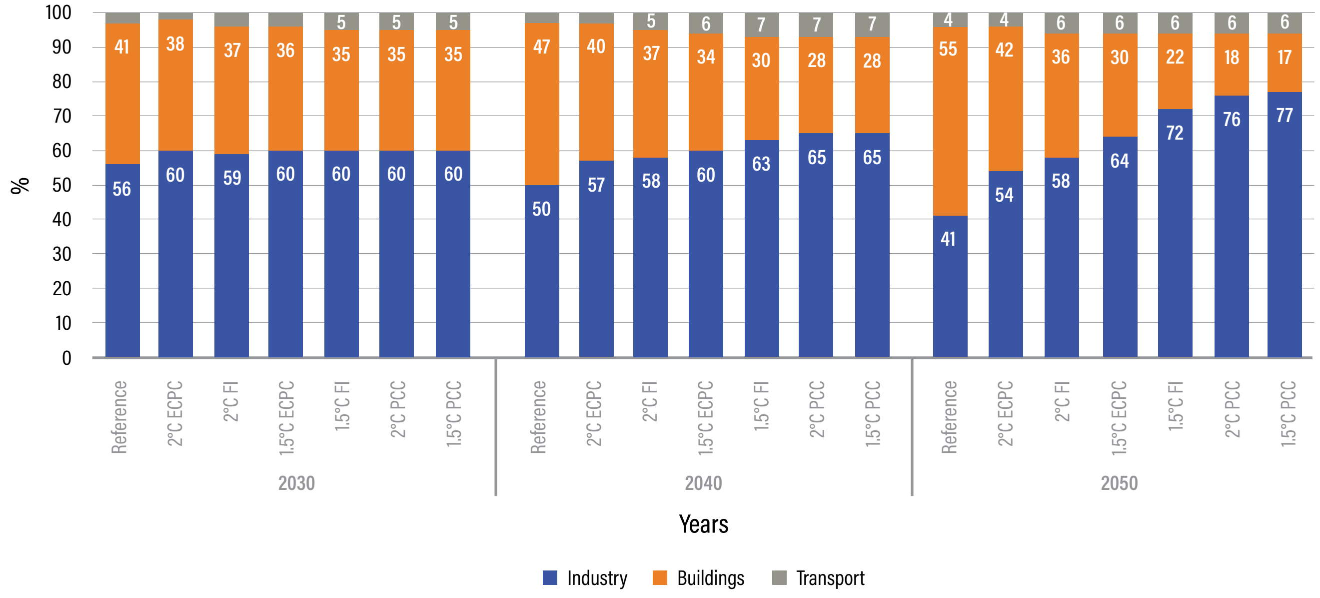


Notes: Models: EPS = Energy Policy Simulator. Scenarios: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

Electricity consumption by sector

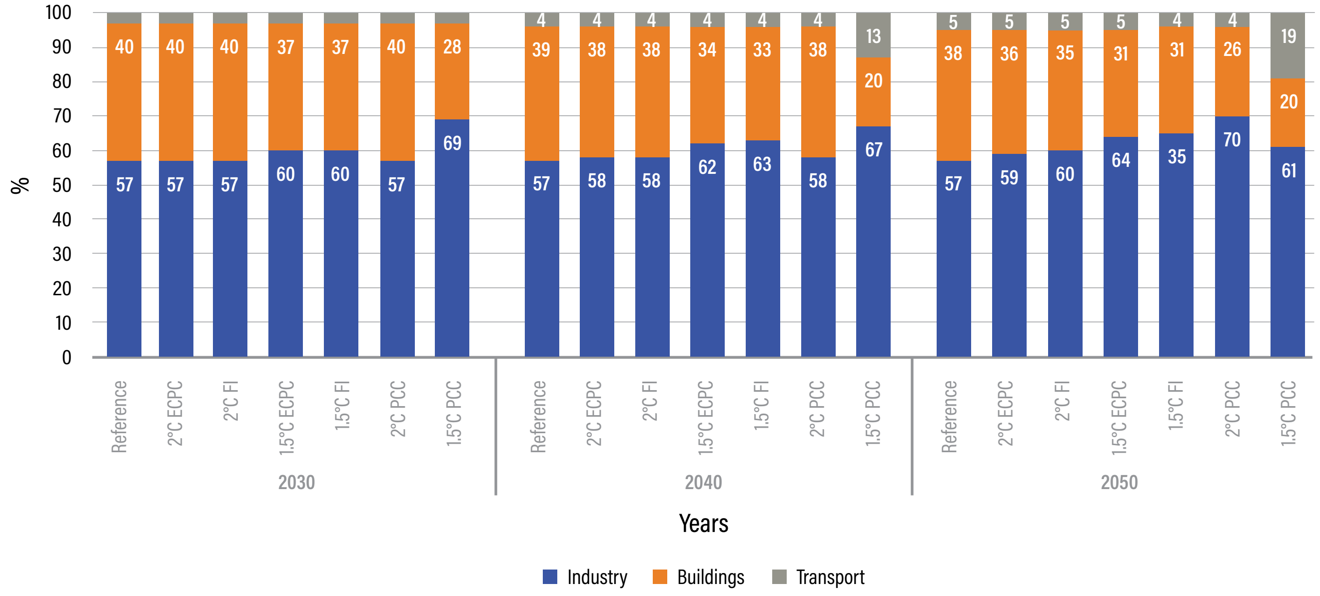
FIGURE C-5 | CGE: Electricity consumption by end use sector (%)



Notes: CGE = Computable General Equilibrium; ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

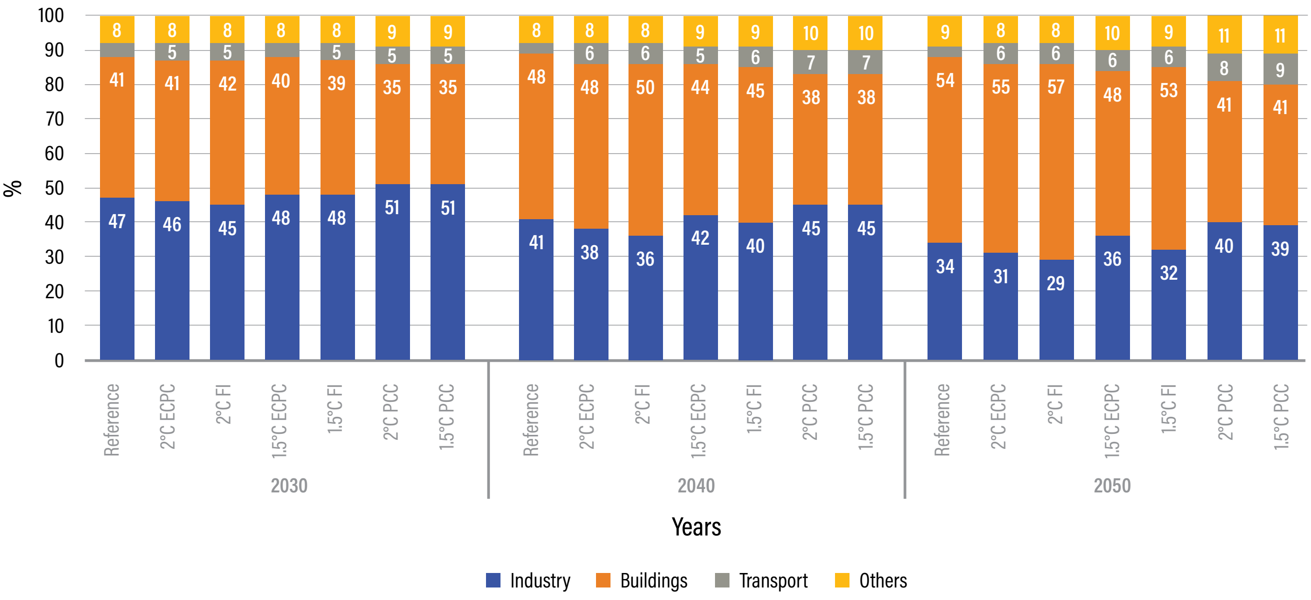
FIGURE C-6 | GCAM: Electricity consumption by end use sector (%)



Notes: ECPC = Equal Cumulative Per Capita Emissions; GCAM = Global Change Analysis Model; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

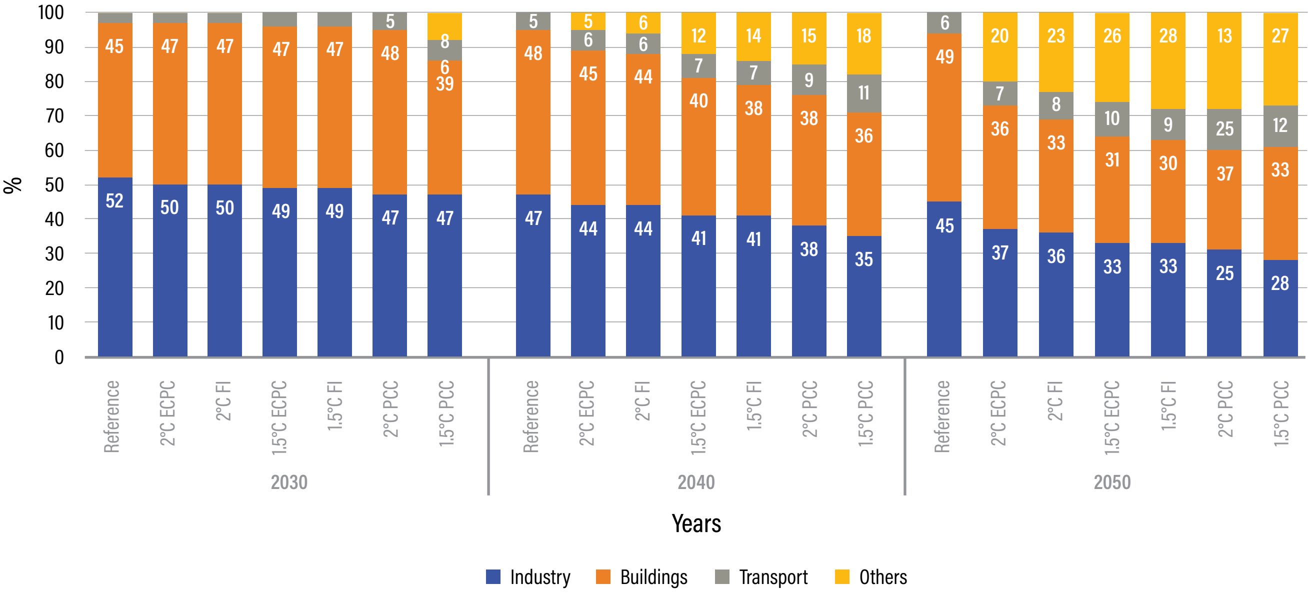
FIGURE C-7 | SAFARI: Electricity consumption by end use sector (%)



Notes: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

FIGURE C-8 | EPS: Electricity consumption by end use sector (%)

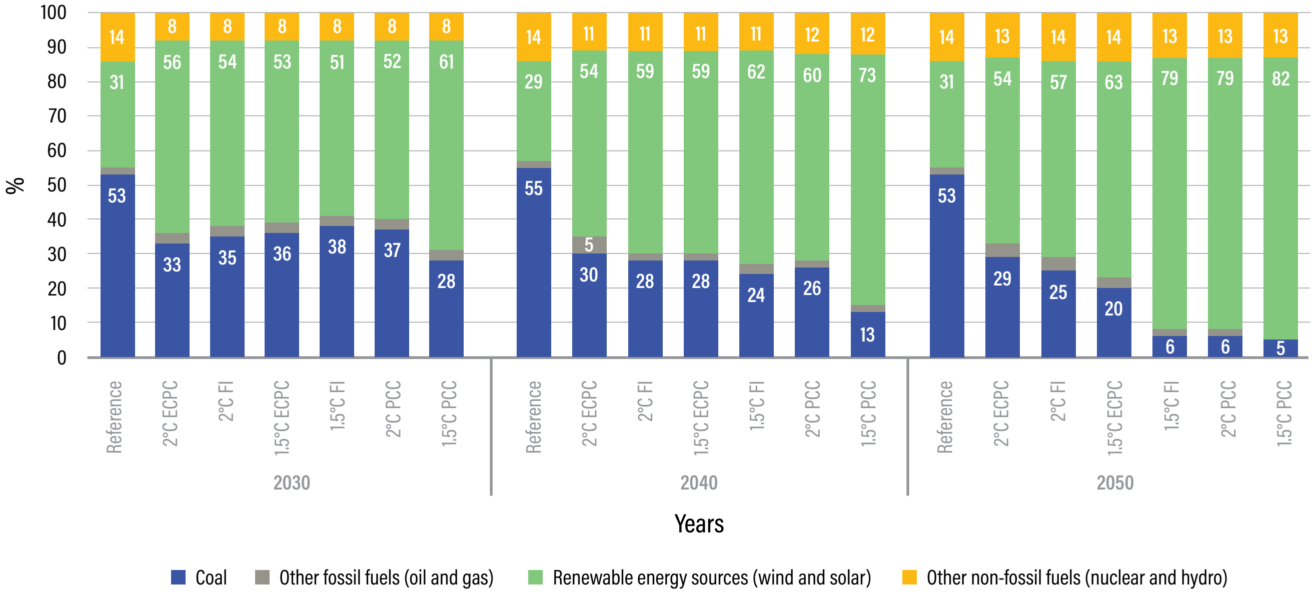


Notes: ECPC = Equal Cumulative Per Capita Emissions; EPS = Energy Policy Simulator; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

Share of electricity installed capacity and generation by fuel type

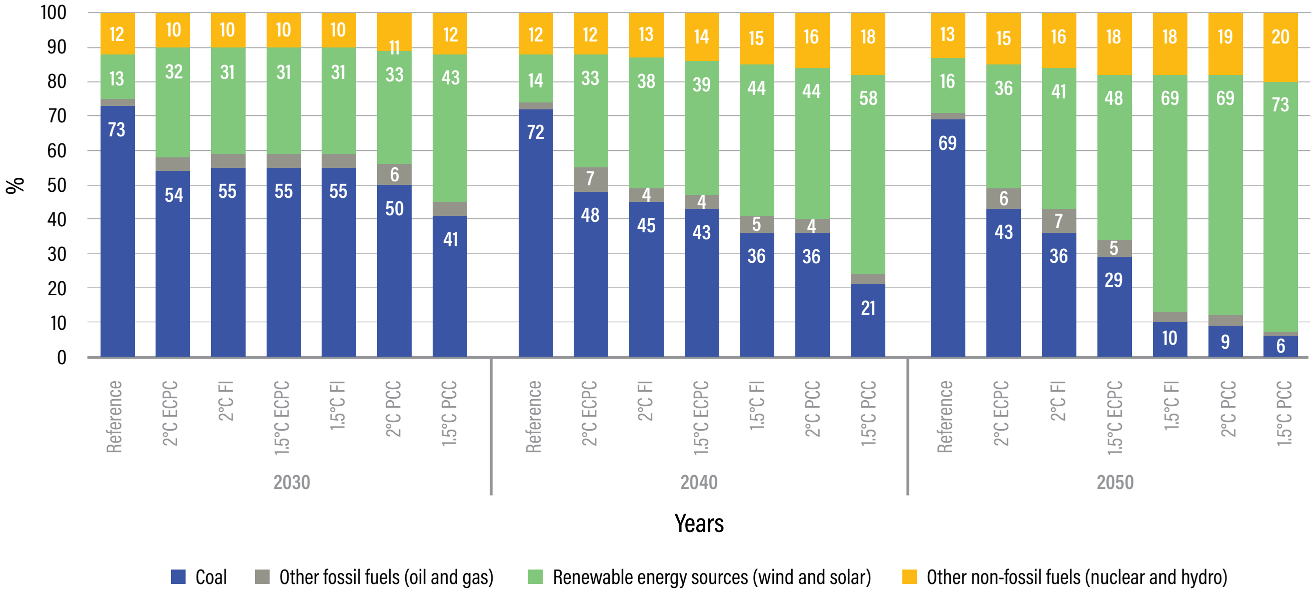
FIGURE C-9 | CGE: Fuel mix of electricity installed capacity



Notes: CGE = Computable General Equilibrium; ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

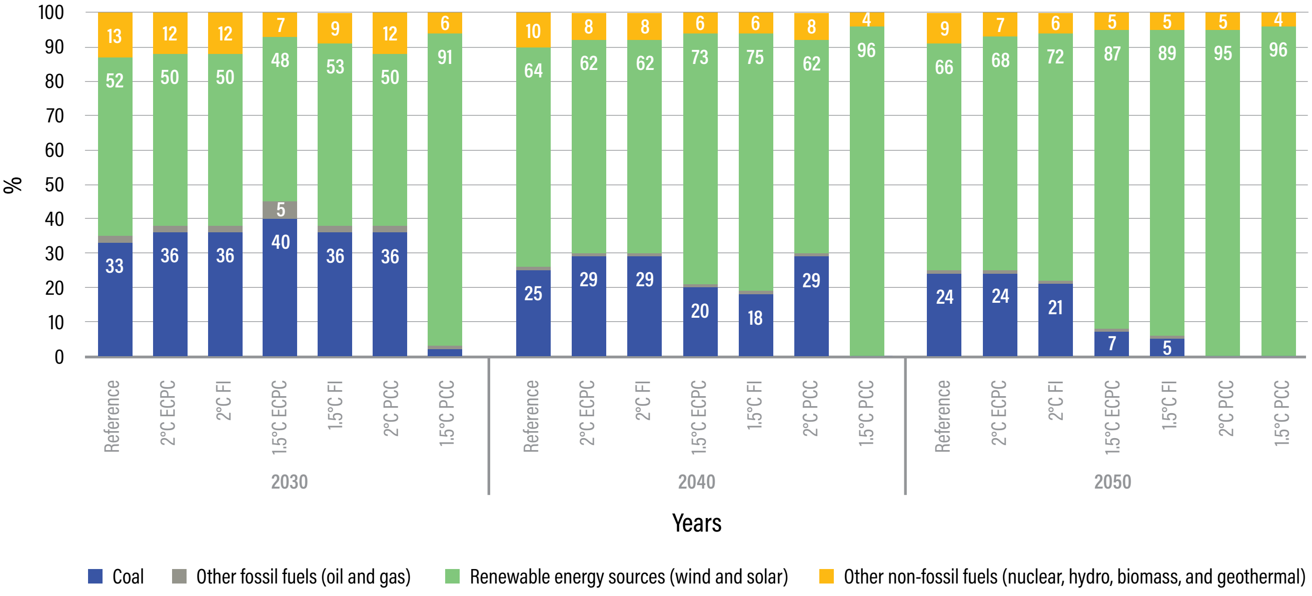
FIGURE C-10 | CGE: Fuel mix of electricity generation



Notes: CGE = Computable General Equilibrium; ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

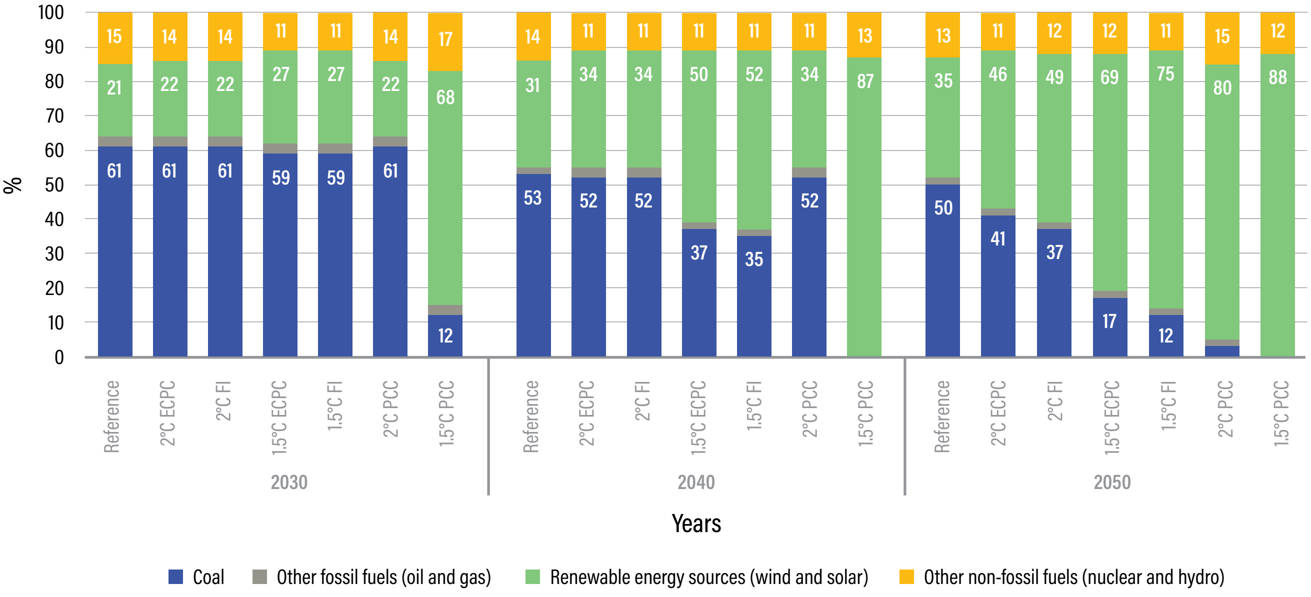
FIGURE C-11 | GCAM: Fuel mix of electricity installed capacity



Notes: ECPC = Equal Cumulative Per Capita Emissions; GCAM = Global Change Analysis Model; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

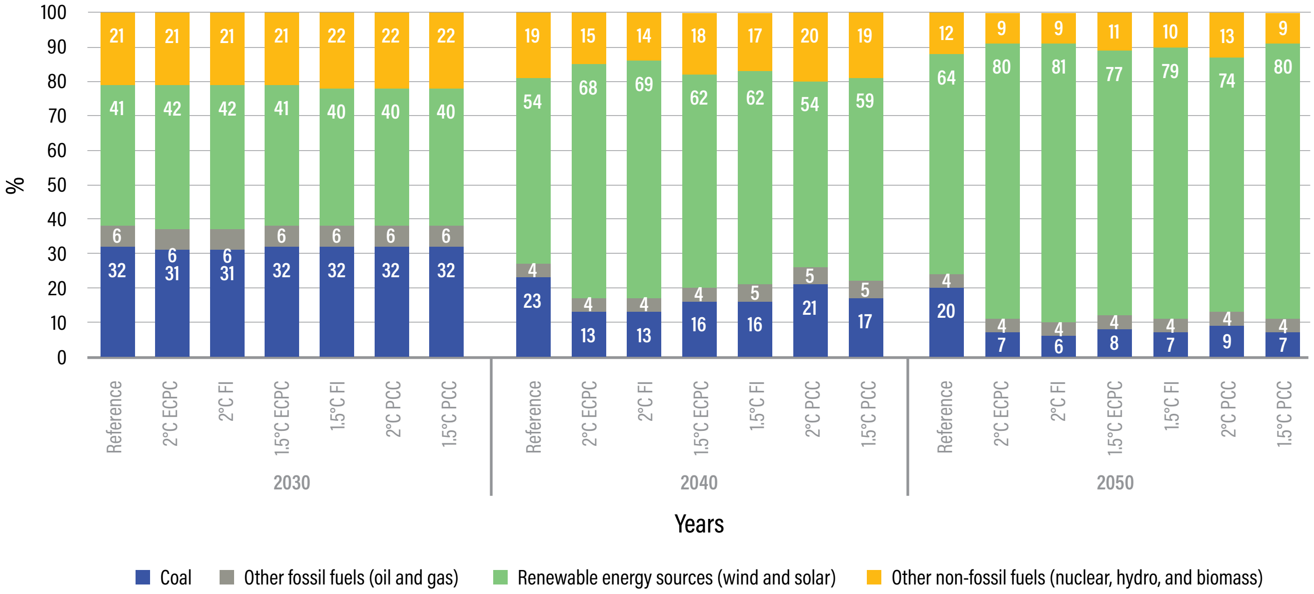
FIGURE C-12 | GCAM: Fuel mix of electricity generation



Notes: ECPC = Equal Cumulative Per Capita Emissions; GCAM = Global Change Analysis Model; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

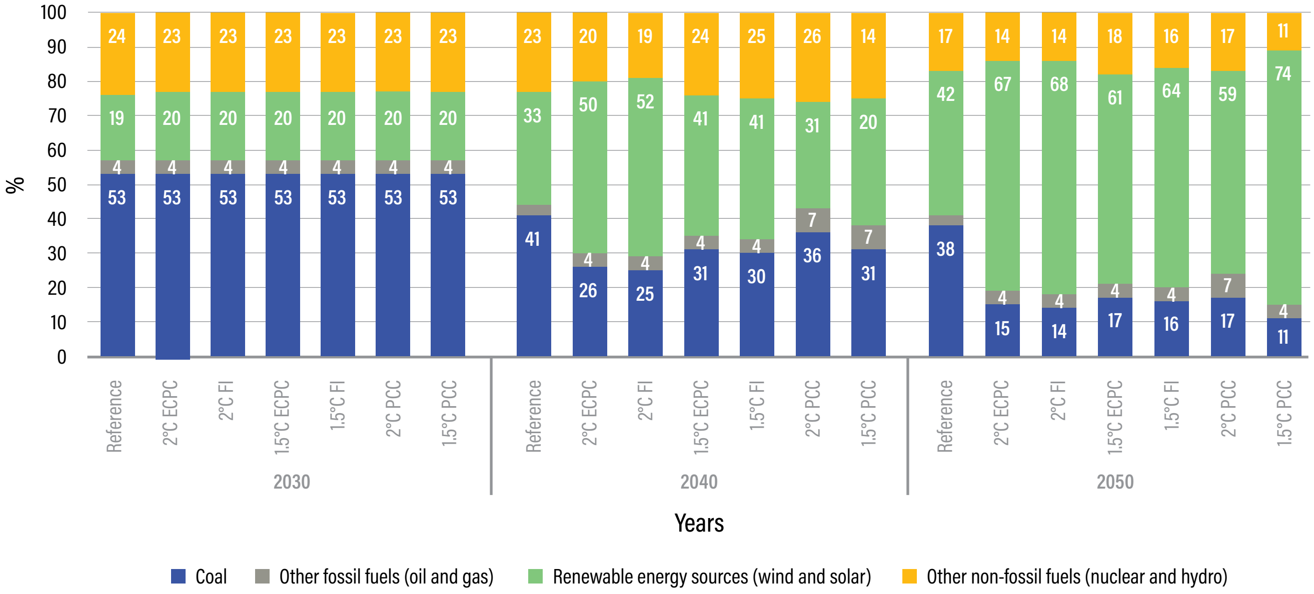
FIGURE C-13 | SAFARI: Fuel mix of electricity installed capacity



Notes: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

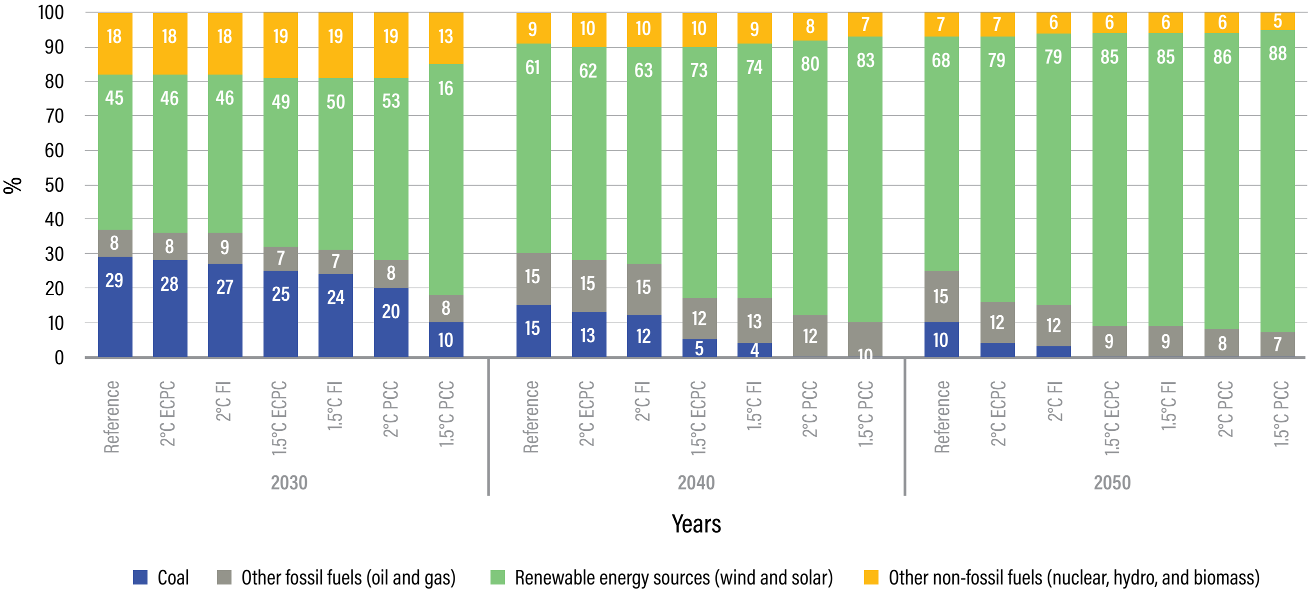
FIGURE C-14 | SAFARI: Fuel mix of electricity generation



Notes: ECPC = Equal Cumulative Per Capita Emissions; FI = Fairness Index; PCC = Per Capita Convergence; SAFARI = Sustainable Alternative Futures for India.

Source: Authors.

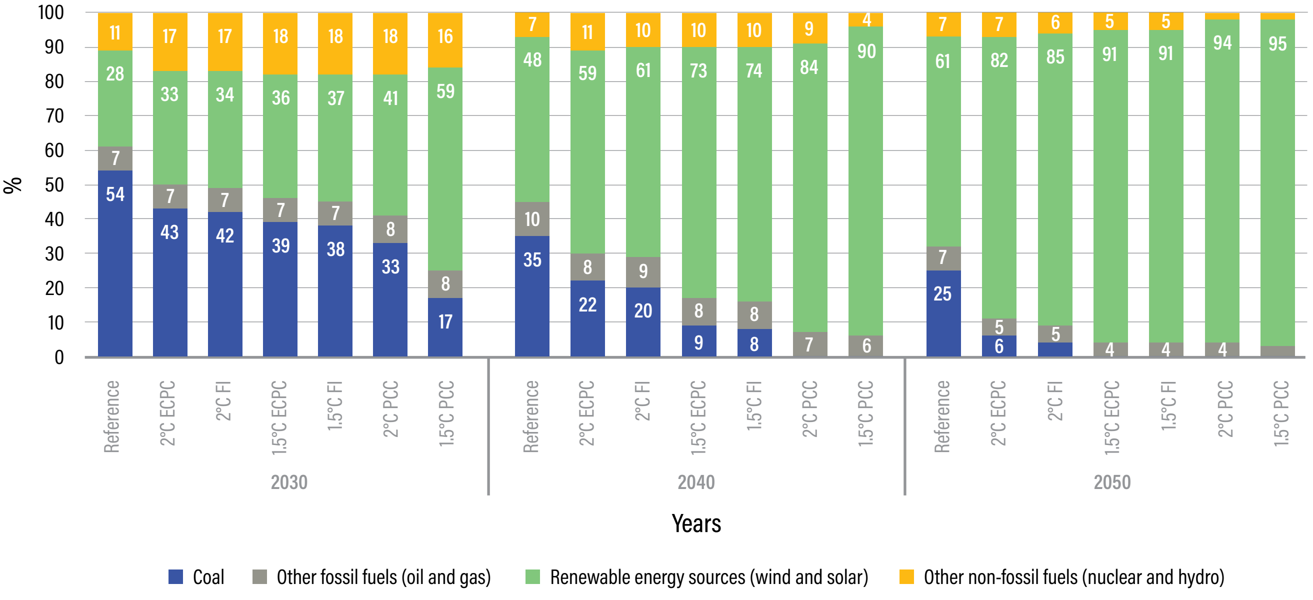
FIGURE C-15 | EPS: Fuel mix of electricity installed capacity



Notes: ECPC = Equal Cumulative Per Capita Emissions; EPS = Energy Policy Simulator; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

FIGURE C-16 | EPS: Fuel mix of electricity generation



Notes: ECPC = Equal Cumulative Per Capita Emissions; EPS = Energy Policy Simulator; FI = Fairness Index; PCC = Per Capita Convergence.

Source: Authors.

APPENDIX D

Land use, land use change, and forestry methodology

Greenhouse gas (GHG) emission/removal from each land use category is estimated using the IPCC-GPG approach and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Of the six greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) estimated and reported in the National GHG Inventory, the land use, land use change, and forestry (LULUCF) methodology accounts for and reports on three GHGs: CO_2, CH_4, and N_2O. The methodological approach adopted (among the tiers of estimates proposed by IPCC), sources of activity data, and emission factors are presented in Table D-1.

Carbon pools

The aggregate and stand-alone carbon pools considered for assessment of carbon stock change under each land use category are presented in Table D-2.

TABLE D-1 | Methodology and emission factor used for GHG estimation

CATEGORY: LAND USE, LAND USE CHANGE, AND FORESTRY (LULUCF)	CARBON DIOXIDE		METHANE		NITROUS OXIDE	
	Methodology used	Emission factor	Methodology used	Emission factor	Methodology used	Emission factor
A. Forestland	T2	CS	T2	D, CS	T2	D, CS
B. Cropland	T2	CS	No		No	
C. Grassland	T2	CS	No		No	
D. Settlement	T2	CS	No		No	

Notes: CS = Country Specific; D = IPCC Default; GHG = greenhouse gas; T2 = Tier 2.
Tier 2 uses the same methodological approach as Tier 1, but applies emission and stock change factors that are based on country- or region-specific data for the most important land use categories (IPCC, 2006).

Source: Authors.

TABLE D-2 | Carbon pools considered for GHG inventorization

POOL		LAND USE CATEGORY			
		Forestland	Cropland	Grassland	Settlement
Biomass	Above ground Biomass	Estimated as change in carbon stock across carbon pools in area under forest cover.	Estimated as change in carbon stock across carbon pools for trees outside forest.	Estimated as change in carbon stock across carbon pools for trees outside forest.	Estimated as change in carbon stock across carbon pools for trees outside forest.
	Below ground Biomass				
Dead organic matter	Dead wood				
	Litter				
Soil	Soil organic matter	Estimated as change in soil organic carbon stock in area under forest cover.	Estimated as change in soil organic carbon stock in area under cropland.	Estimated as change in soil organic carbon stock in area under grassland.	Estimated as change in soil organic carbon stock in area under settlement.

Note: GHG = greenhouse gas.

Source: Authors.

Activity data

Step 1: Estimating the change in carbon stock in a given pool

The change in carbon stock in a given pool is estimated using the *stock-difference method* (IPCC 2006).

$$\Delta C = \frac{(Ct2 - Ct1)}{(t2 - t1)} \ldots..$$

- Where:
    - ΔC: Annual carbon stock change in the pool, *C* tonnes yr–1
    - $Ct2$: Carbon stock in the pool at time *t1*, *C* tonnes
    - $Ct1$: Carbon stock in the pool at time *t2*, *C* tonnes

Step 2: Estimating the annual change in soil organic carbon stock

Land management practices, such as residue management, tillage management, fertilizer management, choice of crop, and intensity of cropping, influence soil carbon inputs and outputs. For mineral soil, changes in soil organic carbon (SOC) stocks over a finite period are computed as the difference in stocks at two points in time divided by the time dependence of the stock change factors:

$$\Delta Cminerals = \frac{(SOC_0 - SOC_0 - t)}{D} \ldots..$$

- Where:
    - $\Delta Cminerals$: Annual change in carbon stocks in mineral soils, *C* tonnes yr–1
    - $SOCo$: Soil organic carbon stock in the last year of an inventory time period, *C* tonnes
    - $SOCo - t$: Soil organic carbon stock at the beginning of the inventory time period, *C* tonnes
    - D: Time dependence of stock change factors, which is the default time period for the transition between equilibrium SOC values, yr

Step 3: Projecting the future scenario

Projection of the future carbon stock/GHG inventory/land use area is conducted using regression analysis based on the following steps:

- The regression equation is first derived for linear, logarithmic, and exponential functions based on historical data.
- The regression equations derived for all functions are further analyzed based on the R2 value.
- The regression equation with the highest R2 value is selected to project the future value.

ABBREVIATIONS

ARRA	American Recovery and Reinvestment Act
ASHRAE	American Society of Heat
°C	degree Celsius
AFOLU	Agriculture, Forestry and Land Use
BAT	best available technologies
BAU	business as usual
BUR	Biennial Update Report
CAFE	Corporate Average Fuel Efficiency
CAGR	cumulative average growth rate
CBAM	Carbon Border Adjustment Mechanism
CBDR-RC	Common But Differentiated Responsibilities & Respective Capabilities
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CDR	carbon dioxide removal
CEA	Central Electricity Authority
CEEW	Council on Energy, Environment and Water
CGE	Computable General Equilibrium Model
COP26	(2021 United Nations Climate Change) 26th Conference of Parties
CSTEP	Centre for Study of Science, Technology and Policy
CUF	capacity utilization factor
ECPC	Equal Cumulative Per Capita Emissions
EE	energy efficiency
EESL	Energy Efficiency Services Ltd
EJ	exajoules
EPS	Energy Policy Simulator
ETS	Emissions Trading System
EU	European Union
EV	electric vehicle
FAME	Faster Adoption and Manufacturing of Electric Vehicles
FF	fossil fuel
F-gases	fluorinated gases
FI	fairness Index
FY	financial year
GCAM	Global Change Assessment Model
GCF	Green Climate Fund
GDP	gross domestic product
GDR	Greenhouse Development Rights
GHG	greenhouse gas
GSAT	global mean surface air temperature
GST	Goods and Services Tax
$GtCO_2e$	gigatonnes of carbon dioxide equivalent
GW	gigawatts
HDV	heavy duty vehicle
IAM	Integrated Assessment Model
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
IESS	India Energy Security Scenario 2047
IIASA	International Institute for Applied Systems Analysis
INR	Indian rupee
IO-SAM	Input-Output Social Accounting Matrix
IPCC	Intergovernmental Panel on Climate Change
IPCC's AR6	IPCC's 6th Assessment Report
IPCC's SR1.5	IPCC's Special Report on 1.5°C
kWh	kilowatt-hour
LCOE	levelized cost of electricity
LDV	light duty vehicle
LPG	liquefied petroleum gas
LULUCF	land use, land use change, and forestry
MoSPI	Ministry of Statistics and Programme Implementation
MSW	municipal solid waste
$MtCO_2$	megatonnes of carbon dioxide
MtoE	megatonnes of oil equivalent
NDC	Nationally Determined Contribution
NEMMP	National Electric Mobility Mission Plan
NFP	National Forest Policy
NG	natural gas
NTPC	National Thermal Power Corporation

NZ	net zero (emissions)
O&G	oil and gas
OEM	original equipment manufacturer
OPGM	Optimal Generation Mix
PAT	Perform, Achieve and Trade
PCC	Per Capita Convergence
PM 2.5, PM 10	(fine) particulate matter 2.5 (microns) & (fine) particulate matter 10 (microns)
PPA	purchase power agreement
PSU	public sector undertaking
R&D	research & development
RCI	Responsibility and Capacity Index
RE	renewable energy
RES	renewable energy sources
RPO	Renewable Purchase Obligation
SAFARI	Sustainable Alternative Futures for India
SEC	specific energy consumption
SSP	Shared Socioeconomic Pathways
T&D	transmission and distribution
TCO	total cost of ownership
tCO	tonne of carbon dioxide
TCRE	Transient Climate Response to Cumulative Carbon Emissions
tcs	tonne of crude steel
TWh	terawatt-hours
UN DESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change
VRE	variable renewable energy
WRII	World Resources Institute India

ENDNOTES

1. The National Forest Policy (NFP) requires 33 percent of the geographical area to be under forest and tree cover.

2. The transport and electricity sectors use least cost logic only in the BAU scenario to determine the technology/energy mix of how demand is met. However, in the policy scenarios, they simply reflect whatever policy is selected (for ex: x percent of RE or EVs).

3. *Direct* economic impacts are those within the affected business itself, caused by the policy or project. For example, if the policy causes the auto manufacturing industry to hire more workers, those added jobs are a direct impact of the policy. *Indirect* economic impacts are those within suppliers of the affected industry. For example, if the growth of the auto industry causes auto manufacturers to buy more steel, and steelmaking companies hire more workers in response, the added jobs at steelmaking companies are an indirect impact of the policy. *Induced* economic impacts are those caused by re-spending of money paid to workers or the government as a result of the growth of the affected industry. For example, the new workers at the auto- and steelmaking companies will spend their wages on various needs, such as dining at restaurants and leisure travel. The resulting job growth in the restaurant industry or in the leisure travel industry is an induced impact. Similarly, if the growth of the auto industry increases government tax revenue (for instance, from workers' income taxes or sales taxes on the additional vehicles sold), and the government spends the money on building new highways, added jobs at highway construction companies are an induced impact (Energy Policy Solutions n.d.)

4. To linearly extrapolate the models' emissions until 2100, we used the "trend" Excel function, which calculates the growth rate of the selected historical data to project future data points at the same "trend."

5. We assume that new investments come in but do not identify the sources, and so the effects of redirecting it from elsewhere are not captured.

6. The outlays for construction activities under housing schemes (PMAY-Urban and Rural), education (NEM), and health (NHM and PMSSY) were estimated to be about 55 percent of the construction sector outlays in the 2015–18 budgets. Assuming the same level of productivity in the construction sector based on historical trends, the SAFARI model's desired quality of life (DQoL) Scenario indicates that during 2020–30, construction activities will grow about 1.4 times the reference scenario levels. Hence, a similar boost is considered under the DQoL scenario in the CGE model.

7. Through the Social Accounting Matrix (SAM), which is the key input to the CGE model and has much higher utilization of labor and capital in the coal sector than in the RE sector.

8. Because the 1.5°C PCC scenario is an outlier and practically infeasible due to its stringency, we do not include it in ranges of indicators where the value is significantly different from the next more stringent budget (2°C PCC).

9. CGE does not disaggregate coal used for combustion or as feedstock, and so the reported figures include both. The other models have only reported coal used for combustion.

10. We have assigned hydrogen 1 percent as a nominal figure (and not 0 percent) to retain it in the energy mix because efforts to increase its share are underway. However, it will continue to need supportive policies to grow.

11. The maximum potential for reduction in energy consumption is 60 percent of energy use.

12. The mode shift policy refers to a policy that reduces the demand for a particular mode of transport by inducing a shift to another mode (for example, from freight HDVs, passenger aircraft, and passenger LDVs to buses, rail, walking, biking, and videoconferencing).

13. The share of RE integration in the total cost of deploying solar energy (with integration) is 24 percent in 2030, 30 percent in 2040, and 27 percent in 2050 (Chaturvedi and Malyan 2021).

14. The cost of storage is not included in the LCOE of RE. To calculate this cost, see Obi et al. (2017) and Pawel (2014).

15. Table VII.c.

16. The future of hydrogen is uncertain now compared to that of electrification, which is already underway in some industrial subsectors. However, electrification + hydrogen is a policy lever in the EPS, and hence they are discussed together.

17. A limitation in the EPS is that only one fuel elasticity factor is used across time. In the short term, the real price elasticity of fossil fuels may be low when alternatives are absent, and so in the real world, the imposition of a carbon tax would raise fuel prices, which could have distributional impacts that are not captured in the EPS. However, in the medium to long term, the real price elasticity of fuels would increase as alternatives become available, and so the distributional impacts would fall and the outputs of the EPS would become more accurate.

18. Given the uncertainty around the future of green hydrogen, the cost projections used in the EPS for the use of hydrogen are also uncertain.

19. Because the 1.5°C PCC scenario is an outlier and practically infeasible due to its stringency, we do not include it in ranges of indicators where the value is significantly different from the next more stringent budget (2°C PCC).

20. Built area of affordable housing, healthcare units, and educational institutions are 40 percent, 70 percent, and 25 percent higher, respectively, in 2050 than in the reference scenario. One hundred percent of urban and rural households shift to clean cooking fuels by 2030, and food security is maintained up to 2050 through increased cropping intensity and better water-use efficiency. All these lead to only a marginal increase in energy, electricity, and emissions by 5–10 percent relative to the reference scenario.

21. The results of the reference scenario are validated through calibration for the period 2013–18 on the major macroeconomic variables of the model such as GDP, investment, consumption growth rates in the economy, overall energy and electricity consumption by each fuel type, and so on. The validation exercise demonstrated that the model reproduced the actual performance of the Indian economy over the period with reasonable accuracy.

22. Table Xi, row 223.

23. The share of RE integration in the total cost of deploying solar energy (with integration) is 24 percent in 2030, 30 percent in 2040, and 27 percent in 2050 (Chaturvedi and Malyan 2021).

24. The cost of storage is not included in the LCOE of RE. To calculate this cost, see Pawel (2014) and Obi et al. (2017).

25. The EPS provides the option to specify the capital cost trajectory for a technology exogenously or to allow it to be determined within the model based on technology deployment. Mature technologies, that is, all technologies except solar PV, onshore and offshore wind, battery storage, and CCS, use exogenous cost trajectories. For solar PV, onshore and offshore wind, battery storage, and CCS, only the capital cost in the start year is specified in the model. The capital costs for all subsequent years are calculated within the model based on cumulative deployment of that technology through that year. The more widely the technology is deployed, the lower the price becomes. This is specified as a percentage cost decline per doubling of cumulative deployment applied to the start year costs.

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