TOPICAL REVIEW

Developing new pathways for energy and environmental decision-making in India: a review

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Abstract
India faces a dual challenge of economic development and responding to climate change. Although India’s per capita emissions are well below global average, the country is one of the world’s largest greenhouse gas emitters. Indian policymakers and stakeholders require high-quality data and research to assess low-emissions, sustainable development strategies. Peer-reviewed literature is a key source of this information and also a key venue for conversation amongst research leaders. This paper examines the recent peer-reviewed literature on India’s 2030 and 2050 pathways. We conducted a systematic literature review to identify key quantitative national modeling studies. From the 34 studies identified, we synthesized scenario data to draw common conclusions and identify critical research gaps. The main focus was on examining the coverage and the state of information available on low-carbon pathways. Overall, we find a few scenarios that are potentially consistent with a 2070 net-zero goal, but more limited assessment of pathways to reach net-zero emissions before this date. Mitigation pathways with greater ambition are required across all energy sectors to ensure a smooth transition to net-zero emissions by or before 2070. The scenarios confirm that reducing emissions to below 2 GtCO2 yr−1 by mid-century would necessitate significant transformations of the Indian energy sector, such as, a decrease in unabated coal power capacity, transportation modal shift, and industrial process switching. The assessment also finds substantial differences in final energy estimates reported across studies, particularly in transportation. The lack of consistency in, and transparency about underlying drivers, assumptions, and even outputs across studies points to the critical need for the sorts of coordinated, multi-model studies that have proven exceptionally valuable for decision makers in other major emitting countries.

1. Introduction

In the face of a growing global consensus to address climate change, countries are grappling with how to reduce their greenhouse gas (GHG) emissions. In the Paris Agreement, countries recognized the importance of reducing emissions and limiting warming to ‘well below 2.0 ˚C’, while making efforts to limit warming to 1.5 ˚C. The Intergovernmental Panel on Climate Change (IPCC) concluded that net global CO2 emissions need to reach zero by mid-century to limit warming to 1.5 ˚C and by around 2070 to limit warming to 2.0 ˚C (IPCC 2018). Limiting warming to well-below 2.0 ˚C will therefore require rapid emissions reductions around the world (Rogelj et al 2016). Under the Paris Agreement, countries are producing nationally determined contributions (NDCs) to outline their near-term climate goals. Many countries are also preparing mid-century strategies (MCs) for reducing emissions (Rose et al 2017).

India is the fourth largest carbon emitter in the world, contributing seven percent of annual global
emissions (Friedrich et al 2020). India's per-capita emissions are still very low and well below the world average. India's decarbonization strategies—like most other countries—will rely on reduced fossil-fuel use, increased use of renewable and other low-emissions energy sources, increasing use of electricity and alternative energy carriers such as hydrogen or biofuels, energy conservation and efficiency, changes in natural and working lands, and potentially even the use of carbon dioxide removal (CDR) options (CDR). At the same time, India has critical development needs and must therefore chart a path forward that navigates between the need to reduce emissions, on the one hand, and, on the other hand, the need for economic growth, decreased air pollution, increased energy access, improved energy security, robust employment, and a range of other development priorities (Fleurbaey et al 2014, Sreenivas and Gambhir 2019). High-quality research is needed to support India's efforts to navigate a low-emissions pathway.

As Indian policy makers look to the research community for guidance, an important question is the state of relevant peer-reviewed literature exploring long-term strategies to reduce emissions. Peer-reviewed literature plays an important role in putting forward credible analyses that are different from, and complementary to, working papers and technical reports. The breadth of the literature is important to establish a rich understanding of possible strategies. Every individual study into mitigation pathways provides only a single glimpse into possible future strategies, and each study can only address a portion of the issues that policy makers are grappling with. It is only as the body of evidence becomes sufficiently large that robust insights and key uncertainties can emerge.

There are relatively few historical studies that have reviewed the state of literature available on India's mitigation pathways. Dubash et al (2018) conducted an interpretive analysis of model-based scenarios from seven selected studies published between 2013 and 2015, and focused on India's energy and emissions pathways up to 2030. Meanwhile, Kumar et al (2019) conducted a meta-analysis on nine low carbon studies published between 2006 to 2016, and reviewed the future electricity mix and emission outcomes. No studies yet have systematically reviewed both India's near-term (2030) and long-term (2050) mitigation pathways, especially from a sectoral perspective. We aim to fill this gap in our review.

This paper reviews the state of, and conclusions on India's near-term (2030) and mid-century (2050) mitigation pathways from peer-reviewed, model-based scenario analyses. The paper is motivated by the following research questions. (a) How robust is the peer-reviewed literature in exploring the deep emissions reductions required to reach the Paris warming goals? (b) What important insights have emerged from the literature about pathways to these goals in key sectors? (c) What are the key gaps in the literature?

The analysis was conducted by examining scenarios from Indian national energy modeling studies with sector-specific information. From these scenarios, we analyzed emissions pathways, energy trends, technological transitions, and policy levers within key sectors (power, industry, transportation, and buildings). We also compared our findings with the high emissions scenarios.

We find a few scenarios that are potentially consistent with a 2070 net-zero goal, but more limited assessment of pathways to reach net-zero emissions before 2070. Even the lowest emission scenarios in the peer-reviewed literature would require a significant shift after 2050 to reduce emissions to net-zero by or before 2070. The scenarios confirm that reducing emissions below 2 GtCO₂ by mid-century will necessitate significant transformations of the Indian energy sector, such as, a decrease in unabated coal power capacity, transportation modal shift, and industrial process switching. Major gaps in the peer-reviewed literature include inconsistencies in scenario data reporting, and the limited number of studies with economy-wide projections on variable renewable energy (VRE) integration, and decarbonization of industry and buildings. The lack of consistency in, and transparency about, underlying drivers, assumptions, and even outputs across studies points to the critical need for the sorts of coordinated, multi-model studies that have proven exceptionally valuable for decision makers in other major emitting countries.

2. Methodology

We conducted a systematic review to identify key national energy modeling studies (Minx et al 2018). The review focused on quantitative national modeling studies (hereafter called 'national studies') from the peer-reviewed literature. We first formulated tailored keyword search terms, surveyed the SCOPUS database, and compiled a list of scenario-based analyses covering India's NDCs and MCSs with sectoral details. The title, abstract, and keywords of the database documents were searched for the following query string occurrence:

India and (Energy) and (NDC or INDC or [Nationally determined contribution] or [Nationally determined contributions] or 2030 or 2050) and (Transport or Building or Residential or Commercial or Industry or Power or Electricity)

The last search for the papers was performed on February 20, 2021, and identified 430 documents. The obtained documents were primarily from double-refereed journals. We then examined whether they were consistent with our predefined criteria for inclusion. The time-period selected for the review was limited to papers published from January 2017
to February 2021 to ensure that any results would be representative of recent data and reflective of Paris commitments.

Global studies which include India as a region, but do not provide detailed national level insights, state and city level studies, policy briefs, historical data reviews, case studies, and other qualitative studies were excluded from our analysis. National studies that did not report either energy or emissions data were also excluded. After screening the initial documents, we identified 34 papers, including (Shukla et al 2017, Dhar et al 2018a, Mittal et al 2018, Chaturvedi et al 2021) which were manually added.

We then synthesized scenario data for individual scenarios across these papers. Data included national CO\textsubscript{2} emissions, supply-side technological transitions (installed power capacity, non-fossil electricity generation share), end-use final energy demand and fuel mixes (buildings, industry, transportation), and policy frameworks. We collected this data directly from the documents’ text, tables, and supplementary material when available (available online at stacks.iop.org/ERL/17/063004/mmedia). Otherwise, we used WebPlotDigitizer (Basile et al 2018, Morton et al 2018, Huang et al 2019) to extract the underlying data from the published figures\textsuperscript{4}.

Finally, we categorized the scenario data into groupings which form the basis of our comparative review. Two types of scenarios analyze sectoral transitions: national scenarios and sectoral scenarios. National scenarios assess economy-wide energy system transitions. Sectoral scenarios investigate individual sectors and provide detailed sub-sectoral information on decarbonization pathways, but they do not assess sectoral synergies and broader trends. Both types of scenarios are important for comprehensive policy analysis and for supplying information on energy transitions.

We grouped national scenarios based on their 2050 CO\textsubscript{2} emissions: ‘below 2 GtCO\textsubscript{2}’, ‘2 to 3 GtCO\textsubscript{2}’, ‘3 to 4 GtCO\textsubscript{2}’, and ‘above 4 GtCO\textsubscript{2}’. This approach to grouping was used to identify the consistency of the scenarios with reaching net-zero emissions in any particular year. It also allows for consistent comparison of national studies based on a common metric. Because they do not report total economy-wide CO\textsubscript{2} emissions, sectoral scenarios were grouped based on stated descriptions, carbon budget assumptions, and alignment of energy use with energy use in economy-wide studies that also contain carbon information. In general, it is not possible to directly compare sectoral scenarios with national scenarios because the former do not consider economy-wide emissions.

An alternative approach would have been to organize studies by their stated policies, emissions goals, or global temperature goals. While useful, the lack of consistency and the lack of transparency among studies makes it difficult to draw comparative conclusions. Moreover, this study is focused on the climate ambition in studies, and emissions are a more direct indicator of ambition than stated policies or strategies. We have, nonetheless, categorized the scenarios by their stated policy goals and linked these to 2050 emissions levels. The advantage of an emissions-based assessment is particularly pronounced given the wide variation in emissions trajectories among scenarios with a similar policy character (see below).

One challenge in this assessment is a lack of consistent reporting of metrics across studies. Assessing sectoral transitions across multiple scenarios requires granular details on key metrics such as final energy consumption, sectoral fuel mix, and CO\textsubscript{2} emissions pathways. However, many scenarios assessed do not report these metrics comprehensively and at the required specificity. A major conclusion from this review is the need for coordinated, multi-model analyses, which are designed to consistently track a range of inputs and outputs under common assumptions.

Overall, the fuel mixes and technological transitions outside of the power sector were largely unreported across national scenarios. Similarly, the sectoral scenarios for the most part did not provide economy-wide CO\textsubscript{2} emission trajectories. In addition, the national scenarios partially reported several of the key energy indicators. Some scenarios did not report the key indicators for specific years (2030 or 2050); others did not provide complete energy data covering all the technologies and subsectors assessed. All these factors made it challenging to compare the available data from a consistent lens. Thus, the scenario results discussed across individual sections of the paper vary, reflecting the literature data availability.

3. Overview of studies

Based on our methodology, we narrowed the national studies down to 16 national and 18 sectoral papers. Each paper contained up to five scenarios. Among the sectoral papers, the power sector was examined the most (\(n = 9\)), followed by the transportation (\(n = 4\)), buildings (\(n = 3\)), and industrial sectors (\(n = 2\)). 23 of the papers extended to 2050 and ten extended only to 2030. The studies were based on a range of energy and integrated assessment models (IAMs). Models differed in their design approach (top-down, bottom-up, hybrid), regional coverage (regional, global), solution methodology (cost optimization, general equilibrium, simulation, accounting), and sectoral coverage. All the analyses reviewed were exclusively focused on India. Optimization models

\textsuperscript{4} Numerous studies across disciplines have used WebPlotDigitizer as a reliable tool to obtain data estimates. While the resulting estimates are accurate, marginal precision errors are observed on a case-by-case basis (Dreven et al 2017). The usage of the tool was necessary because many studies didn’t report the numerical data associated with the figures.
(AIM/ENDUSE, ANSWER-MARKAL, GENeSYS-MOD, IMRIT, TIAM-UCL, \( n = 12 \)) were the most commonly used along with general and partial equilibrium models (AIM-CGE, GCAM, GCAM-IIM, \( n = 6 \)) and hybrid models (AIM/ENDUSE + IMACLIM, AIM/ENDUSE + GEM-E3, \( n = 6 \)). Other modeling frameworks included top-down optimization (IRADe-Neg, \( n = 2 \)), bottom-up simulation/stock accounting (LBNL India Dream, \( n = 1 \)), energy systems simulation (EnergyPLAN, \( n = 1 \)), and statistical forecasting (bass diffusion model, simple logistic model, \( n = 2 \)).

These models were driven by a range of technology, cost, and macroeconomic assumptions, which differed across studies and between scenarios (table 1). GDP growth differed greatly across studies (e.g. ranging between 5% to 8% annual growth from 2010/15-2030). UN median population projections were used by majority of the studies (1.5B. by 2030, 1.75B. by 2050). The technological attributes and cost assumptions were not reported consistently across studies and are not summarized in this paper. They are, however, reflected when possible, in the results discussed in the upcoming sections. Identification of drivers would require more complete and standardized datasets of technological and socioeconomic indicators. Such comprehensive data was not available across the national studies (supplementary material, appendix 1). We strongly encourage multi-model comparison studies as a way to provide a systematic platform for identifying and comparing the drivers that influence the character of the different pathways.

4. India’s national CO\(_2\) emissions trajectories

Forty-three national scenarios, covering a wide range of future emissions, were obtained from fourteen national papers. The scenarios were grouped by their 2050 emissions to examine the alignment of the scenarios with attaining net-zero emissions by or before 2070, and for the purposes of the sectoral assessments in the sections that follow (figure 1). The dataset included three scenarios consistent with emissions below 2 GtCO\(_2\) yr\(^{-1}\) in 2050, six with emissions between 2 to 3 GtCO\(_2\) yr\(^{-1}\), nine with emissions between 3 to 4 GtCO\(_2\) yr\(^{-1}\), and twenty-five with emissions above 4 GtCO\(_2\) yr\(^{-1}\).

Most national scenarios (\( n = 31, 72\% \)) reported total energy-related CO\(_2\) emissions from conventional energy supply (power) and demand sectors (industry, transportation, buildings, agriculture). Some scenarios (\( n = 12, 28\% \)) also estimated non-CO\(_2\) GHG emissions, but at varying degrees of detail. Overall, half the papers (\( n = 7 \)) provided a sectoral breakdown of the estimated emissions trajectories. Energy related non-CO\(_2\) emissions, as well as total GHG emissions from AFOLU, industrial processes, and waste were largely unreported. This is important because most decarbonization studies with multiple GHGs find that it is harder to achieve net zero with non-CO\(_2\) gases than with CO\(_2\) itself. This implies that even the lowest emission scenarios described in this study may have greater difficulty in achieving overall net-zero emissions than it first appears.

Most national papers had at least one scenario assessing India’s NDC (table 1). India’s 2030 NDC includes several components: an overall emissions intensity goal of a 33%–35% reduction from 2005, a power sector goal of 40% non-fossil capacity, a carbon sink commitment of 2.5–3 GtCO\(_2\) (through afforestation), and a set of non-binding sectoral policies (UNFCCC 2016).

Policy targets in national scenarios were implemented using several approaches, which varied across studies and scenarios (supplementary material, appendix 2). Most NDC scenarios were modeled using overall emissions constraints set at India’s NDC targets. However, several scenarios also accounted for detailed sectoral interventions (Byravan et al 2017), and for scenario configurations with varying growth or cost trajectories (Chaturvedi et al 2021). Scenarios focused on long-term warming goals were generally modeled using a carbon tax or constraints, or sectoral policies to some extent. Several of the power-sector studies used other, non-policy approaches, such as multi-criteria optimization or statistical forecasting.

Emissions in 2050 among the NDC scenarios varied by a factor of two and the range roughly matched the range of 2050 emissions outcomes in reference scenarios (figure 2). Most NDC scenarios (\( n = 10, 76\% \)) projected emissions between 3.5 and 4.3 GtCO\(_2\) (5.4%–7.3% GDP growth) by 2030, and few scenarios estimated 5.8–7.4 GtCO\(_2\) under high growth (\( \geq 8\% \)). This indicates very different perceptions of the possible outcome of the Indian NDC and it provides insight into the ambition of the Indian NDC. The 2050 emissions ranges for the 2.0 °C and 1.5 °C scenarios were also broad, indicating differing perceptions of the role of India’s strategy in broader global efforts to limit warming.

An important issue when evaluating emissions mitigation scenarios is the consistency of those scenarios with global warming goals. There are multiple ways that researchers and policy makers have framed the relative roles of individual countries in meeting long-term warming goals. Some have looked to modeling assessments of global least-cost pathways (McCollum et al 2018, Roelfsema et al 2020), whereas others have focused on different equity-based frameworks that might, for example, account for historical emissions, distinct economic and development circumstances (Robiou du pont et al 2017, Holz et al 2018, Van den Berg et al 2020), and social welfare principles (Ackerman et al 2013, Budolfson et al 2021). These different approaches lead to very different conclusions about what level
Table 1. Indian national modelling studies.

| No. | Study                  | Model/s                                      | Time horizon | Scenario (emissions bin)          | 2030 emissions | 2050 emissions | GDP growth rate          | Sectoral coverage             |
|-----|------------------------|----------------------------------------------|--------------|----------------------------------|----------------|----------------|--------------------------|--------------------------------|
| 1   | Vishwanathan et al (2018) | AIM/ENDUSE (bottom-up optimization model)     | 2010–2050    | BAU (Above 4)                    | 4115           | 5885           | 7.03% (until 2030)       | 1—Agriculture, Buildings, Industry, Power, Transport |
|     |                        |                                              |              | INDC (NDC)                       | 3608           | 4727           | 5.44% (until 2050)       |                                |
|     |                        |                                              |              | 2 °C (3–4)                       | 3296           | 3156           |                          |                                |
|     |                        |                                              |              | 1.5 °C (2–3)                     | 3202           | 2244           |                          |                                |
| 2   | Garg et al (2017)       | AIM/ENDUSE                                   | 2000–2050    | BAU (NDC)                        | 3500           | 4183           | —                        | 1                              |
| 3   | Gupta et al (2019)      | AIM/ENDUSE + IMAC-LIM (hybrid bottom-up and top-down model) | 2013–2050    | BAU (NDC)                        | 4160           | 5760           | 5.5/6.5/7.5% (until 2030) |                                |
|     |                        |                                              |              | 2DegLG (2–3)                     | 3150           | 2100           | (until 2030)             |                                |
|     |                        |                                              |              | 2DegMG (2–3)                     | 3180           | 2920           | 4.6/5.6/6.6%            |                                |
|     |                        |                                              |              | 2DegHG (Below 2)                 | 3150           | 1990           | (until 2050)             |                                |
| 4   | Gupta et al (2020b)     | AIM/ENDUSE + IMAC-LIM                       | 2012–2050    | BAU (Above 4)                    | 4180           | 5850           | 6.26/6.61/6.63% (until 2050) |                                |
|     |                        |                                              |              | 2 °C (3–4)                       | 3340           | 3190           | 6.61% (until 2030)       |                                |
|     |                        |                                              |              | 2DSUS (2–3)                      | 4210           | 2610           | 5.78/5.83/5.84/5.83%    |                                |
|     |                        |                                              |              | 1.5 °C (2–3)                     | 3020           | 2390           | (until 2050)             |                                |
| 5   | Parikh et al (2018)     | IRADe-Neg50 (inter-temporal optimization model) | 2012–2050    | DAU (Above 4)                    | 4707           | 13 608         | 7.44/7.34%              |                                |
|     |                        |                                              |              | AMBA (NDC)                       | 3868           | 8225           | 7.33% (until 2050)       |                                |
|     |                        |                                              |              | TCI.5 C (Above 4)                | 2400           | 5592           | (until 2050)             |                                |
| 6   | du Can et al (2019)     | LBNL India Dream model (bottom-up stock accounting and simulation model) | 2015–2050    | Baseline (NDC)                   | 4005           | 7327           | 7% (until 2050)          |                                |
|     |                        |                                              |              |                                  |                |                | 5% (until 2050)          |                                |
| 7   | Mathur and Shekhar (2020) | MARKAL-India (bottom-up cost optimization model) | 2016–2051    | NPi (Above 4)                    | 6498           | 14 115         | 8.3% (until 2030)        |                                |
|     |                        |                                              |              | INDC (NDC)                       | 5847           | 12 347         | 7% (until 2050)          |                                |
|     |                        |                                              |              | NPiH (Above 4)                   | 5400           | 10 413         |                          |                                |
|     |                        |                                              |              | NPiL (Above 4)                   | 4941           | 6819           |                          |                                |
| 8   | IEA Energy Outlook (2021) | World Energy Model                          | 2040         | STEPS (3–4)                      | 3311           | 5656           | 5.4% (2019–2040)         |                                |
|     |                        |                                              |              | SDS (Below 2)                    | 2384           | 4727           | 6% (2019–2040)           |                                |
| 9   | Vishwanathan and Garg (2020) | AIM/ENDUSE                              | 2015–2050    | BAU (Above 4)                    | 3988           | 3279–3680      | 6.91% (2015–2030)        |                                |
|     |                        |                                              |              | NDC (NDC)                        | 3586           | 3479–4119      | 5.55% (until 2050)*      |                                |
|     |                        |                                              |              | 2 °C (3 to Above 4)              | 3279–3680      |                |                          |                                |
|     |                        |                                              |              | 1.5 °C (2–3)                     | 3211           | 2234           |                          |                                |

(Continued.)
Table 1. (Continued.)

| No. | Study                          | Model/s                                      | Time horizon | Scenario (emissions bin) | 2030 emissions | 2050 emissions | GDP growth rate       | Sectoral coverage |
|-----|--------------------------------|----------------------------------------------|--------------|--------------------------|----------------|----------------|-----------------------|-------------------|
| 10  | Byravan et al (2017)           | India Multi Regional TIMES model (hybrid bottom-up cost optimization and accounting model) | 2012–2030    | BAU (Above 4) SD (NDC)   | 5578           | 4064           | 6.5% (until 2030)      | 1                 |
| 11  | Shukla et al (2017)            | AIM-CGE (top-down general equilibrium model) | 2005–2030    | Reference (Above 4) INDC (NDC) 2 °C (3–4) | 8004           | 7479           | 8% (until 2030)        | 2—Buildings, Industry, Power, Transport |
| 12  | Dhar et al (2018a)             | ANSWER-MARKAL (bottom-up cost optimization model) | 2010–2050    | NDC (NDC) 2 °C (3–4) SE4ALL plus 2 °C (2–3) | 4060           | 6590           | 7.1% (until 2050)      | 2                 |
| 13  | Chaturvedi et al (2021)        | GCAM-IIM (dynamic recursive market-equilibrium model) | 2050         | Reference (Above 4)      | 4071           | 6785           | Range from SM         | 2                 |
| 14  | Mittal et al (2018)            | AIM-CGE                                      | 2005–2050    | NDC (NDC) NDC_2D (2–3) 2 °C (2–3) 1.5 °C (Below 2) | 6429           | 11875          | 8.1% (until 2030)      | 2                 |
| 15  | Yu et al (2018)                | GCAM-India (dynamic recursive market-equilibrium model) | 2010–2050    | BAU (Above 4) All Efficiency Policies (Above 4) | 4563           | 7457           | 2030 (3796 billion 2010 USD) | 3—Buildings |
| 16  | Vishwanathan et al (2019)      | AIM/ENDUSE + GEM-E3 (hybrid bottom-up and top-down model) | 2010–2030    | BAU (Above 4) Advanced NDC (2–4) | 4373           | 6756           | 2010–2030 (6.22%)      | 3                 |
| 17  | Sharma et al (2017)            | GCAM-IIM                                     | 2010–2050    | Reference Low Growth     |                |                | 2020–2030 (7.28%,6.11%)  | 3 (Commercial cooling and refrigeration) |

(Continued.)
| No. | Study | Model/s | Time horizon | Scenario (emissions bin) | 2030 emissions | 2050 emissions | GDP growth rate | Sectoral coverage |
|-----|-------|---------|--------------|--------------------------|----------------|----------------|----------------|-------------------|
| 18  | Dhar et al (2020) | ANSWER-MARKAL + material demand model (hybrid model) | 2010–2050 | NDC (NDC) 2 °C conventional 2 °C sustainable 1.5 C (Below 2) | — | — | 2010–2030 (8%) 2010–2050 (over 7%) | 4—Industry (Iron steel and cement) |
| 19  | Jajal and Mishra (2018) | Bottom-up Energy Modeling Approach (Partial Equilibrium) | 2015–2050 | Reference Scenario Energy Efficient Scenario | — | — | — | 4 (Iron, steel, cement, and brick) |
| 20  | Reddy (2018) | Bass diffusion model | 2030 | Reference | — | — | 5—Power |
| 21  | Shearer et al (2017) | Davis and Socolow's method | 2065 | Reference | — | — | 5 |
| 22  | Laha et al (2020) | EnergyPLAN v13.0 (Energy modeling tool) | 2016–2030 | Optimal_RES 2030 | — | — | 5 |
| 23  | Akash et al (2017) | India Energy Security Scenarios 2047 (IESS) tool | 2030 | Medium growth | — | — | 5 |
| 24  | Gulagi et al (2017) | Linear optimization model | 2050 | Country-wide Integrated | — | — | 5 |
| 25  | Malik et al (2020) | MARKAL-India AIM/ENDUSEAIM V2.1 REMIND-MagPIE WITCH, IMAGE GEM-E3, POLES | 2030 | Early action Late action | — | — | 5 |
| 26  | Mukhopadhyay et al (2020) | ORDENA (generation expansion planning software) | 2029–2030 | Reference | — | — | 5 |
| 27  | Chattopadhyay and Sharma (2017) | Statistical modelling | 2016–2030 | Reference | — | — | 5 |
| No. | Study | Model/s | Time horizon | Scenario (emissions bin) | 2030 emissions | 2050 emissions | GDP growth rate | Sectoral coverage |
|-----|-------|---------|--------------|--------------------------|----------------|----------------|----------------|-----------------|
| 28  | Gadre and Anandarajah (2019) | TIAM-UCL (bottom-up, cost optimization model) | 2020–2050 | Reference INDC 2 °C ATP EIC PCC | 2020 (6.9%) 2030 (5.5%) 2050 (3.6%) | 5 |
| 29  | Gupta and Garg (2020a) | AIM/ENDUSE + IMAC-LIM | 2012–2050 | BAU (Above 4) DEVF (Above 4) CNT (Below 2) SYNCH (Below 2) | 6% (2013–2050) | 6—Transport |
| 30  | Dhar et al (2017) | ANSWER MARKAL | 2010–2050 | INDC 2 °C | 7.1% (2010–2050) | 6 |
| 31  | Dhar et al (2018b) | ANSWER-MARKAL | 2010–2050 | BAU (Above 4) NDC (2–4) 2 °C (2–4) 1.5 °C (Below 2) | 7.1% (2015–2050) | 6 |
| 32  | Paladugula et al (2018) | GCAM GCAM-IIM India Multi Regional TIMES model IRADe-Neg-50 TERI Excel-based national macro-model | 2050 | Reference (Above 4) | 6.7% to 8.08% (2015–2050) | 6 (Road Transport) |
| 33  | Singh et al (2019) | Multi-sector applied general equilibrium model | 2011–2030 | Reference (Above 4) Combined (NDC) | 4568 3572 | 5.7% (until 2030) (also, simulate high 7.5% and low GDP variations 5%) 7—Industry, Power, Services, Consumer, Other Sectors |
| 34  | Lawrenz et al (2018) | GENeSYS-MOD (bottom-up cost optimization model) | 2015–2050 | LEO 100% RES | — | 8—Power, Transport, Heating |
of Indian emissions would be consistent with limiting warming to $1.5 \, ^\circ C$ or $2.0 \, ^\circ C$ (supplementary material, appendix 3 and 4). As an example of the cost-effectiveness approach, India’s 2050 total CO$_2$ emissions from the CD-LINKS multi-model study (McCollum et al 2018, Roelfsema et al 2020) range from 0.3 to 3.16 GtCO$_2$ for scenarios limiting warming to $2.0 \, ^\circ C$ (>50%/>66% likelihood) and from $-0.83$ to 0.1 GtCO$_2$ for scenarios limiting warming to $1.5 \, ^\circ C$ (>66% likelihood).

In contrast, scenarios on multiple-effort sharing approaches show that India’s 2050 emission levels consistent with the global climate goals vary, and depend on the equity-based formulations used to allocate the national carbon budgets (Robiou du pont et al 2017, Van den Berg et al 2020, Budolfson et al 2021). Ninety-percent of these effort-sharing scenarios indicate that India’s total CO$_2$ emissions ranging from 1.45 to 3.0 GtCO$_2$ and 0.27–4.0 GtCO$_2$ by 2050 are aligned with global $1.5 \, ^\circ C$ and $2.0 \, ^\circ C$
warming targets respectively (supplementary material, appendix 4 and 5). A range of equity sharing approaches are reported in these studies; organized by the highest assumed allocation for India to the lowest in 2050, these include equal cumulative per capita emissions, greenhouse development rights, utilitarian framework, ability to pay, and contraction and convergence. A few other studies propose alternative effort sharing frameworks and methodologies, which assign higher emission allowances to India (CSO Equity Review 2018, Holz et al 2018); however, their analysis is limited to 2030. Most of the scenarios presented in this paper exceed emission levels consistent with 1.5 °C and 2.0 °C when considering the majority of such equity based allocations.

It is not the purpose of this paper to weigh in on debates (Kartha et al 2018, Van den Berg et al 2020) about the most appropriate 2050 emissions level for India in order to limit warming to 1.5 °C or 2.0 °C. It is possible, however, to put the scenarios in this paper in the context of the net-zero framing that India has used to define its long-term goals. On November 2, 2021, India committed to reduce its net CO2 emissions to zero by 2070 (MEA 2021). All of the scenarios in the literature with emissions between 2 to 3 GtCO2 yr−1 could be considered potentially consistent with that goal, however, they would require a significant shift in their emissions trajectory post-2050 to attain net zero by or before 2070. Scenarios with emissions above 3 GtCO2 yr−1 would require reductions of at least 0.15 GtCO2 yr−1 from 2050 through 2070. For comparison, India’s CO2 emissions have grown by 0.08 GtCO2 yr−1 over the last two decades. Scenarios limiting emissions to about 2 GtCO2 yr−1 appear more consistent with a 2070 net-zero goal, but would require a sustained decrease of 0.1 GtCO2 yr−1. If India were to consider the possibility of reaching net-zero CO2 emissions by 2060, the number of available scenarios in the peer-reviewed literature are drastically reduced. Even the lowest of the emission scenarios would require major reductions of 0.2 GtCO2 yr−1. No scenarios in the reviewed literature are consistent with net-zero CO2 emissions goal much before 2060. In other words, while a few of the scenarios are in principle consistent with net-zero CO2 emissions in 2070, additional analysis is needed. For example, mitigation costs typically rise as one gets closer to net zero, and non-CO2 gases may be harder to completely eliminate.

5 While some analysts have questioned whether ambitious technological and policy options should be explored in post-2050 scenarios to achieve high emission reduction rates, for example, lower mitigation costs, or barriers for implementing mitigation technologies such as large-scale CDR, we review the scenarios as they are, without assessing other options they could have considered. Multi-model comparison and future research can explore additional uncertainties and scenario assumptions.

5. Sectoral analysis and technological transitions

5.1. Power sector
All national scenarios (n = 16, 100%) provided information on power sector transitions. Installed power capacity and electricity generation were consistently reported across papers. In addition, 15 sectoral scenarios (9 power sector papers) provided analysis of coal transitions (Shearer et al 2017, Malik et al 2020), short-term power sector developments (Laha et al 2020, Mukhopadhyay et al 2020), and long-term renewable development pathways (Gulagi et al 2017, Gadre and Anandarajah 2019).

Most national and sectoral scenarios (72%) estimated that electricity generation will rise to 2100–3300 TWh yr−1 by 2030 and to between 2700 and 8200 TWh yr−1 in 2050 (supplementary material, appendix 7, figure 56). Multi-model comparison could help tease out the underlying drivers that differentiate assumptions about future electricity demand growth, recognizing that the studies at hand neither apply consistent inputs nor report consistent outputs.

Overall, several national and sectoral scenarios indicate it is likely India will achieve its power sector NDC target of 40% non-fossil capacity by 2030 with limited or no additional effort beyond stated policies (Shukla et al 2017, du Can et al 2019, Singh et al 2019). Several scenarios indicate that India is likely to outperform this target and achieve non-fossil capacity from 45% to 59% in 2030 (Chattopadhyay and Sharma 2017, Chaturvedi et al 2021, IEA 2021).

India’s above 4 GtCO2 scenarios, meanwhile, forecast an expansion of India’s installed coal capacity (figure 3), although the percentage of coal in electricity generation decreases. Electricity demand growth is anticipated to be high enough to allow for India to meet its NDC low-emissions power goal while simultaneously increasing coal generation, especially if renewables growth does not keep up with the demand growth (Garg et al 2017, Gupta et al 2020b). Several of these scenarios estimate that coal capacity will increase to approximately 270–460 GW by 2030 (Byravan et al 2017, Chattopadhyay and Sharma 2017, Mathur and Shekhar 2020, Mukhopadhyay et al 2020); some expect it to increase as high as 550–740 GW (Shukla et al 2017, Mittal et al 2018) under high growth (8% annual GDP growth until 2030).

There is a lack of consensus on the role of natural gas in the above 4 GtCO2 scenarios. In the near term, natural gas generation increases in some studies, along with renewable generation, as the reliance on coal decreases. They estimate that gas capacity might increase to 70–110 GW in 2030 (Garg et al 2017, Shukla et al 2017, Vishwanathan and Garg 2020). This increase would likely depend on large domestic reserve discovery, TAPI pipeline
construction, international LNG trade, and high-volume exploitation of shale gas in India (Malik et al 2020). Several researchers acknowledge, however, that due to constraints on domestic gas reserves supply, high prices of imported LNG, potential to create carbon lock-ins, and competing interests with other sectors, India’s future power system may have difficulties incorporating large-scale gas-based generation. Its growth might remain limited (20–60 GW) (Byravan et al 2017, Chattopadhyay and Sharma 2017, Malik et al 2020, Mathur and Shekhar 2020). Scenarios generally indicate a small role for nuclear and hydropower, with most projecting a capacity increase to 10–40 GW and 50–80 GW by 2030. The range of installed power capacity by technology obtained from the literature is summarized in the supplementary material (appendix 8, table S5).

Reducing coal capacity in the next ten years is required to limit emissions to well below 4 GtCO₂ in 2050. Multiple scenarios show that achieving emission reductions (between 2 to 4 GtCO₂ by 2050) necessitates coal capacity reduction to about 160–270 GW by 2030 (Shukla et al 2017, Mittal et al 2018, Vishwanathan et al 2018, Vishwanathan and Garg 2020). For deeper emission reductions (below 2 GtCO₂) a further decrease in coal capacity (to about 68–221 GW by 2030) is warranted (Mittal et al 2018, Gadre and Anandarajah 2019, IEA 2021).

The literature suggests that a near-term coal fleet expansion will lead to increased stranded assets, impede renewable development, and make it challenging for India to achieve more ambitious climate goals in the medium to long-term (Shearer et al 2017, Malik et al 2020). Coal expansion in the short-term could lead to an estimated 133–227 GW of stranded coal capacity from 2030 to 2050 (Gadre and Anandarajah 2019, Malik et al 2020, Vishwanathan and Garg 2020). Alternatively, early retirement of coal power plants would make the transition more economical by reducing stranded assets (to about 14–159 GW) and make way for renewable and nuclear development (Malik et al 2020). Shearer et al (2017) estimate that limiting coal capacity development to operational and under construction projects (between 2015 and 2030) is sufficient to meet India’s NDC emissions intensity goal.

There are different perspectives on the role and implications of carbon capture and storage (CCS) in national studies. On one hand, several papers have demonstrated that the deployment of CCS technologies in power and industrial sectors plays an important role in reducing long-run CO₂ emissions (Mittal et al 2018, Vishwanathan et al 2018, Vishwanathan and Garg 2020). On the other hand, some papers acknowledge the potential of CCS to reduce emissions, but they do not consider CCS technologies as an option in their scenarios, arguing that cost uncertainties, technological nascency, feasibility concerns, and economic barriers associated with commercialization in India render CCS a small contributor at best (Shearer et al 2017, Mathur and Shekhar 2020). Few papers, in addition, investigate alternative low-carbon pathways both with and without CCS (Gadre and Anandarajah 2019, Gupta et al 2020b).

India’s fossil-fuel power capacity either must fall precipitously or has to be retrofitted with CCS to achieve long-term emissions reduction (below 4 GtCO₂ in 2050). The below 4 GtCO₂ pathways, as indicated by the national scenarios, are largely reliant on early penetration of CCS (about 10–60 GW by 2030) in the short term, and large-scale deployment.
of CCS in the long-term (about 150–850 GW by 2050). Alternatively, some sectoral and national scenarios explore transitions reliant largely on renewable electricity. In these scenarios coal generation share reduces drastically in the long-term. Such scenarios forecast a meagre 3%–5% coal generation share (Gulagi et al. 2017, Lawrenz et al. 2018, Gadre and Anandarajah 2019) or a completely phase out by 2050 (Malik et al. 2020, Gupta et al. 2020b). Drop in coal generation is substituted rapidly by solar generation (>50% share), succeeded by wind, hydropower (Gulagi et al. 2017, Lawrenz et al. 2018 (not shown in figure 4)) and nuclear (Gadre and Anandarajah 2019). The total VRE generation share reported ranges from 52% to 100%. Gupta et al. (2020b) demonstrates an alternative pathway where a high renewable share (50%) is supplemented by high gas generation to provide back-up peak-load.

In their narratives, the high-VRE scenarios highlight changes and investments needed to integrate a high share of intermittent renewable power in the power grid. This includes upgrading transmission and distribution networks, investing in battery storage and smart grid technologies, optimizing power systems operations, implementing demand response programs, and planning flexible back-up generation capacity that can ramp-up production when renewable dispatch drops (Lawrenz et al. 2018, Gadre and Anandarajah 2019, Laha et al. 2020, Gupta et al. 2020b). The models used to develop these scenarios, however, are only capable of exploring a fraction of these issues. Reporting the type and amount of storage required is very important in the integration of high share VRE; yet most mitigation studies do not report these. In addition, only a few scenarios investigate VRE integration at granular time steps, which is vital in understanding VRE supply and demand matching (Gulagi et al. 2017, Laha et al. 2020, Mukhopadhyay et al. 2020). Further research is required to establish the feasibility of large-scale VRE integration in India.

Policy makers want to know the types of policies needed to decarbonize power. Renewable energy expansion policies assessed in the literature focus largely on stringent capacity targets to further renewable and storage expansion, and a national carbon price to facilitate aggressive market penetration of renewables and CCS (Mittal et al. 2018, Vishwanathan et al. 2018, Singh et al. 2019). Meanwhile, policies pertaining to coal transitions include early retirement of inefficient coal power plants, limiting new coal

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6. Lawrenz et al. (2018) didn’t provide information on installed power capacity. However, electricity generation estimates were reported.

7. Some studies use a range of mechanisms to roughly model VRE integration. This includes: (a) improved modeling parametrization to ‘incorporate investment dynamics, power system operation, storage and grid requirements, and temporal matching of supply and demand’ (Malik et al. 2020), (b) additional cost accounting for VRE grid integration (Chaturvedi et al. 2021), (c) setting solar penetration limits (Gadre and Anandarajah 2019), (d) estimating aggregate solar with storage capacities (Mathur and Shekhar 2020, Vishwanathan and Garg 2020). Chaturvedi et al. (2021), in their analysis, conclude that even a nominal VRE integration cost, would have a major impact on India’s renewable forecasts. Further studies with more focus in VRE integration are therefore recommended.

8. Few studies estimate the storage requirements (GW) for India. These range from around 34–40 GW in 2030 (for 344–530 GW VRE (Mukhopadhyay et al. 2020, IEA Outlook 2021) and about 323 GW in 2050 for 1512 GW of VRE (Gulagi et al. 2017).
development to cleaner technologies (integrated gasification combined cycle, supercritical, ultrasupercritical), coal moratoriums to prevent stranding of coal assets, increased nuclear and gas power generation, and eventual phaseout of conventional coal power (Vishwanathan et al 2018, Malik et al 2020, Gupta et al 2020b). These policies are supported by grid initiatives focused on reducing transmission and distribution losses, developing high-voltage direct current (HDVC) transmission lines, and providing universal electricity access. (Gulagi et al 2017, Gupta et al 2020b).

Several of these policies/targets are already in place. Initiatives such as the National Solar Mission, National Smart Grid Mission, National Mission on Transformative Mobility & Battery storage were introduced by the Indian government to promote solar power, modernize transmission and distribution networks, and develop domestic battery storage manufacturing expertise. In addition, India has announced a 500 GW renewable energy target to further expand its clean energy generation.

While India’s power sector has been explored extensively, there is significant scope for both national and sectoral studies to assess alternative pathways focused on a high share of VRE and storage technologies. In addition, multi-model efforts could further provide robust evidence on the drivers of electricity demand and technology mix across national models.

5.2. Industry
There are few detailed assessments of India’s industrial transitions. Most national papers assess the industrial sector in aggregate (n = 14, 87%), but do not quantify energy breakdown by fuel and technological transitions. Limited national papers report key metrics such as: specific energy consumption (n = 4), industrial output and growth rates (n = 3), and energy by subsector/fuel (n = 3). Two sectoral papers provide more comprehensive information (Jajal and Mishra 2018, Dhar et al 2020), but that information is limited to iron and steel, cement, and brick sectors (supplementary material, appendix 8, table S6).

Nonetheless, national scenarios generally agree that industry will remain India’s largest energy consumer and that its energy demand and emissions will grow rapidly. Across all scenarios, industrial energy is estimated to increase 1.6–3.5 times by 2030 and 3.1–6.2 times by 2050, relative to 2019 (figure 5). Economic development and government initiatives such as ‘Make in India’ will likely promote this growth (Mittal et al 2018, Parikh et al 2018, du Can et al 2019).

Several above 4 GtCO₂ scenarios (n = 7) share common perspectives on industrial coal consumption, electrification, and energy efficiency. Industry continues to rely heavily on coal in these scenarios. This is especially true in energy intensive industries, where it is used as a process feedstock and to generate high-temperature heat. This sustained coal dependency is largely due to the reallocation of coal supply from the power sector, abundance of domestic coal, economic advantage over low-carbon fuels, and high industrial electricity prices. Furthermore, industrial electricity demand is expected to rise from the uptake of electric motor drives and other equipment, and energy efficiency improvements will be beneficial in reducing energy and emissions. Yet, the transition to low-carbon solutions and wider electrification will be gradual without supporting decarbonization policies.
In 2008, the Indian government introduced PAT, a market-based compliance program, designed to fast-track energy efficiency improvements in energy-intensive industries. Phase I/II of the program (2012-2019) were highly successful in achieving emissions reduction (0.09 GtCO₂), energy savings (21.95 mtoe) and cost savings (₹4955 crores) in 1099 industrial facilities from eleven subsectors (Aluminum, Cement, Chloralkali, Fertilizer, Iron & Steel, Paper & Pulp, Thermal Power Plant, Textiles, Refineries, Railways and DISCOMs) (PAT Cycle 2020).

A small number of sectoral ($n = 2$) and national scenarios ($n = 4$) explored provide detailed information on industrial sector transformations. Iron, steel, and cement decarbonization (below 4 GtCO₂ in 2050) necessitates enhanced energy efficiency, process switching, material efficiency, and CCS. Dhar et al (2020) in their ‘way below 2°C’ scenario demonstrates 70% emissions reduction (from 1 GtCO₂ to 0.3 GtCO₂) in the iron and steel sector by 2050. This entails massive energy intensity reductions (0.25toe/ton-steel), material demand reductions (456 Mt, 26% decrease from their baseline scenario), high adoption of electric arc furnace with recycled scrap (78%), and decarbonization of the power system (0.5 kgCO₂ kWh⁻¹). Similar energy intensity reductions (0.28 toe/ton-steel) are observed in Vishwanathan et al (2018). For emissions reductions in the cement industry, scenarios ($n = 5$) illustrate a complete transition from wet to dry process, high adoption of CCS (Dhar et al 2020), greater production of blended cements (slag, gypsum, pozzolana, and fly ash) and optimal facility operations (Jajal and Mishra 2018, Vishwanathan et al 2018, Dhar et al 2020, Vishwanathan and Garg 2020). Despite favorable results, there is considerable scope to build upon these initial research efforts, and further establish the viability these pathways.

Policy is another significant aspect of industrial mitigation scenarios. These scenarios, together, model a few sectoral policies needed for promoting mitigation options and reducing sectoral emissions. Numerous national scenarios use the perform trade and achieve (PAT)⁹ framework to model energy efficiency improvements in the industrial subsectors. A small group of scenarios ($n = 4$) model material efficiency through material substitution, intensive material use, higher recycling, and reuse. Dhar et al (2020), in particular, conducts a detailed material flow modeling for a range of policy futures. To promote rapid transition to low carbon technologies and CCS, however, these scenarios largely depend on an economy-wide carbon tax, and do not provide further policy detail.

It is widely recognized that it will be challenging to decarbonize the industrial sector (Papadis and Tsatsaronis 2020). All scenarios show that the sector will play an important role in reducing emissions. Considering the anticipated role in demand and high fossil-fuel dependency, pathways assessing decarbonization potentials across industrial subsectors are essential and require heightened-attention. During our review period (2017–2021), we identified only a handful of sectoral studies investigating India’s industrial decarbonization pathways. These studies provided detailed information on India’s iron and steel, and cement transitions, but did not cover other subsectors due to restricted scope. Meanwhile, national scenarios evaluated industry’s overall decarbonization potential but failed to provide complete information on technological transitions, demand breakdown by fuel, or efficiency assumptions, which are crucial in understanding these transitions.

There still remain several research gaps in the literature; the technological options and potentials to decarbonize chemicals, paper and pulp, textile, glass, fertilizers, micro, small, and medium enterprises (MSME),¹⁰ food and beverages, aluminum, mining, and other industries are largely unexplored in a comprehensive manner; the role of green hydrogen and bioenergy as alternative process fuel hasn’t yet been thoroughly investigated, and limited studies have assessed the emissions implications of process electrification, material efficiency, CCS, and digitalization.

5.3. Transportation

Most national papers ($n = 14, 87\%$) give details on transportation sector transitions. Several national papers ($n = 5, 36\%$) provide information on final energy by fuel (Mittal et al 2018, Mathur and Shekhar 2020, Chaturvedi et al 2021, IEA Energy Outlook 2021) or final energy by mode (du Can et al 2019). The rest do not report these breakdowns and largely rely on aggregate results. Besides, multiple sectoral papers ($n = 4$) investigate a range of transportation pathways and provide some important conclusions (Dhar et al 2017, 2018b, Paladugula et al 2018, Gupta and Garg 2020a).

All sectoral scenarios ($n = 10$) and a few national scenarios ($n = 5$) report transportation service demand estimates (in vehicle kilometers travelled). According to these estimates, the service demand is projected to grow rapidly in the medium and long-term. Rising incomes, accelerated urbanization, infrastructure development, and industrial growth are all potential drivers (Gupta and Garg 2020a). These studies, in their baseline scenarios, estimate road

⁹ In 2008, the Indian government introduced PAT, a market-based compliance program, designed to fast-track energy efficiency improvements in energy-intensive industries. Phase I/II of the program (2012-2019) were highly successful in achieving emissions reduction (0.09 GtCO₂), energy savings (21.95 mtoe) and cost savings (₹4955 crores) in 1999 industrial facilities from eleven subsectors (Aluminum, Cement, Chloralkali, Fertilizer, Iron & Steel, Paper & Pulp, Thermal Power Plant, Textiles, Refineries, Railways and DISCOMs) (PAT Cycle 2020).

¹⁰ MSMEs, in particular, were identified by some studies, for having large untapped efficiency potential. These studies addressed the difficulties in implementing efficiency measures in MSMEs, since they operate using diverse technologies and fuels, are remote scattered units, and don't benefit from economies of scale (Vishwanathan et al 2018, Mathur and Shekhar 2020). Further research should be undertaken to investigate the decarbonization options in this sector.
passenger service demand to grow 3.5–5.4 times by 2050 from 2010 to 2012 measures. Similarly, they estimate the road freight demand to grow 6.7–22 times by 2050 (Paladugula et al. 2018, Dhar et al. 2018b, Gupta and Garg 2020a). Most of these scenarios project the 2050 road freight service demand to lie between 3500 and 9500 bktm yr\(^{-1}\); however, the TERI model (Paladugula et al. 2018) produces a high estimate that is twice the second-highest model projection (supplementary material, appendix 9).

The magnitude of final energy demand varies significantly in the above 4 GtCO\(_2\) scenarios (figure 6). It is estimated to increase 1.1–2.8 times by 2030 and 2.5–6.5 times by 2050 (from 2019). In their multi-model analysis of India’s road transport, Paladugula et al. (2018) found that the estimated service demand, energy consumption by mode, vehicle load factor, and base year assumptions varied substantially across participating models. These variations were attributed to differing data collection sources and modeling methods. Nevertheless, they have a significant impact on the final energy and emissions estimates. Future investigations should take these variables into account and harmonize the key model assumptions.

Many above 4 GtCO\(_2\) scenarios (\(n = 9\)) exhibit similar trends across their transportation fuel mix. Although the absolute final energy values vary significantly in the above 4 GtCO\(_2\) scenarios, the narratives driving them are similar. Oil dominates the transportation energy consumption. Traditional transportation fuels such as petrol and diesel continue to provide the majority of final energy in both the short and long term. Some scenarios indicate an increase in natural gas vehicles, whereas others expect it to play a small role. The usage of low-carbon transport fuels (electricity, bioenergy, hydrogen) remains limited. Demand intensification coupled with increased oil dependency will likely put India’s energy security further at risk (Byravan et al. 2017, Dhar et al. 2017, Paladugula et al. 2018, Vishwanathan et al. 2018).

Several sectoral and national scenarios (\(n = 6\)) investigate decarbonization of the Indian transportation sector with emissions reduction below 2 GtCO\(_2\) in 2050. These scenarios show that energy efficiency, fuel-switching, and service demand reduction are key strategies in achieving such emissions reductions. In these scenarios, the observed final energy demand shows flat trends; some scenarios estimate a marginal increase, while others show a slight decrease, both relative to 2019. Accordingly, the final energy varies 0.5–1.4 times in 2030 and 1.1–1.7 in 2050 (figure 5). The projected drops in final energy use are predominantly due to electrification and modal shift from road to rail and public transit, which in turn improves the energy efficiency of these services. Overall, the market share of alternative fuel vehicles rises across all the below 2 GtCO\(_2\) scenarios as costs drop, and oil demand becomes noticeably constrained. Although oil accounts to 60%–75% of final energy by 2030, by 2050, the majority of transportation energy (>50%) comes from a combination of electricity, biofuels, and hydrogen. Modest service demand reductions (\(n = 5\)) are also attained through increased adoption of digital technologies which encourage trip-substitution and telecommuting. (Dhar et al. 2018b, Gupta and Garg 2020a).

Transportation sector policies are consistently modeled across papers. Some papers depend on an economy-wide carbon tax to model emissions mitigation. Several national (\(n = 12\)) and sectoral papers (\(n = 4\)) assess the implications of India’s NDC sectoral policies; these policies include electric vehicle subsidies, biofuel blending targets, higher share of public transport and freight rail, vehicle fuel

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**Figure 6.** India transportation sector final energy demand (2030 and 2050).
efficiency standards, and demand reduction (Dhar et al. 2017, Vishwanathan et al. 2018, Mathur and Shekhar 2020, Gupta and Garg 2020a). To model emissions mitigation (below 2 GtCO$_2$), studies implement sector-specific policies, economy-wide carbon tax, or a combination of both. Dhar et al. (2018b) models an economy-wide carbon tax to facilitate transition to low-carbon technologies, improve cost-competitiveness of fuel-efficient vehicles, and propel electrification. Gupta and Garg (2020a), meanwhile, assesses the energy and emissions implications of stringent sectoral policies to achieve similar decarbonization levels.

Overall, the sectoral analyses reveal the need for inter-model consistency, especially in road transportation. It is important for the future multi-model efforts to focus on understanding the model differences, key uncertainties, and data requirements for model harmonization. In addition, these studies may investigate the linkages between decarbonization policies and air pollutants (CO, PM, SO$_2$, NO$_x$) in the Indian context. Furthermore, to develop a full picture of transportation decarbonization, studies will be needed that research into low-carbon aviation and shipping fuels, road freight electrification, hydrogen, and sustainable urban forms. Finally, electric vehicle grid integration presents several challenges and synergistic opportunities. These range from increased electricity demand, price volatility, grid stability issues to likely increased renewable share, smart charging, and vehicle-to-grid capabilities (Jochem et al. 2014). Further studies will need to be undertaken, in order to quantify these potentials and identify the constraints.

5.4. Buildings

Most national papers ($n = 13, 80\%$) examine India’s buildings sector. Several national papers ($n = 10, 60\%$) assess interventions across buildings services (lighting, cooking, appliances, cooling, and buildings) and buildings type (residential and commercial). A few national papers ($n = 4$) analyze the technological options for rural and urban households separately (Byravan et al. 2017, du Can et al. 2019). However, only some ($n = 5, 30\%$) provide complete information on final energy by fuel (Vishwanathan et al. 2018, Chaturvedi et al. 2021, IEA Outlook 2021) or final energy by services (du Can et al. 2019, Mathur and Shekhar 2020). Meanwhile, the two identified sectoral papers provide detailed insights on final energy by fuel as well as technological transitions (Yu et al. 2018, Vishwanathan et al. 2019).

A small group of national ($n = 3$) and sectoral papers ($n = 2$) provide buildings floor space estimates (supplementary material, appendix 8, table S6). Papers that report these estimates anticipate an increase in buildings floorspace due to rapid urbanization (50\%–60\% by 2050), population growth, and improving standards of living. The urban residential floorspace is estimated to rise about 6–6.5 times from 2010–2015 to 2050; whereas, commercial floor space is expected to grow substantially, increasing about 7–16 times from 2010 to 2050 (Sharma et al. 2017, Yu et al. 2018, du Can et al. 2019, IEA Outlook 2021).

The building final energy trends do not vary significantly across emission groups. They increase only 0.88–1.7 times by 2030 and 1.1–3.0 by 2050, the lowest of all end-use sectors (figure 7). The substitution of inefficient biomass to oil, gas, and electricity, along with appliance efficiency improvements largely contributes to this effect. In 2030, the final energy of more than half of the ‘Above 4 GtCO$_2$’ scenarios are comparable to that of ‘Below 4 GtCO$_2$’ scenarios. This gap becomes more prominent by 2050 in some scenarios. But overall, they are closely packed, and highlight further decarbonization potential.

Few national scenarios investigate building-sector decarbonization pathways with emissions reduction below 4 GtCO$_2$ in 2050. The sectoral scenarios reviewed, meanwhile, only examine India’s NDC buildings policies (having emissions above 4 GtCO$_2$ in 2050). This narrow body of literature does not provide sufficient evidence to derive robust conclusions for reductions below 2 GtCO$_2$. However, it provides several insights on NDC policy implementation. Thus, the remainder of the discussion is largely focused on assessing mitigation strategies from the low-ambition pathways (above 4 GtCO$_2$) and identifying the key research gaps.

Almost all above 4 GtCO$_2$ scenarios focus on clean cooking transitions to reduce dependence on traditional biomass. Most papers ($n = 10$) estimate that traditional biomass demand declines as clean cooking technologies become more accessible. LPG (liquefied petroleum gas) for cooking is expected to rise in both rural and urban areas. The market share of improved cooking stoves, piped natural gas, and electric cooking is also expected to increase marginally. Vishwanathan et al. (2019), in their building sector analysis, finds that the biomass to oil/gas transition might increase the buildings sector direct CO$_2$ emissions. Upcoming studies could investigate the transition to electric cooking to achieve deeper emission reductions.

Numerous scenarios ($n = 10$) examine household transitions to energy efficient lighting. These scenarios indicate a transition from kerosene lamps, incandescent lights and CFLs to efficient LED lights (Byravan et al. 2017, Vishwanathan et al. 2019, Mathur and Shekhar 2020). Some scenarios ($n = 4$) investigate the prospects of solar water heating as they provide an economical and low-carbon alternative to biomass, fossil, and electric heating (Byravan et al. 2017, Vishwanathan et al. 2018, Yu et al. 2018).

11 Couple of studies identify retail, offices, and hotels, in particular, for showing the highest decarbonization potential within the commercial sector (du Can et al. 2019, Mathur and Shekhar 2020).
Several scenarios show that appliance efficiency (\(n = 10\)) upgrades are important in reducing energy consumption of the buildings sector. Higher ownership rates of air conditioners (ACs) and modern appliances are expected to increase the buildings sector’s future electricity demand (du Can et al. 2019). In order to offset this demand growth, increased market penetration of energy efficient ACs and other appliances is required. Sectoral scenarios show that energy efficient ceiling fans in the near-term and ACs in the medium-term can provide the highest energy savings for space cooling applications (Yu et al. 2018, Vishwanathan et al. 2019). du Can et al. (2019) points to an increase in indirect CO\(_2\) emissions at higher ACs ownership rates, making it even more important to decarbonize the electricity grid. Sharma et al. (2017) discusses the importance of lower GWP refrigerants in avoiding high HFC emissions from commercial air cooling and refrigeration. Additional research is required to further identify sustainable cooling pathways for India that are aligned with reductions below 4 GtCO\(_2\) in 2050.

Limited scenarios (\(n = 4\)) have assessed the benefits of building envelope improvements and retrofits (Vishwanathan et al. 2018, Yu et al. 2018, Mathur and Shekhar 2020, Gupta et al. 2020b). Envelope efficiency improvements in new buildings presents an enormous opportunity in reducing the energy demand. Yu et al. (2018) demonstrates that the average energy use intensity of new building developments can be reduced to 0.38 GJ m\(^{-2}\) by 2050 (from 0.44 GJ m\(^{-2}\) baseline) if building energy codes are implemented with high compliance (99% by 2025). For old buildings, energy retrofits can significantly improve efficiency. Since considerable building stock has not been built yet, the prospect of incorporating efficient practices from the design/construction phase is very promising; more studies are needed that thoroughly examine the energy reduction potential of envelope improvements and retrofits in India.

Building sector studies and scenarios have focused on several policy elements. These are centered around the existing subsidies for clean cooking fuels, market transformation initiatives, appliance efficiency standards and labels, and building energy codes. Other implemented policies include universal electricity access, subsidies for solar water heating, and variable electricity tariffs (Yu et al. 2018, Gupta et al. 2019, Vishwanathan et al. 2019, Mathur and Shekhar 2020).

This review highlights several research gaps. First, clearer reporting is needed on indicators that help define and compare future energy use in buildings across studies, such as buildings floorspace, appliance ownership rates, energy use by fuel and services, and discount rates/non-monetary factors impacting low-carbon purchases. Most national scenarios in our assessment do not report these indicators, making it difficult to understand the model variations and uncertainties. Second, only some studies, while analyzing the residential sector, separately assess the buildings energy use for rural and urban areas; such characterizations are important as these areas have distinct technological use patterns and require unique policies. Third, there are no sectoral papers explicitly analyzing building sector decarbonization pathways consistent with emissions reduction below 2 GtCO\(_2\) in 2050; in addition, neither national nor sectoral...
scenarios have yet evaluated net-zero pathways for the Indian buildings sector.12

6. Conclusions

The objective of this paper was to investigate the recent peer-reviewed literature (2017–2021) on India’s climate mitigation pathways. In order to identify the India-centric quantitative model-based scenario analyses with sector-specific information, we conducted a thorough systematic literature search, and identified 34 studies. From individual scenarios of these studies, we synthesized relevant energy and emissions data, derived key conclusions, as well as identified important research gaps in the power, industry, transportation, and buildings sector. While the main focus of the analysis was on examining the coverage and the state of information available on low-emission scenarios, we also drew conclusions from moderate policy scenarios.

The findings of our review highlight several conclusions and reveal several research gaps which need further investigation: (a) While a few scenarios in the literature may be consistent with India’s net-zero 2070 goal, a significant pivot in their trajectories will be needed post-2050. To ensure a smoother transition to net-zero emissions by or before 2070, mitigation pathways with greater ambition are required across all energy sectors. (b) There are gaps in the technologies covered across national and sectoral studies; for example, in the power sector, only a few studies have assessed pathways with a high share of renewable energy by 2050. (c) The assessed decarbonization scenarios indicate that India must reduce coal-fired power capacity within the next decade to reduce emissions to below 4 GtCO₂ yr⁻¹). Similar significant shifts must occur in the transportation sector, where fuel switching, modal shift (road to rail), and service demand reduction can substantially reduce emissions. (d) There are large variations in the final energy estimates across studies (especially in the transport sector); as few studies report their key model assumptions and outputs, it becomes increasingly difficult to assess the inter-model consistency, estimate model uncertainties, and draw policy conclusions. In brief, these are all important aspects for future research to address and are vital in informing policy makers in their efforts to make long-term policy decisions aligned with ambitious climate targets.

There are possible avenues forward to address many of these key research gaps. A standard modeling protocol with common diagnostic and baseline scenarios (i.e. with harmonized population and GDP assumptions) would be helpful in understanding the differences in model structures, base year data, techno-economic assumptions, and the resulting future projections. Making the underlying data publicly available in common reporting frameworks would advance the discussion on the most suitable data assumptions for India, while providing policymakers and the research community access to robust quantitative evidence. These measures will help future studies to better explain differences in their results, as well as identify the current data availability and future data collection needs.

The India Energy and Climate Modeling Forum (IECMF) has created mechanisms for researchers to conduct multi-model assessments which provide consistent assumptions across studies and a platform for researchers to assess the reasons for differences in model estimates. These assessments will cover a broad range of topics such as sectoral demand estimation, alternative fuels, state of technologies, and low carbon scenario modeling. Policy makers from multiple line ministries will also be participating, which will further help with understanding and integrating results into policy making.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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12 The reviewed literature highlights further opportunities in investigating building decarbonization potential through: (a) enhanced building energy codes, (b) complete phase-out of biomass cooking, (c) distributed rooftop solar, home batteries, heat pumps, (d) efficient HVAC technologies, (e) digitalization technologies (smart meters, thermometers, Internet of Things), (f) demand side management, (g) low-carbon building construction, and (h) behavioral changes.
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