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India's energy sector choices—options and implications of ambitious mitigation efforts

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Abstract

This article examines the choices that might be needed for India's energy sector under alternative mitigation scenarios. The article draws on the CD-LINKS study—a collaborative EU project under which seven pathways based on different combinations of carbon budget (high and low) and policy implementation (early and late) were developed and examined. This study uses the MARKAL energy system model to develop these scenarios. The three broad strategies that emerge for India include decarbonisation of electricity, electrification of end-uses and improvement in energy efficiency. We conclude that by undertaking early action, India can potentially prevent carbon lock-in and leapfrog to renewables from coal in the power sector. However, early action scenarios exhibit higher cost than their delayed action counterparts. Several other barriers and challenges also need to be addressed in order to enable large-scale uptake of low-carbon technologies. India may need to come up with innovative mechanisms to ensure a smooth and just transition for the economy.

Keywords Climate mitigation pathways · India · Energy sector · NDC · Low carbon development · Energy system modelling

1 Introduction

Following the Paris Agreement in 2015, all the signatory nations have set out to move along their nationally determined contribution (NDC) targets. However, studies indicate that

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emission reduction in 2030, as achieved by the cumulative NDC targets, falls short of the emission reduction required to limit the global temperature rise to 2 °C above pre-industrial levels (Fawcett et al. 2015; Rogelj et al. 2016; IEA 2016; CAT 2015; UNEP 2016). It is clear that much more is needed to be done across both developed and developing countries to constrain emissions within these budgetary limits. The techno-economics of several mitigation options has improved significantly over time, and ratification of the Paris Agreement has strengthened the drive towards upscaling low-carbon and energy-efficient alternatives globally. At the national level, different countries seek to align their move to alternative fuels and technologies with their national priorities. Likewise, India's decarbonisation story needs to be synergistic with the multiple development prerogatives of the county including poverty alleviation, providing access to affordable and reliable energy to its population, mitigating air pollution, etc. (Mathur et al. 2019).

India's NDC consists of eight targets, two of which relate to the energy sector (GOI 2015): (a) to reduce the greenhouse gas (GHG) emission intensity of its GDP by 33% to 35% by 2030 from 2005 levels and (b) to achieve about 40% cumulative electric power installed capacity from non-fossil fuel–based energy sources by 2030, subject to international finance and technology transfer. CAT (2019) classifies these targets as "2 °C compatible" and India has already made significant progress towards the realization of its NDC targets through a range of mitigation actions (MOEFCC 2018).

India occupies a unique position when it comes to discussing its mitigation challenges and opportunities, since it must attempt to harness low-carbon and efficient options (which often entail higher upfront costs) while providing increasing levels of energy to fuel the requirements of a rapidly developing nation. Around 30% of India's population of 1.21 billion people (Chandramauli 2011) continue to live in poverty (MOEFCC 2018) and roughly 19 thousand households lack access to electricity (MOP 2019) and modern fuels. This renders the provision of basic infrastructure and modern fuels a high priority for the Indian Government, imposing pressure of providing for the additional energy needs to a large and growing nation. Further, the country is historically locked into a high fossil fuel base with around 40% of its primary energy consumption being coal based and sectors such as transport being majorly dependent on petroleum products (TERI 2019). However, much of India's infrastructure is yet to be built. For instance, about 50% of India's commercial building stock is yet to be built (Kumar et al. 2010). About 30% of the existing built-up area was air-conditioned in 2016 and is estimated to increase to around 45% by 2037 (MOEFCC 2019). This provides an opportunity for India to leapfrog to efficient, state-of-the-art technologies rather than locking itself further into carbon-intensive development.

Several studies have developed low-carbon scenarios for India using various energy system/macroeconomic models but with different objectives. Thambi et al. (2018) focus on developing trajectories corresponding to India's NDC, Gupta et al. (2019) examine the macroeconomic impacts of India's NDC trajectories, whereas Byravan et al. (2017) evaluate the NDCs from a quality of life perspective. Other studies contextualize low carbon development in India across widely ranging standpoints. For instance, Chaturvedi et al. (2017) study decarbonisation of the Indian power sector within the ambit of Shared Socioeconomic Pathways (SSP), from the perspective of water demand, Shukla and Chaturvedi (2012) explore the impact of renewable energy targets on the prospective technology choice within the Indian energy system, Shukla et al. (2008) assess the impact of sustainability scenarios on key development indicators in India, etc. Studies like Luderer et al. (2016), Gambhir et al. (2014), den Elzen et al. (2016), etc. have used global models with an explicit representation of India to analyse energy pathways consistent with various temperature targets for India, but these studies usually lack a detailed representation of the country (Dubash et al. 2018). Some recent studies like Parikh et al. (2018), Vishwanathan et al. (2018) and Vishwanathan and Garg (2020) also developed energy scenarios corresponding to various temperature targets but by using a national model. Vishwanathan and Garg (2020), which is also published in this special issue, remains the only study conducted using national level model to align India's emission trajectory with cost-optimal carbon budget allocation for India; the other two national studies noted above followed an equal cumulative per capita emission approach. Thus, there is a limited number of studies which use a detailed national level model to examine scenarios consistent with temperature targets of the Paris Agreement. This article fills this research gap by attempting to align India's carbon emissions with cost-optimal carbon budget allocation. It seeks to delineate the key options for India in the energy sector if the country were to go beyond the NDC targets and successively push itself to more limited carbon space. It also discusses what deeper action might imply in terms of the choices and preferences across sectors and the associated challenges and opportunities.

2 Methodology

This section describes the storylines of the scenarios examined in this study, the modelling framework used to represent them and the underlying assumptions across these scenarios.

2.1 Modelling framework

This study uses the MARKAL model framework for India to represent and analyse seven explorative scenarios developed with common storylines across a number of national and global models as part of the CD-LINKS project.[1] The MARKAL-India model[2] is a single-region, dynamic least cost optimization model with a detailed representation of the Indian energy sector at the national level (TERI 2020; TERI 2006[3]). The model follows the rational expectation hypothesis for inter-temporal optimisation. It is currently set up over the time frame of 2001 to 2051 at five yearly intervals. Energy demands are disaggregated across five end-use sectors, viz. the agriculture, commercial (service sector), industrial, residential and transport sectors, and various end-use demands can be satisfied via alternative fuels and technologies (TERI 2018a, 2018b). Technological change in the model is exogenous with full substitutability based on lowest cost, and more efficient technologies replace the less efficient ones based on the broad storylines of the scenarios. The model primarily covers CO_2 emissions from energy, which constituted about 71% of India's total GHG emission in 2014 (MOEFCC 2018) and is considered a proxy while evaluating India's decarbonisation indicators.

2.2 Description of scenarios

The seven scenarios (Table 1) assume a combination of long-term carbon budgets and short-term policy dimensions. The low and high carbon budgets correspond to global carbon budget

[1] The details of the project can be found at http://www.cd-links.org/.
[2] The current version of the model was developed with inputs from Ms. Aayushi Awasthy, Ms. Sugandha Chauhan, Mr. Kabir Sharma, Ms. Kamna W Mahendra and Mr. Aman Agrawal.
[3] The time horizon of the model in TERI (2006) extended from 2001 to 2031. However, the overall structure of the model is similar to that in this study.

Table 1 Scenario design based on short-term policy dimension and long-term cumulative carbon budget

		Long-term CO_2 budget (2011–2051 cumulated)		
		None	Low (66% probability)	High (50% probability)
Short-term policy dimension	No policy	NoPOL		
	National Policies Implemented (NPi)	NPi	*NPi Low* ^Global Models: 25–86 ^^MARKAL-India: 182	*NPi High* ^Global Models: 37–114 ^^MARKAL-India: 226
	INDC	INDC	*INDC Low* ^Global Models: 32–91 ^^MARKAL-India: 189	*INDC High* ^Global Models: 88–117 ^^MARKAL-India: 226

^The range provided by the global models represent the range of carbon budget (in $GtCO_2$) for India as obtained by a set of global models based on cost-optimal budget allocation. The details of the global models used in this study can be found in Krey et al. (2019)

^^These numbers represent the carbon budget for each of the scenarios for India (in $GtCO_2$) as obtained by the MARKAL-India model

corresponding to 50% and 66% probability of restricting global warming to 2 °C. The policy dimension on the other hand represents early action (i.e., planned policies until 2020 and deeper mitigation thereafter) and delayed action (i.e., achievement of (I) NDCs until 2030 and deeper mitigation action thereafter).

The *No Policy* (NoPOL) scenario is a counterfactual scenario without any additional climate or energy policy incorporated in the energy system after 2010. The *National Policies implemented* (NPi) scenario reflects the climate and energy policies that were implemented in the country until 2016. The *INDC* scenario incorporates policies and targets represented in India's NDC submission, along with policies included in the NPi scenario. In case of both NPi and INDC scenarios, the progress of the respective policies is in accordance with their respective quantified targets (where applicable) and is further extrapolated linearly until the end of modelling period. The *INDC high carbon budget* (INDCH) and *INDC low carbon budget* (INDCL) scenarios are aligned to a globally cost-optimal carbon budget allocation for India. Both these scenarios assume a pathway similar to INDC until 2030 and assume deeper mitigation actions only after 2030. The *NPi high budget* (NPiH) and *NPi low budget* (NPiL) scenarios are set up to replicate the cumulative carbon budgets achieved in INDCH and INDCL, respectively, but by pushing in early action. The strategies adopted in these scenarios are essentially the same as their respective INDC counterparts but consider a head start from 2020 itself, to examine the implications of the decarbonisation pathways if the alternative options were adopted earlier on. The policies included in these scenarios are listed in Tables S1, S2 and S3.

2.3 Assumptions

The scenarios presented in this article assume uniform macroeconomic assumptions in terms of India's GDP and population growth. The population trajectory is based on the forecast by Population Foundation of India, Scenario B (medium fertility rate), which projects India's population at 1.75 billion by 2050 (PFI and PRB 2007).[4] An average GDP growth rate of 8.3%

[4] World Population Prospects, 2019 estimates India's population to range between 1.49 billion (low fertility) and 1.79 billion (high fertility) in 2050 (UNDESA 2019).

was assumed between 2016 and 2031 based on India's aspiration as described in India's NDC submission to the UNFCCC and 7% thereafter.[5]

We also assume that, with technological progress, the cost of solar electricity achieves parity with coal beyond 2030. However, solar with storage is assumed to be cost-competitive only in INDCL and NPiL scenarios. The penetration of natural gas, particularly in the power sector, is assumed to be low because India has limited domestic reserves of natural gas, and imported gas fails to achieve cost-competitiveness with coal. Penetration of nuclear power plants is limited based on current expansion plans of the Indian Government. Also, we have not considered carbon capture and storage (CCS) as an option, not only due to the high and uncertain costs but also concerns around its feasibility in India given the limited potential CCS sites and issues related to sociopolitical acceptance in India (Viebahn et al. 2011, 2014; Sood and Vyas 2017). We also assume a restricted role of biofuels, given that they have failed to pick up in India despite focused policies to promote them (Das and Priess 2011). Further, since biofuels are considered a means to reduce dependence on imported petroleum products (PIB 2018), we also restrict the import of biofuels. The pace and level of penetration of efficient and less carbon-intensive alternatives is allowed to vary in accordance with the scenario storylines towards achievement of different stringency levels in overall carbon budgets allowed. While the model works on the basis of cost optimality, given the tendency to select one corner solution at a time, we apply multiple user constraints (Table S4) to guide the choices based on the scenario storylines by limiting the range available to alternative choices.

2.3.1 Discussion on carbon budgets

Table 1 presents the scenarios, carbon budget range as estimated by the global models and the level obtained across scenarios for India using MARKAL-India model.

The budget obtained by the global models is cost-optimal budget allocation, i.e. they apply a uniform carbon tax across all regions. As indicated in van den Berg et al. (2019), this method allocates the lowest carbon space for India among the various effort sharing regimes. The global models not only assume a lower GDP growth[6] for India reflecting lower end-use service demands but also follow both inter-temporal and inter-regional optimisation, thereby tending to apportion higher mitigation action towards the developing countries, which are still in the process of providing for basic infrastructure needs and focusing on other development priorities. Consequently, global models tend to be more optimistic in reflecting earlier and deeper carbon reduction actions in developing countries, while national models are able to depict a more practical trajectory as they reflect several of the ground realities.

While we attempted to align the national carbon budgets with those estimated by the global models, the national levels are somewhat higher as indicated in Schaeffer et al. (2020). This is because of our assumptions on limits to penetration of some decarbonisation options based on practical feasibility. Lower cumulative emissions for India are achievable in scenarios where CCS is allowed, e.g. Vishwanathan and Garg (2020). However, the carbon budget obtained through our national level model is fairly consistent with a 2 °C world under alternative carbon budget allocation principles. Parikh et al. (2018) estimate India's share in global carbon space for a 1.5 °C world (following RCP2.6) at around 160 $GtCO_2$ under an equal per capita allocation principle.

[5] OECD forecasts India's GDP growth at 5.1% between 2016 and 2051 (OECD 2018).

[6] The global models assume GDP growth rate based on SSP2 "Middle-of-the-Road" Scenario (Mathur and Shekhar 2019).

3 Results

This section discusses the implications of the alternative scenarios for India. We first present some broad indicators related to CO_2 emissions and energy across scenarios to explain the variation in emission trajectories and indicate the nature of incumbent changes in energy demand and supply options that India might face under varying levels of carbon stringency. Subsequently, we zoom into the broad emission reduction strategies for India and finally discuss the implications on costs and investments to realize these scenarios.

3.1 Comparison of key indicators

Figure 1 presents the CO_2 emissions and CO_2 emissions intensity of GDP emanating from India's energy sector across the seven scenarios. In 2051, energy-related CO_2 emissions exhibit a range of 10 $GtCO_2$ across these scenarios. Cumulative emission between 2011 and 2051 (Table 1) could range from as high as 324 $GtCO_2$ in NOPOL to 182 $GtCO_2$ in NPiL. As evident from Fig. 1, the scope for decarbonisation benefits is more limited on the demand side vis-a-vis the supply side potential. This needs to be understood in light of the numerous efforts that the country has already initiated through energy efficiency or demand side management policies and measures over the years. Comparatively, the thrust on alternative fuels is relatively recent and larger scope for transitions seems to be available on the energy supply side.

The growth rate of emissions in INDCL beyond 2040 is close to 0% implying that under the most extreme decarbonisation scenario, India's energy sector emissions would need to plateau off around 2040. Nearly 80% of the decarbonisation in this scenario is on account of the power sector, with renewables replacing coal-based capacities, while energy efficiency improvements and electrification of end-use technologies on the demand side largely account for the rest[7].

In terms of emission intensity of GDP, NOPOL exhibits a decline of only 17% from 2006 levels by 2031 (as compared with a decline of 28% in NPi and 35% in INDC) and of 53% by 2051, indicating that the additional policies and measures directed towards India's NDC targets have been important contributors to India's current emission intensity reduction path. INDCL reflects the highest decline in emission intensity, at around 82% from 2006 levels by 2051. While per capita emissions in NOPOL and NPi indicates an increase from around 0.9 t in 2001 to 9.4 t and 8 t, respectively, in 2051, these would need to be restricted to around 3.5 t in INDCL by 2051—which is even below the global per capita CO_2 emission level of 5.0 t in 2014 (World Bank 2019a).

Energy consumption across each of the seven scenarios is a function of two opposing forces: increase in energy demands with increased access to reliable electricity, higher incomes, urbanization and changing lifestyle, and reduction in energy demand due to improvements in process and technological efficiencies. Consequently, primary energy demand is projected to range from 210 EJ in NOPOL and 184 EJ in NPi to 112 EJ in INDCL in 2051 (Fig. 2). The per capita primary energy is expected to increase from 28 GJ in 2016 to 119 GJ in NOPOL and 105 GJ in NPi to 64 EJ in INDCL in 2051 as against a global per capita energy use of 80 GJ in 2014 (World Bank 2019b).

[7] The relatively higher share of emission reduction on the supply side is partly attributed to the emission accounting methodology of the model. Emissions from electricity are accounted on the supply side, while the end-use electricity-based technology is considered to be carbon neutral. Consequently, emission savings from demand sectors due to electrification are accounted on the supply side.

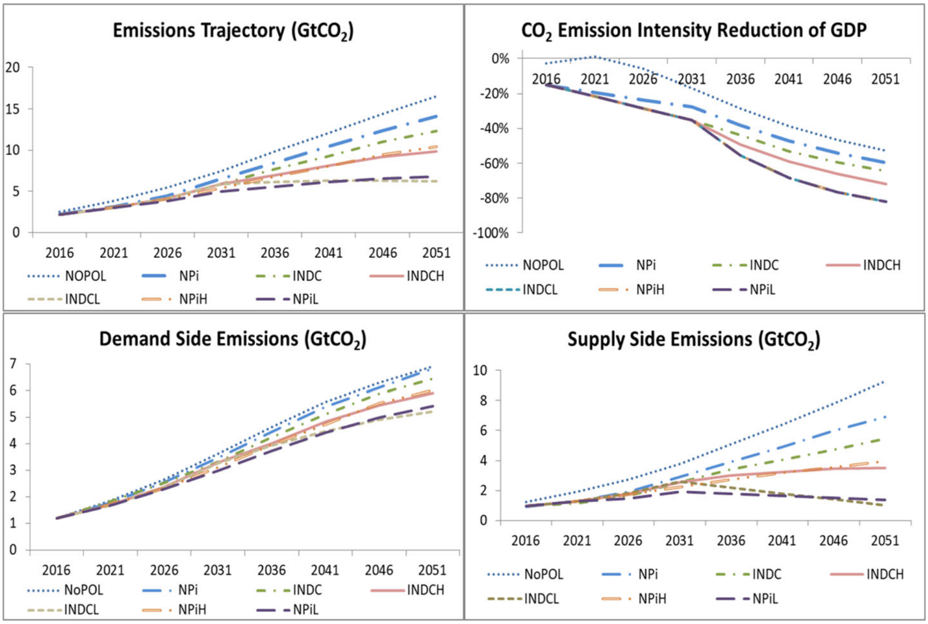

Fig. 1 Key CO_2 emission-related indicators between 2001 and 2051

The share of fossil fuels in total primary energy mix in 2051 is projected at 95% in NOPOL, 93% in NPi and 90% in INDC. This is expected to decline further to 85% in INDCH and 88% in NPiH and 72% in INDCL and 77% in NPiH. The share of coal in primary energy is estimated to change from around 40% in 2016 to 62% in NPi, 57% in INDC, 50% in INDCH and 52% in NPiH in 2051. Peaking of coal is observed around 2036 in INDCL and 2046 in NPiL and its share in primary energy is projected to decline to 37% and 41% in 2051, respectively. The share of renewables increases from 3% in 2016 to a maximum of 8% in 2031 in NPiL and 20% in 2051 in INDCL largely due to solar energy.

The share of electricity in final energy is expected to increase by around 7% to 10% in 2051 across scenarios from around 18% in 2016. This increase is also governed by two opposing forces across scenarios—increasing electrification of end-uses which leads to the increase in electricity requirement and a concomitant improvement in energy efficiency leading to reduction in the same. The share of electricity in final energy is interestingly highest in NOPOL at 28% and lowest in NPiL at 26% in 2051. While this may seem counter-intuitive, substitution by electrified options generally results in significant efficiency gains.[8] Moreover, despite a large number of low-income households achieving electricity access, affordability constraints are assumed to limit rapid penetration of electrical appliances preventing rapid increase in electricity demands. Additionally, given that power generation continues to be majorly coal dominant, the preference for electric vehicles is also gradual and increases with higher decarbonisation of the power sector across scenarios.

The decline in cumulative emission between 2011 and 2051 with respect to NPi (Table 1) is around 19% in the high budget scenarios and is roughly 34% in the low-budget scenarios. This

[8] Electric pumps for irrigation are 1.8 times more efficient than their diesel counterparts; appliances used for electric cooking are 6–7 times more efficient than traditional biomass-based cookstoves.

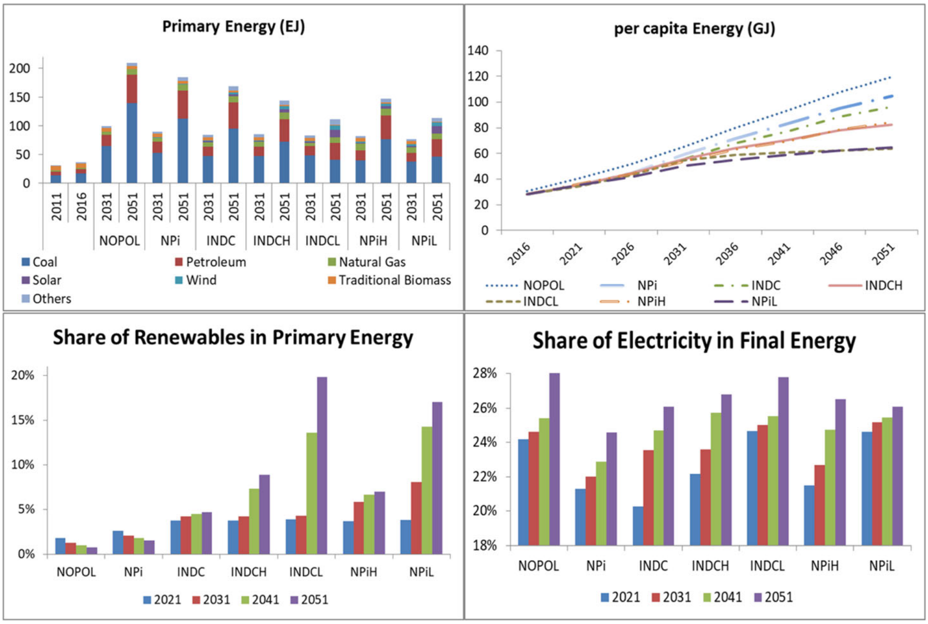

Fig. 2 Key energy-related indicators between 2001 and 2051

reduction is achieved through decarbonisation of electricity on the supply side and end-use electrification and energy efficiency measures on the demand side, as discussed below.

3.2 Decarbonisation of electricity

Our results indicate that decarbonisation of electricity is among the key options for India for transitioning to a low-carbon energy system. The share of non-fossil-based installed capacity would need to increase from 34% in 2016 to 41% in INDC, 57% in INDCH, 77% in INDCL and 71% in NPiL by 2051 (Fig. 3). This necessitates significantly large scale-up of solar (highest at 759 GW in NPiL) and wind power (highest at 750 GW in INDCL) across all scenarios by 2051. The share of renewable electricity generation in 2031 is expected to be around 14% in INDC family of scenarios and around 19% and 31% in NPiH and NPiL. However, by 2051, this is expected to be around 56% in INDCL and 64% in NPiL. Given our assumption that cost of renewable electricity with storage achieves parity with coal-based thermal generation beyond 2030 in INDCL and NPiL, renewable electricity increases significantly in these scenarios. Estimates peg India's wind power potential at 302 GW at a hub height of 100 m (NIWE 2015) and 695 GW at a hub height of 120 m (NIWE 2019) and solar power potential at about 750 GW (Bandyopadhyay 2017; MNRE 2019). Accordingly, ambitious decarbonisation levels as envisaged in INDCL and NPiL would require technological progress such that exploitation of renewable capacities of this order is viable and/or these technologies see a significant improvement in utilization efficiencies.

Increased penetration of renewables across each family of scenarios largely replaces coal-based power plants.[9] Coal-based capacity is estimated to decline from 1307 GW in INDC in 2051

[9] We do not consider coal-based power plants with CCS in this study due to reasons discussed in Section 2.3.

to 969 GW in INDCH and 473 GW in INDCL. Similarly, coal capacity is projected to decline from 1605 GW in NPi to 1113 GW in NPiH and 539 GW in NPiL in 2051. The share of coal-based electricity in 2051 declines from 86% in NPi and 69% in INDC to 54% and 62% in INDCH and NPiH and 17% and 26% in INDCL and NPiL, respectively. The corresponding unutilised capacity of coal plants after 2031 ranges between 12 and 15% in INDC and INDCH but increases to as much as 40% in INDCL. The same is less than 16% in NPi and NPiH but increases up to 20% in NPiL after 2020. High levels of unutilised capacity point towards the need to plan ahead for a smooth transition to renewables and focus on the political economy of India's power sector; else a situation of low plant load factor (PLFs) of coal power plants could end up hurting the uptake of renewables in India. Therefore, any further investments in coal-based thermal power plants need to be carefully planned and evaluated so as to avoid carbon lock-in in this sector.

Our results also indicate that the role of natural gas-based power plants in the Indian electricity sector is limited and investing in them may create further carbon lock-ins. Gas-based generation capacities decrease from 127 GW in 2051 in NPi and INDC to 107 GW in INDCH and 68 GW in INDCL. In the NPiH and NPiL, these are 104 GW and 70 GW, respectively. As in the case of coal-based capacities, their utilization declines as the level of decarbonisation across scenarios increases. The unutilized capacity of gas power plants in INDCL beyond 2031 ranges between 27% and 56%, whereas it ranges between 22% and 32% in INDCH. In NPiL, this increases to 48% beyond 2021, whereas it ranges between 27% and 40% in NPiH. Given that gas is a relatively less emission-intensive fuel than coal, it is interesting to note that it finds some significance in contributing to power sector decarbonisation when the emission reduction pathway is not very stringent. However, the stringent decarbonisation scenarios necessitate leapfrogging directly to large scale-ups of renewable capacities. This again points to the need for careful deliberation regarding investments in additional gas-based capacities, as these plants may need to stop operating much before their economic lifetime.

3.3 Electrification of end-uses

Given that electricity has the ability to lend itself to decarbonisation via renewables most readily, stringent carbon reduction scenarios indicate a shift to increased electrification of end-uses where possible. Our results reflect this shift prominently across three end-uses, viz. water pumping in agriculture, cooking in residential sector and surface passenger movement in the transport sector (Fig. 4).

The shift to electricity-based options in rural India could be spurred by the current trend of electrification in rural India[10] and increased reliability of electricity supply across all regions. Under such a scenario, India could witness a higher penetration of electric pump sets (through grid-based electricity as well as decentralized solar pump sets) for irrigation in agriculture vis-a-vis diesel pump sets in the low-carbon scenarios.[11] Accordingly, NPiL reflects a complete shift away from diesel use for irrigation by 2051 and electricity consumption for irrigation also decreases by 0.2 EJ in both NPiH and NPiL as compared with NPi due to improvement in energy efficiency of pump sets. Land preparation for agriculture, however, continues to rely on diesel across scenarios due to lack of commercially viable substitutes for tractors and tillers.

[10] Out of around 214.49 million households in India, 214.47 million households have been electrified as on 31 March 2020, and 18,734 households remain to be electrified (MOP 2019).

[11] Low-carbon scenarios include INDCH, INDCL, NPiH and NPiL.

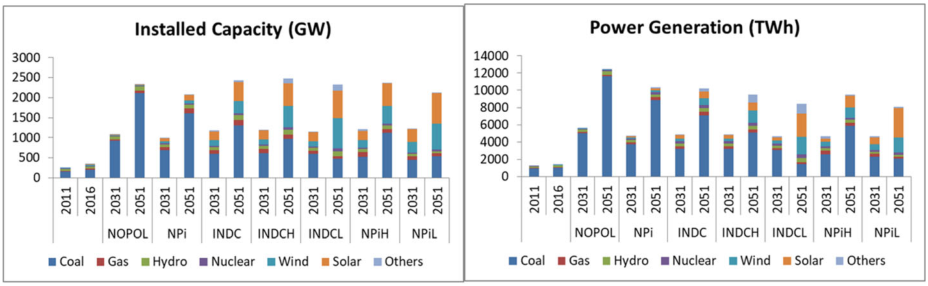

Fig. 3 Installed capacity for electricity generation and power generation across scenarios for 2031 and 2051, Other sources of power generation include biomass, waste to energy and very small amounts of geothermal and tidal electricity

Multiple fuels like traditional biomass, kerosene, liquefied petroleum gas (LPG), piped natural gas (PNG) and electricity are currently used by Indian households for cooking (Grové et al. 2017). While urban households have largely shifted to modern fuels like LPG/PNG and electricity, rural households still rely significantly on traditional fuels like crop residue, animal dung and firewood (Rohra and Taneja 2016). As availability and affordability of modern fuels like LPG and electricity increase for rural households, they are expected to increasingly shift away from the inefficient and polluting traditional fuels. Accordingly, it is interesting to note that while all the scenarios reflect an increasing shift towards modern fuels like LPG and PNG over time, the ambitious decarbonisation scenarios, viz. INDCL and NPiL, also indicate that rural households may prefer to leapfrog to electricity-based cooking with increasing access to reliable electricity. Consumption of traditional biomass accordingly reflects a decline from 6 EJ in 2016 to 5 EJ in NOPOL, to 3 EJ in NPi and to as little as 0.7 EJ in INDCL in 2051.

Electrification of surface passenger transportation is among the key decarbonisation strategies for the transport sector, since petroleum fuels currently service nearly 98% of the energy demand in this sector. Despite efforts to increase the share of public transport and rail-based movement, and enhance the use of relatively less carbon-intensive fuels like compressed natural gas (CNG) and biofuels, the positive effects of efficiency improvements and fuel substitution measures have largely been negated due to the increasing mobility demands arising from growth in the sector. Accordingly, although a variety of interventions (like carpooling, use of railways and public transportation system over private modes, fuel efficiency improvement and vehicular electrification) are expected to decrease the energy consumption in this sector by 10 EJ between NPi and INDCL, the sector continues to reflect a fairly high dependence on fossil fuels due to lack of commercially viable decarbonisation options for trucking, aviation and shipping even in INDCL and NPiL.

India has been promoting CNG-based vehicles since the last decade in order to address the issue of air pollution. Meanwhile electric vehicles (EV) are becoming increasingly viable with global technological progress. Our results indicate a gradual pick-up of EVs with a higher penetration of CNG vehicles in the interim, as uptake of EVs aligns with progressive electricity decarbonisation across scenarios. INDCH reflects the highest level of CNG consumption at 2 EJ in 2051. As EVs penetrate to higher levels in INDCL and NPiL, the consumption of CNG is estimated to decline to less than 1 EJ. NPiH, (the early action counterpart of INDCH) also indicates a decline in CNG consumption in 2051 (1.1 EJ). On the other hand, electricity consumption in 2051 is around 0.5 EJ in INDCH and NPiH, 1.0 EJ in NPiL and 1.5 EJ in INDCL. Thus, the scenarios requiring more stringent and rapid decarbonisation reflect a swift leapfrog towards electrification, as opposed to a gradual and continued uptake of both CNG and electric vehicles in the less stringent

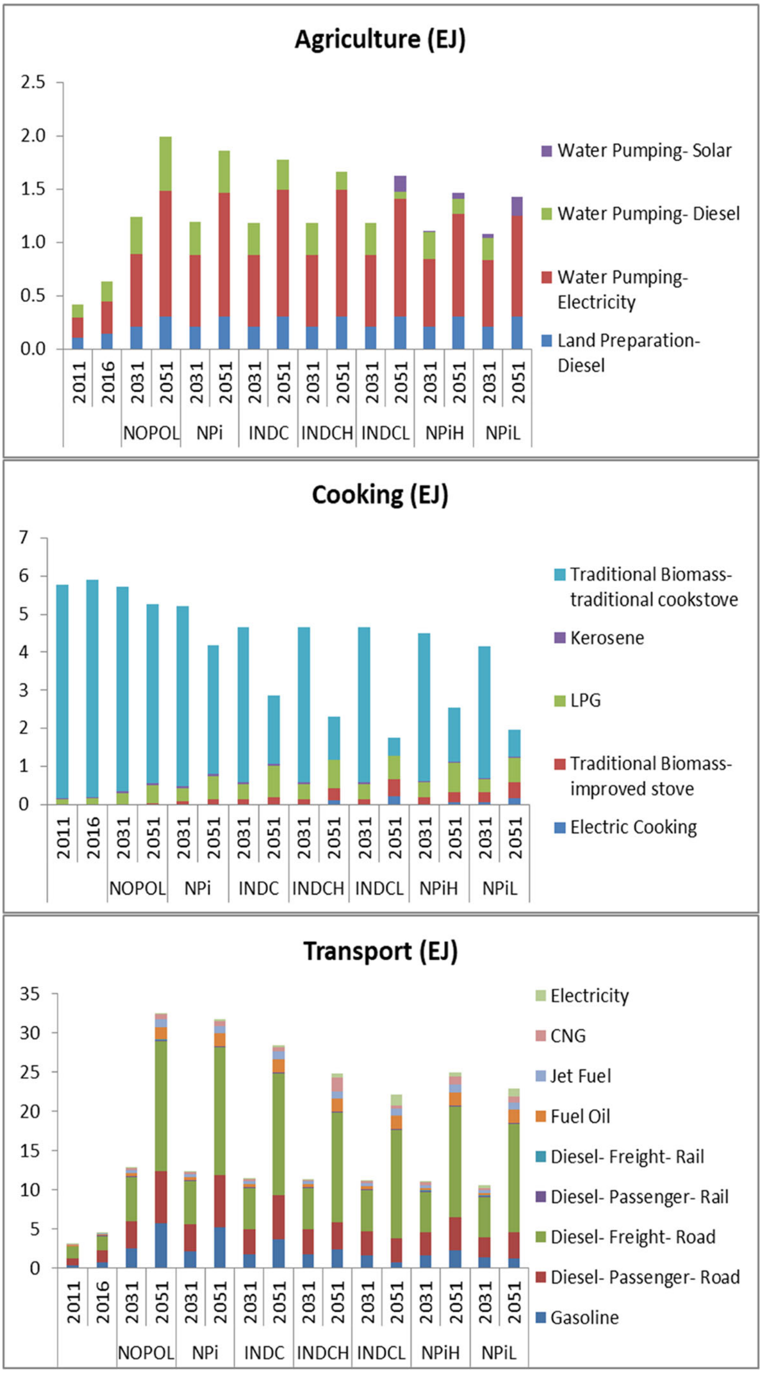

Fig. 4 Fuel-wise energy consumption in agriculture, residential cooking and transport in 2031 and 2051 across the scenarios

decarbonisation scenarios. These results signal towards the need for carefully planning the transition in the transport sector and evaluating the pros and cons of investing in additional CNG infrastructure vis-a-vis EV-based infrastructure in the coming years.

3.4 Energy efficiency improvement

Energy efficiency plays a significant role across all sectors and is estimated to result in energy saving of 5–12% during 2021–2041 (TERI 2018b). Appliances in residential sector, buildings in commercial sector and industries are the three key sectors where the role of energy efficiency is most significant (Fig. 5). While energy efficiency holds relevance in the transport sector as well, our results indicate that emission reduction in this sector is most responsive to electrification of the vehicle fleet.

The three major end-uses in the residential sector include space conditioning, refrigeration and lighting, of which space conditioning is the most energy intensive. Our results indicate savings of around 43% in 2051 between the NPi and INDCL, due to large-scale deployment of the most efficient air conditioners, while 14% and 33% energy savings are expected in the case of lighting and refrigeration between these scenarios in 2051.

Commercial buildings are rapidly emerging as a new category of large energy consumers in India, especially as the country's service sector strengthens. Our results indicate that up to 3 EJ could be saved by 2051 between NPi and NPiL by shifting to energy-efficient buildings. The results indicate that the largest potential for savings exists in shops and malls (1.2 EJ in 2051) between NPi and NPiL, followed by offices (0.6 EJ) and hotels (0.5 EJ).

The analysis of our results also indicates emission reductions in industries occur mainly due to energy efficiency improvements across scenarios, and the sector has relatively few options for moving to less carbon-intensive fuels. The shift from coal to natural gas has limited scope, both due to availability constraints and the economic preference for coal. Savings of around 4 EJ can be realized by 2051 between NPi and NPiL through efficiency improvements across industry subsectors. The iron and steel industry is projected to offer the highest saving of around 3 EJ by shifting to more efficient technologies and a large shift towards scrap-based steel.

The micro, small and medium enterprises (MSMEs) offer the second largest potential of energy saving—around 0.9 EJ between INDC and INDCL (and 0.3 EJ between NPi and NPiL). The challenge with MSMEs, however, is that they are widely dispersed, use a variety of technologies and fuels and do not offer advantages of scale. Further, new and efficient technologies generally have high upfront costs that deter these small enterprises from making the shifts. Given the wide spread of fuels and processes used across these units, MSMEs would need significant hand-holding both in terms of financial and technical support in order to transition to low-carbon alternatives.

3.5 Implication on costs

Figure 6 presents the total discounted system cost[12] and the undiscounted system cost for 2031 and 2051 with their constituents (i.e. investment cost of the technologies, fixed and variable operations and maintenance (O&M) costs and fuel costs). It must be noted that our model

[12] The discount rate used in this study is 10% which is based on opportunity cost with respect to alternative investment avenues.

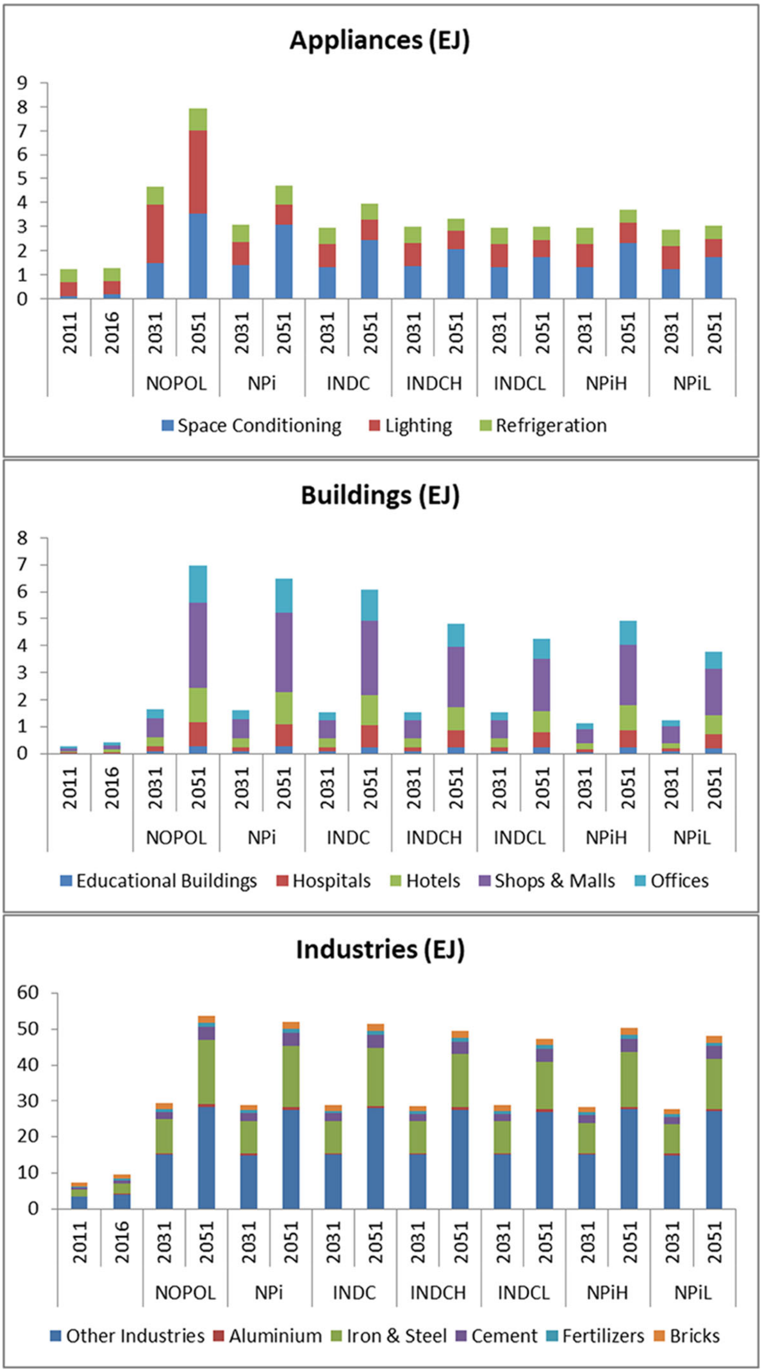

Fig. 5 Energy consumption across scenarios for 2031 and 2051 for major end-uses in appliances, commercial buildings and industries

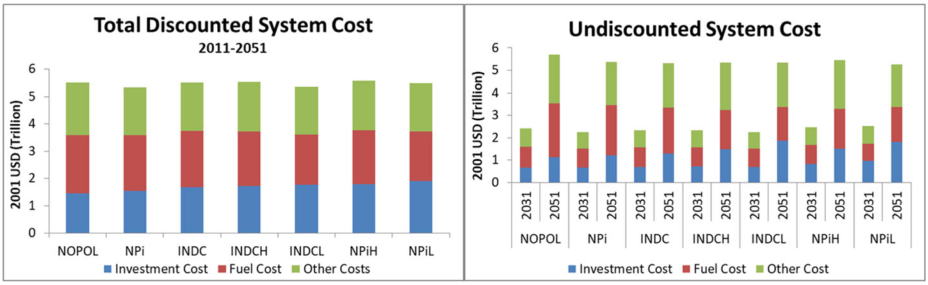

Fig. 6 **a** Total discounted system cost (2011–2051). **b** Undiscounted system cost in 2031 and 2051

underestimates some of the transaction costs that would be required in the stringent mitigation scenarios like additional institutional or infrastructure-related costs for new technologies and fuels (like charging infrastructure for EVs), research and development (R&D) costs, etc. Moreover, other macroeconomic costs that might accrue to the government for providing appropriate incentives to promote efficient appliances and equipment or costs that households may bear in terms of reduction of their disposable incomes due to higher upfront costs of appliances or fuels are not included in our analysis.

We see that the overall system costs can interestingly play out quite differently under varying levels of decarbonisation, largely on account of the savings in fuels costs that a high share of renewables is able to achieve. The upfront investment costs are higher in all the alternative scenarios when compared with NPi (for instance, the investment cost of INDCL is 55% higher than NPi in 2051). The cumulative investment cost between 2011 and 2051 in INDCL is 13.8% higher than NPi, whereas the cumulative fuel cost and the cumulative O&M costs in INDCL are, respectively, 8.9% and 0.5% lower. Accordingly, total system cost over this period in INDCL is merely 0.4% higher than NPi, since higher investment costs are offset by lower fuel costs over time in INDCL.

The early action scenarios exhibit a higher total system cost with respect to their delayed action counterparts (0.8% and 2.3% between high- and low-budget scenarios, respectively). In both cases, investment cost increases by 4% and 8%, respectively, while fuel cost declines by 1% and 2%, respectively, in the early action scenarios. Thus, despite allowing for a more gradual phase-out of carbon-intensive technologies, we observe that their total system cost is higher than their delayed action counterparts because fuel costs do not reduce sufficiently. The key takeaway from these results is that although India could find it challenging to leapfrog to more expensive technologies due to higher costs, it may be in its longer-term interest to plan for mechanisms by which transformative changes can be enabled early.

4 Discussion of results

Our study indicates that the three most promising elements for India's energy system decarbonisation are decarbonisation of its electricity sector, electrification of end-uses to the extent possible and maximizing energy efficiency across sectors.

Comparative analysis of the various decarbonisation scenarios indicate that it is in India's interest to leapfrog rapidly to more efficient and low-carbon options from a long-term perspective. Early action is desirable because delays in adopting low-carbon options can potentially lead to higher carbon lock-in in the economy, as is also shown by Lucas et al.

(2013) and Malik et al. (2020). However, our analysis also indicates that the total cost and particularly the investment cost of early action scenarios are higher than their delayed action counterparts. Thus, a developing country like India where investments need to be carefully prioritized to address diverse development issues may be forced to traverse a trajectory like INDCL in a bid to avoid diversion of development expenditure towards relatively high cost energy sector transitions. At the same time, if appropriate financial mechanisms could assist in supporting the higher initial costs of early action, India would undoubtedly benefit by pursuing a trajectory like NPiL.

The shifts proposed between NPi/INDC and NPiL/INDCL through our results may seem formidable and may entail other costs as well, but these transitions need to be viewed holistically in terms of the co-benefits that they could offer. Several options can align closely with other national priorities of reducing energy imports (e.g. petroleum imports in 2051 decline between NPi and NPiL (89%) and NPi and INDCL (93%)), addressing local air pollution (e.g. see TERI (2018a), Mittal et al. (2015)) and managing groundwater consumption (Srinivasan et al. 2018).

While models differ in their structure and assumptions, the major findings of our study are broadly consistent with other similar studies. For instance, Vishwanathan and Garg (2020) in the same issue as this article also highlight the need to increase the capacity of renewables, deepen penetration of efficient appliances and increase electrification of end-uses. However, certain differences in the assumptions lead to some points of divergences. For instance, while they indicate that natural gas can potentially play an important role in bridging the transition between coal and renewables in the power sector, we conclude that it may be advisable for India to leapfrog from coal to renewables and prevent locking itself into carbon-positive, gas-based infrastructure. This mainly stems from our assumption that storage will become an economically viable option by the time that renewables attain a share that the current grid cannot handle without additional investment (Spencer et al. 2020). Additionally, they achieve lower carbon emissions (that align closely with the levels estimated by the global models for India), mainly because they assume a slightly lower GDP trajectory and are optimistic about CCS as an option for India. It must be noted that energy consumption and related emissions in our model are highly sensitive to GDP growth rates. TERI (2018a) estimates that a reduction of 2% in GDP growth assumption could lead to a 32% decline in energy consumption in 2051 in a business-as-usual scenario. In reality, high GDP growth could translate into higher household incomes facilitating uptake of efficient/low-carbon alternatives with high upfront costs. However, given that energy system models do not explicitly consider these linkages, higher GDP growth trajectories tend to exhibit higher energy requirements and consequently call for stronger actions to achieve desired carbon budgets.

Implementation of many of the proposed options is fraught with barriers and challenges as well. One of India's biggest developmental challenges is to achieve household energy security by providing access to reliable and affordable energy. Programmes like Pradhan Mantri Ujjwala Yojana (PMUY) provide subsidized LPG cylinders to poor households, but affordability issues compel users to switch back to traditional fuels once their quota of subsidized cylinders is exhausted (Ghosh 2020). This is further substantiated by NSSO (2014) which indicates that only 21% of households in rural areas consumed LPG while 83.5% of households consumed firewood and chips as the primary fuel for cooking in 2011. This indicates the need for deeper, long-lasting measures to improve the affordability of households and induce a more permanent shift in behaviour and choices. Moreover, while providing access to LPG helps alleviating indoor air pollution and improving overall quality of life, the challenge of climate mitigation remains unsolved because LPG is a fossil fuel. Accordingly, there may be larger long-term benefits as indicated through our scenarios if electricity-based cooking could also be promoted in rural areas to meet the dual objective of providing energy access as well as enabling climate mitigation.

While EVs have emerged as the most promising option to address the massive dependence of transport sector on fossil fuels, their scale-up must be synchronized with decarbonisation of India's electricity sector to achieve overall emission reductions. In the interim, improving fleet efficiencies, enabling modal shifts and use of less carbon-intensive fuels such as CNG should continue to be pursued while carefully planning the transition to EVs such that stranded capacities are minimized during the transition. With limited availability of alternative substitutes to replace diesel in trucks, jet fuel in aviation and fuel oil in shipping, there is also a need to examine prospects for further decarbonisation of the transport sector.

Keeping in mind the importance of electricity in decarbonisation, India should meticulously plan the electrification of end-use demands as well. India will need to identify ways to ramp up the share of renewable electricity while managing the intermittency issues over time and ensuring a smooth phase-out of fossil-based capacities to avoid a situation of low plant utilizations or stranded thermal capacities.

Similarly, India's industrial sector is complex and varies widely in terms of efficiencies, availability of alternatives and challenges. Much of the scope for emission reduction has so far been dependent on efficiency improvements. Subsectors like cement and fertilizers have improved their efficiencies significantly over the last few years (see BEE 2018; Nand and Goswami 2011), while subsectors like iron and steel exhibit further scope of improvement (TERI 2018b). However, there are practical limits to efficiency improvements in many cases. For example, while scrap-based steel production is more energy efficient, there may be practical limits to the level of steel production based on recycled scrap.[13] Additionally, diverse processes and technologies are used across subsectors and especially in the MSMEs, making it difficult to replicate learning among units and bring in changes at scale. Small disaggregated units have limited scope to shift to alternative technologies without making large process-related changes, generally lack both upfront capital and requisite skills or knowledge and may face issues related to loss of competitiveness in the absence of being able to reap the advantages of scale. Moreover, given that industry is dependent on fossil fuels especially for heat generation, there is a need to find alternative fuels to decarbonize this sector.

Challenges in achieving stringent emission reductions as in the case of NPiL or INDCL also arise from apprehensions associated with high investment costs of alternative fuels or emerging technologies which are yet to be commercialized/adapted under Indian conditions. Even where efficient and commercialized technologies are available, switching to these options may often entail significant upfront costs, require significant infrastructure to be put in place or require behavioural changes. India would need to implement and/or further strengthen a range of innovative policies, measures and initiatives to overcome such barriers and enable these shifts. Programmes like Standards and Labelling, UJALA and PAT schemes have already led to significant energy savings in India (see MOEFCC 2018; EESL 2020; BEE 2017, 2020). However, continued thrust including incentives, innovative business models, policy nudges and other form of government support are likely to be required to induce behavioural changes, enable uptake of efficient options and create an environment conducive for large-scale green

[13] Recent guidelines suggest that around 60–65% of steel produced in India by 2030 should be produced via the Basic Oxidation Furnace (BF-BOF) route (MOS 2017).

investment and to effectuate changes at the scale listed in Table S4. There also need to have focussed R&D efforts to find appropriate technological solutions and alternative fuels where low-carbon options do not readily exist.

5 Conclusion

In sum, it is essential for India to build on its development strategy in such a way that the transition to alternative decarbonisation pathways is smooth at each progressive stage and available choices can find effective uptake across consumers. It needs to focus on the country's overall development aspirations of strengthening its infrastructure, building human capital and livelihood opportunities and ensuring robust economic development while considering the most appropriate decarbonisation options at each stage. This can go a long way in enabling progress towards the key options proposed such that it not only aligns to mitigation efforts required to address the climate change issues but also fulfils the national priorities.

While it is essential to evaluate the feasibility and practicality of various options in the Indian context at each stage, the options and strategies should also be evaluated continuously with regard to the progress of other options and best practices globally. In a dynamic environment where technologies are constantly evolving and rapidly changing, there is need for flexible, nimble and judicious planning of the transitions so that recent investments are not stranded, and the country does not lock itself into large-scale carbon-positive infrastructure as a result of inconsistent policies and decisions across sectors. At the same time, it will need to pay attention to country-specific issues in order to ensure that the objectives of inclusive and sustainable development is fulfilled as India progresses towards the shared goal of emission mitigation.

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References

Bandyopadhyay S (2017) Renewable targets for India. Clean Technol Environ Policies. https://doi.org/10.1007/s10098-017-1335-z

BEE (2017) Achievements under Perform, Achieve and Trade (PAT). Bureau of Energy Efficiency. https://beeindia.gov.in/sites/default/files/Booklet_Achievements%20under%20PAT_May%202017.pdf. Accessed 16 September 2020

BEE (2018) Cement. Bureau of Energy Efficiency. https://beeindia.gov.in/node/166. Accessed 01 April 2020

BEE (2020) Impact of energy efficiency measures for the year 2018–19. Bureau of Energy Efficiency, New Delhi

Byravan S, Ali MS, Ananthakumar MR et al (2017) Quality of life for all: a sustainable development framework for India's climate policy reduces greenhouse gas emissions. Energy Sustain Dev. https://doi.org/10.1016/j.esd.2017.04.003

CAT (2015) CAT statement- statement on COP21 Paris Agreement. Climate Action Tracker. http://climateactiontracker.org/publications/briefing/256/Paris-Agreement-near-term-actions-do-not-match-long-term-purpose-but-stage-is-set-to-ramp-up-climate-action-.html. Accessed 03 March 2020

CAT (2019) India. Climate Action Tracker. https://climateactiontracker.org/countries/india/. Accessed 16 September 2020

Chandramauli C (2011) Census of India 2011- primary census abstract data highlights India series 1. Ministry of Home Affairs, New Delhi

Chaturvedi V, Koti PN, Sugam R, Neog K, Hejazi M (2017) Implications for shared socio-economic pathways for India's long-term electricity generation and associated water demands. Council on Energy Environment & Water, New Delhi

Das S, Priess JA (2011) Zig-zagging into the future: the role of biofuels in India. Biofuels Bioprod Biorefin 5:18–27

den Elzen M, Admiraal A, Roelfsema M, van Soest H, Hof AF, Forsell N (2016) Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. Climatic Change 137 (3-4):655–665

Dubash NK, Khosla R, Rao ND, Bhardwaj A (2018) India's energy and emissions future: an interpretive analysis of model scenarios. Environ Res Lett. https://doi.org/10.1088/1748-9326/aacc74

EESL (2020) National Ujala dashboard. Energy efficiency services limited. http://www.ujala.gov.in/. Accessed 01 April 1, 2020

den Elzen M, Admiraal A, Roelfsema M, van Soest H, Hof AF, Forsell N (2016) Contribution of the G20 economies to the global impact of the Paris Agreement climate proposals. Clim Chang. https://doi.org/10.1007/s10584-016-1700-7

Fawcett AA, Iyer GC, Clarke LE et al (2015) Can Paris pledge avert climate change? Science. https://doi.org/10.1126/science.aad5761

Gambhir A, Napp TA, Emmott CJ, Anandarajah G (2014) India's CO_2 emissions pathways to 2050: energy system, economic and fossil fuel impacts with and without carbon permit trading. Energy. https://doi.org/10.1016/j.energy.2014.09.055

Ghosh SK (2020) Making Ujjwala Yojana the livewire of rural India post the LPG price increase. Ecowrap 73:1–3

GOI (2015) India's intended nationally determined contribution: working towards climate justice. Government of India, New Delhi

Grové J, Lant PA, Greig CR, Smart S (2017) Can coal-derived DME reduce the dependence on solid cooking fuels in India? Energy Sustain Dev 37:51–59

Gupta D, Ghersi F, Vishwanathan SS, Garg A (2019) Achieving sustainable development in India along low carbon pathways: macroeconomic assessment. World Dev. https://doi.org/10.1016/j.worlddev.2019.104623

IEA (2016) World Energy Outlook 2016. International Energy Agency, Paris

Krey V, Guo F, Kolp P et al (2019) Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models. Energy. https://doi.org/10.1016/j.energy.2018.12.131

Kumar S, Kapoor R, Deshmukh A, Kamath M, Manu S (2010) Total commercial floor space estimates for India. USAID, New Delhi

Lucas PL, Shukla P, Chen W, Ruijven BJ, Dhar S, Elzen MG, van Vuuren DP (2013) Implications of the international reduction pledges on long-term energy system changes and costs in China and India. Energy Policy. https://doi.org/10.1016/j.enpol.2013.09.026

Luderer G, Kriegler E, Delsa L et al (2016) Deep decarbonisation towards 1.5°C–2°C stabilisation: policy findings from the ADVANCE project

Malik A, Bertram C, Despres J et al (2020) Reducing stranded assets through early action in the Indian power sector. Environ Res Lett. https://doi.org/10.1088/1748-9326/ab8033

Mathur R, Shekhar S (2019) India: decarbonisation pathways - options & implications. COMMIT. https://themasites.pbl.nl/commit/wp-content/uploads/COMMIT-Fact-Sheet-India-Decarbonisation-Pathways-Options-and-Implications-1.pdf. Accessed 16 September 2020

Mathur R, Vats G, Shekhar S (2019) India's conundrum: aligning emission mitigation with development. Yojana 1(2):7–9

Mittal S, Hanaoka T, Shukla PR, Masui T (2015) Air pollution co-benefits of low carbon policies in road transport: a sub-national assessment for India. Environ Res Lett. https://doi.org/10.1088/1748-9326/10/8/085006

MNRE (2019) Solar energy. Ministry of New and Renewable Energy. https://www.mnre.gov.in/solar/current-status. Accessed 31 March 2020

MOEFCC (2018) India: second biennial update report to the United Nations framework convention on climate change. Ministry of Environment Forest & Climate Change, New Delhi

MOEFCC (2019) India cooling action plan. Ministry of Environment, Forest and Climate Change, New Delhi

MOP (2019) Saubhagya Dashboard. Ministry of Power. https://saubhagya.gov.in/. Accessed 31 March 2020

MOS (2017) National Steel Policy, 2017. Ministry of Steel, New Delhi

Nand S, Goswami M (2011) Energy efficiency and CO_2 generation in Indian ammonia plants. Ammonia Tech Manual:191–198

NIWE (2015) Wind power potential at 100m agl. National Institute of Wind Energy. https://niwe.res.in/department_wra_100m%20agl.php. Accessed 30 March 2020

NIWE (2019) India's Wind Potential Atlas at 120m agl. National Institute of Wind Energy. https://niwe.res.in/assets/Docu/India's_Wind_Potential_Atlas_at_120m_agl.pdf. Accessed 30 March 2020
NSSO (2014) Household consumption of various goods and services in India 2011–12. Ministry of Statistics and Programme Implementation. Government of India, New Delhi
OECD (2018) OECD Economic Outlook. OECD Publishing, Paris
Parikh KS, Parikh JK, Ghosh PP (2018) Can India grow and live within a 1.5 degree CO_2 emissions budget? Energy Policy. https://doi.org/10.1016/j.enpol.2018.05.014
PFI and PRB (2007) The future population of India: a long-range demographic view. Population Foundation of India & Population Reference Bureau, New Delhi
PIB (2018) Cabinet approves National Policy on Biofuels - 2018. Press Information Bureau. https://pib.gov.in/Pressreleaseshare.aspx?PRID=1532265, Accessed 09 September 2020
Rogelj J, den Elzen M, Höhne N et al (2016) Paris Agreement climate proposals need a boost to keep warming well below 2°C. Nature. https://doi.org/10.1038/nature18307
Rohra H, Taneja A (2016) Indoor air quality scenario in India—an outline of household fuel combustion. Atmos Environ. https://doi.org/10.1016/j.atmosenv.2016.01.038
Schaeffer R, Köberle A, van Soest HL et al (2020) Comparing transformation pathways across different regions and countries. Clim Chang. https://doi.org/10.1007/s10584-020-02837-9
Shukla PR, Chaturvedi V (2012) Low carbon and clean energy scenarios for India: analysis of targets approach. Energy Econ. https://doi.org/10.1016/j.eneco.2012.05.002
Shukla PR, Dhar S, Mahapatra D (2008) Low-carbon society scenarios for India. Clim Pol. https://doi.org/10.3763/cpol.2007.0498
Sood A, Vyas S (2017) A review: carbon capture and sequestration in India. Int J Mech Eng Technol 8(2):1–7
Spencer T, Rodrigues N, Pachouri R, Thakre S, Renjith G (2020) Renewable power pathways: modelling the integration of wind and solar in India by 2030. The Energy and Resources Institute, New Delhi
Srinivasan S, Kholod N, Chaturvedi V et al (2018) Water for electricity in India: a multi-model study of future challenges and linkages to climate change mitigation. Appl Energy. https://doi.org/10.1016/j.apenergy.2017.04.079
TERI (2006) National Energy Map for India Technology Vision 2030. The Energy and Resources Institute, New Delhi
TERI (2018a) Assess the human health and agricultural co-benefits of a low carbon pathway for India. The Energy and Resources Institute, New Delhi
TERI (2018b) Energy efficiency potential in India. The Energy and Resources Institute, New Delhi
TERI (2019) TERI Energy & Environment Data Diary and Yearbook 2018/19. The Energy and Resources Institute, New Delhi
TERI (2020) Reference card- MARKAL-India. IAMC wiki. https://www.iamcdocumentation.eu/index.php/Reference_card_-_MARKAL-India. Accessed 04 September 2020
Thambi S, Bhatacharya A, Fricko O (2018) India's energy and emissions outlook: results from India energy model. NITI Aayog, New Delhi
UNDESA (2019) World Population Prospects. Department of Economic and Social Affairs, United Nations
UNEP (2016) The Emissions Gap Report 2016. United Nations Environment Programme, Nairobi
van den Berg NJ, van Soest HL, Hof AF et al (2019) Implications of various effort-sharing approaches for national carbon budgets and emission pathways. Clim Chang. https://doi.org/10.1007/s10584-019-02368-y
Viebahn P, Höller S, Vallentin D, Liptow H, Villar A (2011) Future CCS implementation in India: a systemic and long-term analysis. Energy Procedia. https://doi.org/10.1016/j.egypro.2011.02.172
Viebahn P, Vallentin D, Höller S (2014) Prospects of carbon capture and storage (CCS) in India's power sector – an integrated assessment. Appl Energy. https://doi.org/10.1016/j.apenergy.2013.11.054
Vishwanathan S, Garg A (2020) Energy system transformation to meet NDC, 2 °C, and well below 2 °C targets for India. Clim Chang. https://doi.org/10.1007/s10584-019-02616-1
Vishwanathan SS, Garg A, Tiwari V, Shukla PR (2018) India in 2°C and well below 2°C worlds: opportunities and challenges. Carbon Management. https://doi.org/10.1080/17583004.2018.1476588
World Bank (2019a) CO_2 emissions (metric tons per capita).World Bank Data. https://data.worldbank.org/indicator/EN.ATM.CO2E.PC. Accessed 30 March 2020
World Bank (2019b) Energy use (kg of oil equivalent per capita).World Bank Data. https://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE?view=chart. Accessed 30 March 2020

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