Energy and Climate Change 2 (2021) 100031

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.elsevier.com/locate/egycc

Pathways towards India's nationally determined contribution and mid-century strategy

Vaibhav Chaturvedi [a,*], Poonam Nagar Koti [a], Anjali Ramakrishnan Chordia [a,b,c]

[a] Council on Energy, Environment and Water, Sanskrit Bhavan, A-10, Qutub Institutional Area, Aruna Asaf Ali Marg, New Delhi 110067, India
[b] Technische Universität, Berlin, Germany
[c] Mercator Research Institute in Global Commons and Climate Change, Berlin, Germany

ARTICLE INFO

Keywords:
NDC enhancement
India
Scenarios
Uncertainties
Climate policy
Paris agreement

ABSTRACT

India's emission mitigation policy, as reflected in its Nationally Determined Contribution (NDC), focuses on two energy sector related variables- share of non-fossil sources in the electricity generation sector, and emission intensity of India's GDP. We undertake a scenario-based uncertainty assessment to understand if there is room to enhance the mitigation ambition of India's energy sector related NDC targets and inform long-term decarbonisation. We find that while there is room to enhance ambition on the electricity sector mitigation target, some key uncertainties related specifically to the industrial sector need to be better understood before enhancing ambition on the emission intensity reduction front. We highlight that renewable energy integration cost and decarbonisation of industrial energy use are going to be key challenges for India's long-term decarbonisation strategy, and that electricity sector reforms in India are going to be critical to address both these challenges. Finally, we conclude by highlighting that India could demonstrate leadership by taking additional burden for the world by adopting a peaking year for its power sector emissions as a part of its Mid-Century Strategy.

1. Introduction

The synthesis report on the aggregate effect of Intended Nationally Determined Contributions (INDCs) on global emission pathway concludes that *'much greater emission reduction efforts than those associated with the INDCs will be required in the period after 2025 and 2030 to hold the temperature rise below 2°C above pre-industrial levels'* [1]. Compared to the 2 °C scenario, aggregate GHG emission levels resulting from INDC implementation are expected to be higher by 36 per cent (range 24-60 per cent) in 2030. Clearly, countries across the world need to enhance their mitigation efforts to achieve the goals of the Paris Agreement.

In the global climate regime, India's role is becoming increasingly important. Per capita energy consumption is much lower in India than in the developed world, but it is expected to grow at a significant pace, and impact global greenhouse gas (GHG) emissions and climate change. Of the eight NDC targets submitted by India for the period 2021–2030 [2], two are directly linked to quantified mitigation targets for India's energy systems: achieve by 2030, 40 per cent cumulative electric power installed capacity from non-fossil-based energy resources; and reduce, also by 2030, the emissions intensity (EI) of its GDP by 33 per cent to 35 per cent relative to the 2005 level. This would be subject to transfer of technology and access to low-cost international financing.

Globally, countries are coming forward with declarations for enhancing ambition of NDCs [3], and the global climate debate is now moving towards an understanding of the potential[1] to enhance NDCs across countries. Assessment of the potential to enhance country specific NDC would help in reducing the gap between the global emissions as expected due to collective NDCs, and emissions required to achieve deep decarbonisation to the extent possible. Given the developments in the country, energy markets, and global climate debate, it is timely to understand the potential of enhancing India's NDC targets, as well as analyse scenarios for deeper decarbonisation in the long-term context, that can inform India's Mid-Century Strategy (MCS), as expected to be submitted under the Paris Agreement.

Though several assessments an understanding of the challenges in India's transition towards a low-carbon pathway [4–23], no study in our knowledge has explicitly analysed the potential and limits of enhancing India's internationally stated decarbonisation targets. Most of these

[1] Potential could be defined differently by different stakeholders - e.g. technical potential, economic potential, or socioeconomic potential. Technical potential for any resource could be large, but economic potential could be limited and depend on the relative costs and economics of a resource. The focus of our analysis is the potential to enhance India's NDC in terms of the economics of different options.

* Corresponding author.
E-mail address: vaibhav.chaturvedi@ceew.in (V. Chaturvedi).

https://doi.org/10.1016/j.egycc.2021.100031
Received 12 April 2020; Received in revised form 15 December 2020; Accepted 28 February 2021
Available online 6 March 2021

studies are based on energy optimization or energy simulation modelling assessments analysing long term pathways for India's decarbonisation. Many adopt the framing of sustainable development that emphasises the criticality of co-benefits. In the first such study in India, Shukla, Dhar and Mahapatra (2008) [4] use an optimization modelling framework to analyse three scenarios for India for up to 2050- a business-as-usual scenario, a 550 ppmv CO2 e stabilization scenario assuming a conventional development pattern, and a 550 ppmv CO2 e stabilization scenario assuming a sustainable development pattern characterised by diverse response measures typical of a sustainability paradigm- and present a comparative analysis of the alternative development strategies on multiple indicators such as energy security, air quality, technology stocks and adaptive capacity. In another analysis with a similar framing using an energy simulation model, Shukla and Chaturvedi (2013) [5] analyse two emission stabilization approaches for India – a conventional approach relying on carbon price to influence fuel switch and carbon capture and storage responses, and a sustainability approach that aims to conserve resources and push solar and wind in India's energy systems. Shukla et al. (2015) [6] similarly present a conventional and a sustainable deep decarbonisation scenario where, interestingly, the mitigation actions under the sustainable scenario are back casted from the national sustainability goals set for 2050. Importantly, this analysis presents and highlights the importance of 'social value of carbon' and argues that a carbon price based on social value would be much lower than a conventional carbon price for achieving the same mitigation goal. In another analysis within the sustainable development framing, Mathur (2017) [7] presents the implications of an INDC low scenario and an INDC high scenario and highlights the importance on not just the choices we make, but also the timing of adoption and scale up of alternative options. Byravan et al. (2017) [8] place quality of life at the centre of their assessment within the framing of sustainable development and reveal the potential for improvement in a range of sustainable development conditions including a reduction in air pollution, savings in water and land use, and savings in material and resource requirements.

Other modelling analyses, while not explicitly using the framing of sustainable development, similarly use sophisticated modelling approaches for understanding long-term energy and emission scenarios for India. A report by the Planning Commission, Government of India (2014) [9] frames the analysis as informing 'inclusive' growth and recommends policies for all the energy use sectors in India based on input-output modelling framework and a low carbon inclusive growth scenario. The International Energy Agency's World Economic Outlook 2015 special report (IEA, 2015) [10] also focuses on long term scenarios for India and assesses the implications of major Government of India (GoI) policies like '24 × 7 power to all' and 'Make in India' on India's energy outlook. Bery et al. (2016) [11] present the implications of critical trends in India like rapid urbanisation, growing energy access, and greater integration with the global energy markets on India's energy future. A report by NITI-IEEJ (2017) [12] analyses multiple critical issues in India's energy policy debate, including natural gas demand, the impact of high penetration of renewable electricity on the Indian grid in 2047, and the impact of clean coal technology on the overall energy scenario. Chaturvedi et al. (2019) [13], in the first India focused study within the framework of shared socioeconomic pathways (SSPs), present the implications of alternative development pathways on India's long-term electricity-water nexus. The study also presents India specific water coefficients for electricity generation technologies to aid analysis of the impact on water resources, a critical element of the sustainable development perspective, and highlights the importance of looking at the dry cooling technology for thermal cooling of power generation plants in India. In a macroeconomic assessment that is rare for India specific climate policy literature, Gupta et al. (2019) [14] show that a 2 DegC scenario has a comparable economic growth rate relative to the Busines as Usual (BAU) scenario, at the cost of reduced household consumption but significant positive impact on foreign debt accumulation. As compared to energy focused analysis, Rao et al. (2018) [15] also use an optimisation framework to assess the importance of climate friendly diets in India in an analysis that focuses on decarbonisation through the lens of diets and nutrition, TERI (2017) [16] analyses two alternative scenarios for India's electricity sector, focusing on a high renewable scenario and a low renewable scenario, based on econometric and statistical analysis.

Along with the optimisation and simulation focused long-term modelling assessments for India, there are other important studies that are relevant for Indian energy and climate policy and use alternative methodologies and are sector specific. Shrimali and Tirumalachetty (2013) [17] present a detailed analysis of renewable energy certificate markets in India, which has not been very successful in achieving its objectives. Chawla and Agarwal (2016) [18] present the contribution of various underlying factors in the cost of solar electricity and highlight that cost of finance is the most important variable for India and other emerging economies. Jethani (2016) [19] focuses on the wind energy programme in India and the challenges it is facing. Garg et al. (2017) [20] focus on a much neglected technology in the Indian energy and decarbonisation debate- Carbon, Capture and Storage (CCS)- and present a cost effective architecture of CCS grid in India based on detailed spatial mapping of coal power plants and potential geological reservoirs for carbon dioxide storage in India. Garg (2011) [21] focuses on the potential health co-benefits of climate change policies at the city level and presents a detailed spatial assessment of this for the city of Delhi.

Apart from these important and interesting non-modelling based assessments, some other important articles present a high level narrative for India. Ghosh and Ganesan (2015) [22] present their assessment of India's energy strategy and highlight the importance of off-grid RE along with centralised RE, rationalising fossil fuel subsidies, and a shift towards a less energy intensive industrial mix. Dubash and Khosla (2015) [23] in their assessment of India's INDC reflect a 'middle of the road' kind of choice that neither disrupts the international consensus on the issue nor creates pressure for urgent global climate action.

Critically, in our assessment of the literature as presented above, no India specific study in our knowledge considers the implications of key uncertainties that could impact the pathways towards India's NDC targets and potential MCS targets. We undertake a robust assessment across uncertainties related to the cost of electricity generation technologies, cost of integration of variable renewable energy, economic growth, end-use energy efficiency, and energy demand behaviour in the end-use sectors to understand if (and by how much) there is a potential to enhance India's energy sector related NDC targets (40 per cent share of non-fossil energy sources in India's electricity generation capacity by 2030, and reduction in the emissions intensity (EI) of India's GDP by 33 per cent-35 per cent between 2005 and 2030) and inform potential MCS.

We seek to build on the knowledge base created by existing studies on India's energy and climate policy and to address some key gaps in the literature. Through our analysis, we answer the following research questions: (i) What is the potential to enhance the NDC target of 40 per cent share of non-fossil sources (all forms of RE and nuclear energy) in India's electricity generation capacity in 2030, given the key uncertainties for this sector?, (ii) What is the potential to enhance the NDC target of 33-35 per cent decline in India's emissions intensity of GDP between 2005 and 2030, given the key uncertainties for the economy?; and (iii) What are the policy insights from an uncertainty based assessment for India's long-term decarbonisation and Mid-Century Strategy?

The novelty of our methodological approach is that for the first time in our knowledge of India specific literature, we have characterised key uncertainties, and derived robust insights for enhancing India's NDC and understanding challenges to long-term decarbonisation through an assessment of implications of these. The key contribution of our paper is highlighting the potential of enhancing India's energy sector specific NDC targets, as well as informing the potential Mid-Century Strategy on the basis of the insights. We use the modelling framework of GCAM (IIM Ahmedabad version) for our analysis. We model a business and usual or Reference (Ref) scenario, and then 222 scenarios to model the uncertainty span around the Ref scenario results by exploring sensitivities related to critical variables (economic growth, urbanisation rate, electricity generation technology cost, integration cost, energy efficiency, and energy demand behaviour in end-use sectors) across the electricity generation and end-use energy demand sectors.

2. Modelling for a scenario-based uncertainty assessment

Many researchers have focused on and highlighted the importance of uncertainties modelling for informing decisions, including energy and emissions modelling [24–33]. For our analysis, we adopt the general definition of uncertainty as: "*any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system*" [26]. We use the approach of scenario analysis within a deterministic model, GCAM. This approach is useful and apt for our purpose, as it requires the selection of key parameters and input assumptions, and helps in understanding the robustness of model results to these key input assumptions. We undertake a large set of scenario runs based on various combination of key inputs, to understand the ranges, median values and broad direction related to output variables of our interest for a relatively robust assessment of these as compared to that available in the India specific literature.

There are two pillars of our methodological approach – (i) Stakeholder engagement, and (ii) Integrated assessment modelling. We engaged with expert stakeholders from National Thermal Power Corporation (NTPC, a thermal power behemoth in India), MNRE (Ministry of New and Renewable Energy, GoI), solar and wind power plant developers, and other policy and sector experts for informing our assumptions as well as storylines. Our framing of uncertainties is based on a literature review as well as understanding based on our engagement with experts[2]. This section presents the different aspects of our methodological approach, including modelling framework, uncertainty assessment approach, as well as climate policies, among other aspects.

2.1. Modelling framework – Global Change Analysis Model (GCAM)

We use the modelling framework of GCAM, IIM Ahmedabad version for our analysis. GCAM is a model with a detailed energy sector module and a land use module, has been an important part of IPCC assessments on modelling related literature, and has been used extensively for national and international exercises since over three decades. Modelling analysis based on GCAM has been extensively published in high impact international journals [34–46]. GCAM is housed at the Joint Global Change Research Institute (USA), and models 32 regions of the world with India as a separate region. GCAM-IIM version was set up during 2007–09, and since has been used extensively for India-specific analysis [5,13,37,43,45]. GCAM-IIM models the rural and urban residential energy demand separately, as compared to core GCAM that focuses on the residential sector without any further disaggregation. All the cost and technology characteristic related assumptions across sectors in GCAM-IIM are based on India specific data, whereas technology assumptions are based on global datasets in the core GCAM version used for global analysis.

Modelling electricity generation growth and technology share

Electricity in GCAM can be generated based on nine fuel types (coal, gas, oil, nuclear, solar, wind, hydro, biomass, combined heat and power), which could be associated with multiple technologies, e.g. photovoltaic (PV) and CSP for solar. The share of any given technology within GCAM is based on its cost relative to the cost of all other technologies and is modelled based on modified logit formulation (Clarke and Edmonds, 1993). In the electricity sector, the market share of individual fuels is determined endogenously in the model based on the following formulation:

$$s_{i,r,t} = \frac{\left(SW_{i,r}\right)\left(P_{i,r,t}\right)^{\lambda}}{\sum_i^n \left(SW_{i,r}\right)\left(P_{i,r,t}\right)^{\lambda}}$$

where SW is the share weight, Pi is the cost of generating power based on a specific fuel i in region r at time t (includes the capital, operation & maintenance, and endogenously determined fuel cost), λ is a cost distribution parameter[3], and n is the number of fuels competing in the electricity generation sector as stated above. The share weight is a calibration parameter, and the cost distribution parameter regulates the degree to which future price changes would be reflected in fuel shifts. In case of a price levied on emissions (e.g. carbon price), the endogenously determined fuel costs changes for fossil fuels resulting in a different electricity generation mix.

In this formulation, even if a technology has a higher average cost than other technologies in the choice set, it would take a small share in the energy mix. This reflects the real world scenario – even if the average cost of a technology is higher, it could still be competitive in some regions due to numerous local factors and constraints. GCAM assumes that the capital cost of the existing vintage of stock in any given year is sunk, so these costs do not Figure in the future operating decisions. Production from existing vintage is not subject to competition from new technologies. If in the year 2030 total electricity demand is 100 units, 70 units are already generated in 2025[4], and no electricity generation capacity is retired between 2025 and 2030, competition happens between new technologies only for the balance 30 units. Existing vintage plants may be temporarily shut down if input fuel cost is higher than the average revenue from the electricity generated. This could be the case in the event of a high carbon price that increases the generation cost from a coal-based power plant even more than the average revenue, in which case generation from this vintage would be temporarily shut down.

Demand for electricity generation and other forms of energy is determined in the end-use sectors, where the penetration of electricity-based technologies (e.g. air-conditioning) and other-fuel based technologies (e.g. oil-fuelled cars) increases as income increases. Details of modelling demand for electricity and other fuels in the end use sectors are given in separate sections below. Generally speaking, alternative technologies compete with each other for providing energy for any given service in the end-use sectors based on their relative costs and efficiencies, e.g. electric cars and oil-fuelled cars compete to provide passenger transportation service in the transportation sector, while LEDs and fluorescent light bulbs compete to provide lighting service in the building sector. As the demand for electricity grows in the end-use sectors, electricity generation grows to meet this demand.

As India moves towards a higher share of variable renewable energy (VRE), i.e. solar and wind electricity, in the grid, there could be challenges in managing the transition. The current share of VRE in the

[2] Before framing the scenarios and assumptions, the authors of the study met each of the key stakeholders (government and industry) in person, and engaged with experts from academics and think tanks once the first set of scenario results were out for their detailed perspectives and to refine the scenarios. The detailed list of experts who were consulted, and the reviewers of the study have been mentioned in the acknowledgement section.

[3] λ, or the cost distribution parameter, is an important parameter for the model as it determines how large the price ratio (between the price of competing fuels) must be to produce a significant difference in market share. A higher value of λ implies an aggressive technology substitution behaviour, while the lower value implies a moderate switching behaviour. The value that has been chosen for different sectors and technologies in GCAM is for the best possible representation of technology switching behaviour for given sectors within the model. What is important to highlight for our analysis is that across all our 222 scenarios, the values that this parameter takes across sectors has not been changed, i.e. it is scenario invariant. This implies that the shift in technology mix across sectors across pathways that we observe in our results is only a result of a change in the assumptions related to economic growth, technology costs, and variables related to the end-use sectors and not λ, the cost distribution parameter.

[4] GCAM operates in five-year time steps.

electricity generation is less than 10 per cent. But as this share grows to 15 per cent, 25 per cent, 50 per cent, and even higher in the long-term future, there could be a new set of challenges that the country might face. For addressing intermittency related issues, technical interventions either in the form of storage technologies or back up systems like gas based turbines would be required. These technical interventions would have a cost attached to them. We, hence, levy a nominal cost on top of the base solar and wind electricity cost to account for the cost of integration[5]. In the supplementary material, we also present scenario with no integration cost (which simply means that the cost of technical interventions for managing grid integration is borne by the government), and a scenario with a higher integration cost. This sensitivity analysis tells us the criticality of this variable for India's power systems. The assumption related to the additional cost of integration levied on solar and wind electricity is given in the supplementary material.

We do not model rooftop solar or decentralised mini-grid based electricity generation, and hence in our results, the utility related electricity demand might be higher than what is seen in the future if at least some part of the demand is met through such off-grid sources. Our results exclude captive generation by industries, which we believe would be a very small fraction of India's total electricity demand in the long run.

Modelling end-use energy sectors

GCAM models three end-use energy sectors – buildings, industry, and transportation. In GCAM-IIM, the buildings sector is disaggregated into commercial buildings, rural residential, and urban residential sectors. Energy service demand is modelled for air-conditioning (high and low efficiency), cooking (biomass, coal, electricity, liquefied petroleum gas (LPG), and natural gas), lighting (fluorescent bulbs, incandescent bulbs, kerosene lamps, and LEDs), refrigeration (high and low efficiency), ventilation (low- and high-efficiency ceiling fans), television, water heaters (electricity, LPG, solar) and 'other appliances' as a category. Demand for each energy service grows in response to income and service prices. Technologies compete on the basis of cost and efficiency to provide a given service. For example, LED, incandescent and fluorescent lighting technologies compete on the basis of cost and efficiencies to provide lighting services. A detailed theoretical formulation for the building sector as modelled in GCAM-IIM can be found in Chaturvedi et al. (2014). A brief explanation is given in Appendix 1 in the supplementary material.

The energy demand in the transportation sector is modelled for passenger transport (road, rail and aviation), freight transport (road and rail), and international shipping with the demand for each service being driven by per capita GDP and population. Each type of service demand is met by a range of competing modes. For passenger transport, two-wheelers, three-wheelers, cars, buses, railways, and aviation compete with each other for providing passenger service. Changes in modal shares in future periods depend on the relative costs of the different options, modelled using a logit choice formulation. Costs in the passenger sector include the time value of transportation, which tends to drive a shift towards faster modes of transport (light duty vehicles, aviation) as incomes increase. Many of the modes (including light duty vehicles) include competition between different vehicle types, which also uses a logit choice mechanism that is calibrated to base-year shares; for example, in the GCAM-IIM, the passenger car segment comprises four types of cars. For new or emerging technologies (such as electric or hydrogen vehicles), costs also consider infrastructural constraints, non-economic consumer preferences and as such are especially high in the near-term future time periods. No upper limits of battery electric vehicles (BEV) or fuel cell vehicles (FCV) use are implemented. In GCAM-IIM, population and income (GDP) are the exogenous drivers of passenger service demand expressed in passenger kilometres travelled (PKT). Further, in GCAM-IIM the passenger service demands by mode are estimated endogenously based on the total travel costs (monetary cost per passenger kilometre travelled, USD/PKT) by mode, fuel, technology and time cost of travel which itself is a function of the average hourly wage rate of the employed population, the mode-specific value of travel time (VTT) and travel speed. Freight service demand is based on simple functions of population, GDP, and fuel prices in GCAM-IIM. Freight trucks (five categories) and railways compete for servicing freight demand in GCAM-IIM. The rate of efficiency improvement of each represented vehicle technology is exogenous in GCAM-IIM. Details related to transportation in GCAM can be found in Kyle and Kim (2011) and Mishra et al. (2013). A brief explanation is given in Appendix 1 in the supplementary material.

The industrial sector in GCAM-IIM is modelled in an aggregate way, with industrial service demand responding to income growth and fuel prices. Various fuels (biomass, coal, electricity, natural gas and oil) compete on the basis of relative prices for providing energy service for meeting industrial energy demand. Current model version only tracks the energy mix (for energy use and feedstock use) and emissions from an aggregate industrial sector and includes energy demanded in the agricultural sector.

As GCAM is a detailed energy sector model, fuel use in one sector impacts its use in other sectors through the fuel price. For example, if oil demand in the transport sector reduces due to shifts towards electricity based vehicles, its price would decline, which would lead to an increased usage of oil in other sectors.

In GCAM, energy efficiency improvements in the end-use sectors are modelled with the help of exogenous assumptions, as well as endogenous price responses. Sectoral energy efficiency improvements for all the end use sectors in the Ref and sensitivity scenarios are presented in Appendix 1, Table S4. We also model endogenous price responses at the appliance/technology level, which leads to improvements in average efficiencies. E.g. we have a high-efficiency air conditioner (AC) and a low-efficiency AC. If the price of electricity increases due to any intervention, we would see a shift towards ACs with higher efficiency. At the vehicle technology level, energy efficiency impacts the fuel cost of a vehicle. If the cost of fuel of a given technology (say a car) increases due to any intervention, the given technology becomes less competitive. In the end-use sectors, shares of technologies/fuels respond to price signals. E.g. if coal becomes expensive in the end-use sectors due to say carbon tax, its share would decline the competing technology would fill the gap.

Detailed equations for modelling demands in the end use sectors and technology mix are given in the supplementary material.

2.2. Framing the 'Reference (Ref)' and 'uncertainty' based scenarios for the electricity generation sector and end use sectors

One of India's NDC targets focuses on the share of non-fossil energy sources in electricity generation capacity. India's progress towards this goal, as well as decarbonisation for up to 2050, depends not only on the cost of RE technologies but the relative costs of all key technologies in the portfolio. Also, how fast the electricity generation sector grows could impact the progress towards this target, as a low growth scenario might limit the growth potential of non-fossil sources and impede the pace of transition. Our analysis of this NDC target focuses on these two key uncertainties- the cost of power generation technologies, and economic growth, for understanding India's progress towards this target. For incorporating these uncertainties in our framework, we take two cost pathways each for coal, gas, and nuclear, and three each for solar and wind-based electricity generation. Combining these, we get a total of 72 unique pathways representing various permutations of underlying cost pathways for the five technologies (for a given economic growth scenario). The low- and high-cost trajectories (for all five technologies)

[5] The integration cost would depend on the various balancing options that are employed. As GCAM is not a power dispatch model, the implications of various balancing options can not be analysed in detail in this model. Hence, what we do is use a cost adder to represent a notional integration cost to find its implications. Our results should be interpreted for a high-level generic representation for integration cost, rather than any specific balancing option.

and medium cost trajectories (for solar and wind only) of all these technologies have been decided on the basis of our assessment and inputs from experts in the MNRE, GoI and NTPC; private developers of solar and wind energy power plants; and sector experts. We undertake our analysis of each of the 72 unique cost pathways within three economic growth scenarios. In total, our analysis encompasses 216 scenarios to answer how we expect India's electricity generation sector to evolve in the future, and what this means for India's NDC and Mid-Century Strategy. All the 216 scenarios assume partial implementation of existing policies, and none of these incorporate dedicated climate policy instruments, like a carbon tax. We do not assume that India will achieve the domestic policy target of 175 GW of RE by 2022 and let our modelling analysis inform us. Our assumptions of technology cost trajectories and economic growth trajectories are detailed in the supplementary material.

We assess the key uncertainties in the demand sectors- the rate of energy efficiency improvements across all end use sectors, the rate of energy demand growth across all sectors, and the share of electricity in the industrial sector- to understand India's progress towards the NDC target related to the emission intensity of GDP. Our assessment focuses only on energy sector-related carbon dioxide emissions, which cover a large part of the overall GHG debate, CO_2 from land-use as well as other GHGs are excluded in our analysis.

We model six additional scenarios to explore various combinations of these, taking the total number of scenarios that we use for our uncertainty analysis to 222. Table 1 presents our scenario framing.

The Ref sc reflects a particular combination of how the technical and economic assumptions evolve across sectors. For the electricity sector, we assume the medium cost trajectories for solar and wind, high cost trajectory for natural gas, and low cost trajectories for coal and nuclear based electricity (Appendix 1, Table S3). Assumptions related to energy efficiency improvements in the Ref scenario across end use sectors are presented in Appendix 1, Table S4; and those related to the behaviour of energy demand in the end use sectors are presented in Appendix 1, Table S5. The rate of GDP growth and urbanisation rate in Ref sc are assumed to be the same as the medium growth scenario (Table S1 and S2, Appendix 1). The simulation for uncertainty analysis can be viewed as an uncertainty band around our Ref sc results.

Uncertainty analysis can be characterised in different ways, even for the same energy sector. E.g., one can also undertake a probabilistic analysis for uncertainties related to the electricity generation sector. There could be other ways in which different researchers conceptualise an uncertainty-based analysis. Our approach is only one of the possible ways of undertaking an uncertainty-based analysis. Other researchers can use our approach or formulate alternative approaches for such an analysis.

2.3. Key assumptions and time-frame

The key assumptions in GCAM are related to economic and population growth (Appendix 1, Table S1 and S2) that drive the demand for energy services in the end-use sectors. The capital cost, operations & maintenance cost, and energy efficiency for all technologies across all sectors are critical assumptions in GCAM. The fuel cost is endogenously determined for all fuels across all sectors based on the demand and supply of these.

The cost and efficiency assumptions of technologies across sectors are based on India specific information taken from secondary literature, including company websites, etc. Cost for power generation technologies are based on discussions with sectoral experts from solar and wind power developers, Ministry of New and Renewable Energy (MNRE), and National Thermal Power Corporation (NTPC).

The timeframe for our analysis is up to 2050, as this is the time frame relevant for our discussion on NDC and Mid-Century Strategy.

3. Results

3.1. Electricity, end-use energy, and emissions in the Reference scenario

India's electricity consumption, end use energy and emissions are expected to grow at a significant pace up to 2050, though there would be a significant decoupling of emissions with economic growth. India's electricity generation would grow to 2800 Billion KWh in 2030, and further by 2.3 times between 2030 and 2050 (Fig. 1). Final energy demand in the end use sectors would grow from less than 500 millions of tonnes of oil equivalent (mtoe) in 2010 to more than 850 mtoe in 2030 and 1700 mtoe in 2050 (Fig. 2b).

The significant increase in electricity generation and energy use in the end use sectors would lead to a significant increase in India's carbon dioxide emissions. India's overall CO_2 emissions from energy use would increase from 2.2 $GtCO_2$ in 2015 to 4.2 $GtCO_2$ in 2030, and further to 7.7 $GtCO_2$ in 2050 (Fig. 2a). Irrespective of growth in India's absolute emissions, it is clear that decoupling between emissions and economic growth is happening at a fast pace.

The increase is due to continued, though reduced, reliance of coal in the electricity generation sector, as well as significant fossil fuel consumption in the end use sectors in the absence of any dedicated policy to mitigate carbon dioxide emissions.

Though India's carbon dioxide emissions from energy use would continue to increase for meeting its developmental aspirations, we see significant progress in our Ref scenario as far as the two NDC targets relevant to the energy sector are concerned. We find that India is well on the path to achieving one key NDC target – 40 per cent share of non-fossil energy sources in India's electricity generation capacity – and may well surpass it. In the Ref scenario, we find the share of non-fossil sources in India's electricity generation capacity would be 58% in 2030 and 73% in 2050. The significant progress would be on the back of a rapid increase in solar energy, supported by focused government policies, which would account for a bulk of the increase in India's renewable energy capacity between 2020 and 2030.

In our Ref sc, the EI of India's GDP declines by 47% by 2030, and 67% by 2050, relative to 2005. EI reduction is not only due to the electricity generation mix moving towards RE, but also due to structural changes and significant energy efficiency improvements in the end-use sectors. This is much higher than the 33%-35% NDC target. Our assessment focuses only on energy sector-related carbon dioxide emissions, which cover a large part of the overall GHG debate, CO_2 from land-use as well as other GHGs are excluded in our analysis.

3.2. The impact of key uncertainties on India's progress towards the electricity sector specific NDC target, and insights for long-term decarbonisation of the electricity generation sector

Our uncertainty analysis reveals two important insights at a higher level for India's electricity generation. First, actual electricity generation is determined not just by the economic growth rates, but also by the average cost of electricity (Fig. 1). As our model incorporates the shift in fuel demand in response to prices, we see that even for any given economic growth rate, electricity generation changes by 15 per cent-17 per cent due to change in average electricity cost. Second, given the uncertainty ranges adopted by us, economic growth certainly has a higher bearing on the level of electricity generation in the economy, as compared to technology cost. The variation (between the minimum and maximum) in electricity generation due to economic growth is 22% in 2030, and 44% in 2050, much larger than the variation due to technology cost. The rate at which electricity generation grows is relevant for the progress towards the NDC target of 40% share of non-fossil sources in India's electricity generation capacity, as a higher growth gives more opportunity for adding renewable energy in the mix, provided it is cost competitive.

Table 1
Scenario framework.

GDP Growth	Electricity generation technology cost pathways					End-use efficiency growth pathways			End-use energy demand growth pathway			Electricity share in industrial sector	Number of scenarios	Remarks
	Solar	Wind	Coal	Gas	Nuclear	Bld	Ind	Trn	Bld	Ind	Trn			
High Growth	Three pathways (Ref, high, and low)	Three pathways (Ref, high, and low)	Two pathways (high and low)	Two pathways (high and low)	Two pathways (high and low)	Ref	Ref	Ref	Ref	Ref	Ref	Ref	72 scenarios (3*3*2*2*2*1*1*1*1*1*1)	High GDP growth scenario set for exploring implications of alternative combinations of electricity generation technology cost pathways within high GDP growth
Low Growth	Three pathways (Ref, high, and low)	Three pathways (Ref, high, and low)	Two pathways (high and low)	Two pathways (high and low)	Two pathways (high and low)	Ref	Ref	Ref	Ref	Ref	Ref	Ref	72 scenarios (3*3*2*2*2*1*1*1*1*1*1)	High GDP growth scenario set for exploring implications of alternative combinations of electricity generation technology cost pathways within low GDP growth
Ref (medium) Growth	Three pathways (Ref, high, and low)	Three pathways (Ref, high, and low)	Two pathways (high and low)	Two pathways (high and low)	Two pathways (high and low)	Ref	Ref	Ref	Ref	Ref	Ref	Ref	72 scenarios (3*3*2*2*2*1*1*1*1*1*1)	High GDP growth scenario set for exploring implications of alternative combinations of electricity generation technology cost pathways within Ref (medium) GDP growth
Ref (medium) Growth	Ref	Ref	Ref	Ref	Ref	Low	Ref	Ref	Ref	Ref	Ref	Ref	1 scenario	Low building energy efficiency scenario
	Ref	Ref	Ref	Ref	Ref	Ref	Low	Ref	Ref	Ref	Ref	Ref	1 scenario	Low industrial energy efficiency scenario
	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Low	Ref	Ref	Ref	Ref	1 scenario	Low transport energy efficiency scenario
	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	High	Ref	Low	1 scenario	High industrial energy growth and low electricty share in industrial energy use scenario
	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	High	Ref	1 scenario	High transport energy growth scenario
	High	High	Low	Low	High	Low	Low	Low	Ref	High	High	Low	1 scenario	Worst case scenario (high cost of renewable energy, low end-use energy efficiency improvements across sectors, high energy demand growth in industrial and transport sectors, and low share of electricity in industrial sector
TOTAL NUMBER OF SCENARIOS EXPLORED													222 scenarios	

Note: The building sector in India is heavily dependent on electricity. The high economic growth and low electricity cost scenario already captures a high energy demand pathway for the building sector as it captures both the income effect and the price effect adequately. This is not the case for the industrial and transport sectors, which are both heavily dependent on fossil energy, which is why a high energy demand future for these two sectors has been analysed through dedicated scenarios. Also, our scenarios already have a low penetration of electric vehicles (though it increases significantly in the future compared to 2015), so there was no requirement of separately including this in our worst case scenario.

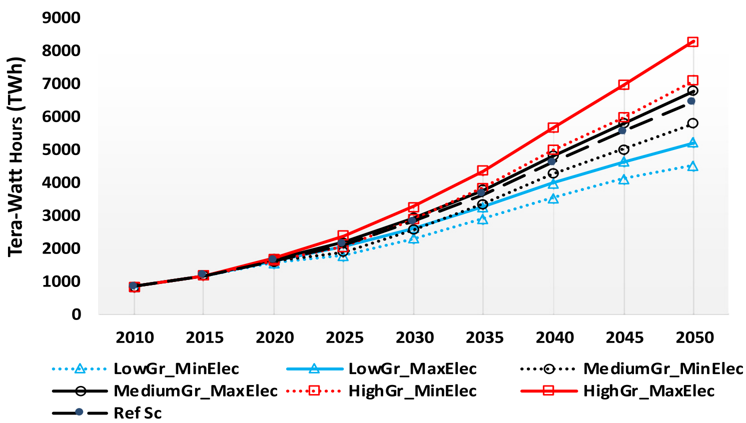

Fig. 1. Utility-based electricity generation (Ref sc and range across economic growth scenarios) – India.
Note: LowGr, MediumGr and HighGr represent economic growth assumptions, and MinElec and MaxElec represent the range across the various cost combination and end use sensitivity scenarios within these different growth paths.

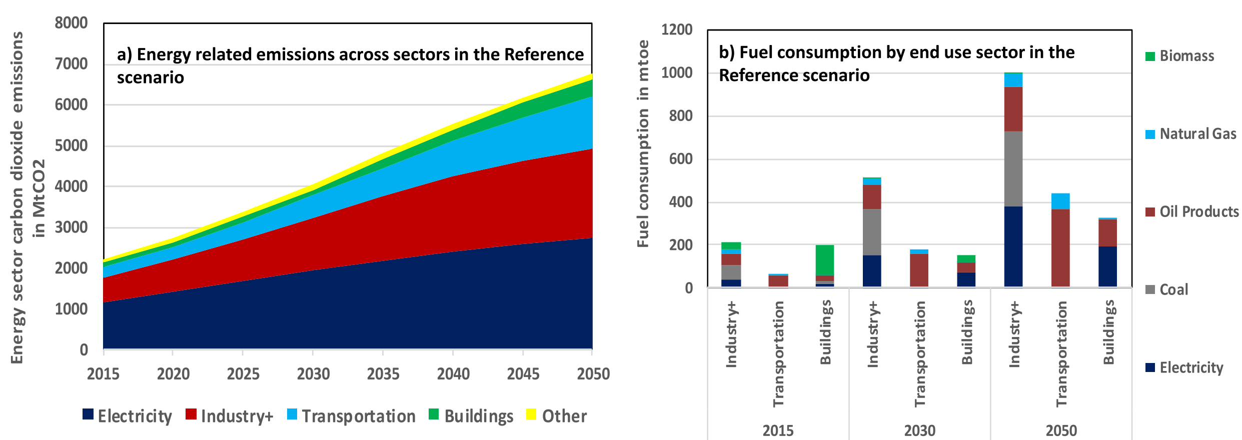

Fig. 2. Sectoral emissions and fuel use in the Reference scenario.

On the electricity generation technology mix, our uncertainty assessment finds that coal-based electricity generation would keep on increasing in the long run in the absence of a policy aimed at reducing coal consumption or taxing carbon (Fig. 3). Even under the most pessimistic scenario as assumed in our analysis (low economic growth and high relative cost of coal), coal would keep on growing. Solar electricity would still grow significantly, at a much faster pace compared to coal, across all scenarios, though penetration would be similar to coal by 2050. However, in the most optimistic scenario (high economic growth and low relative cost of solar), the growth in solar based electricity generation is phenomenal, and this technology would account for almost 50% in India's electricity production by 2050. The penetration of gas and nuclear technologies increases significantly as compared to current levels, though in the bigger picture, their role remains small given the low current base. In overall, the future of India's electricity generation mix would be driven by coal and solar energy, given the current understanding of key uncertainties related to this sector.

We also undertake a sensitivity analysis for Fig. 3 by excluding the cost of integration included in our analysis. The comparative results for two scenarios (with and without grid integration cost), presented in Appendix 2 in the supplementary material, clearly show that even a small cost of integration would have a significant impact on the future evolution of technology mix in India's electricity generation sector.

Though we find that India is well on the path to over-achieving the electricity sector specific NDC target, the way cost of competing technologies evolves, and economic growth shapes, would have significant implications for the rate of progress (Fig. 4). In the most pessimistic scenario, we find that the share of non-fossil in generation capacity would be at least 48 per cent in 2030. Under the most favourable scenario representing low cost trajectories of solar, wind and nuclear and high cost trajectories of coal and gas, and high economic growth, this share could increase to 68 per cent. Thus, irrespective of the scenario, our assessment finds that India would be able to achieve one of the NDC targets by a significant margin. The strong commitment by the Indian government to push RE in the Indian energy generation mix is showing positive results. This gives India space for enhancing its ambition for the 2030 mitigation target (Fig. 5).

In the long-run, however, how relative technology costs (including the cost of integration) and economic growth evolve would have an important bearing, with the share of non-fossil sources in generation capacity fluctuating between 57% in the most pessimistic scenario to 84% in the optimistic scenario. Long-term decarbonisation would come with its own set of additional challenges, particularly RE integration. Indian policymakers need to better understand the cost of integration. The absence of an in-depth long-term India-specific assessment only increases the uncertainty related to this aspect. As of now, there is not enough credible information to conclude if this cost would be high or low.

3.3. The impact of key uncertainties on India's progress towards the economy-wide emissions intensity NDC target, and insights for long-term decarbonisation of the economy

India's EI of GDP[6] declines as a fast pace between 2005 and 2050. A large part of this reduction in EI of GDP can be attributed to the devel-

[6] As highlighted earlier, our assessment focuses only on energy sector-related carbon dioxide emissions, which cover a large part of the overall GHG debate, CO_2 from land-use as well as other GHGs are excluded in our analysis.

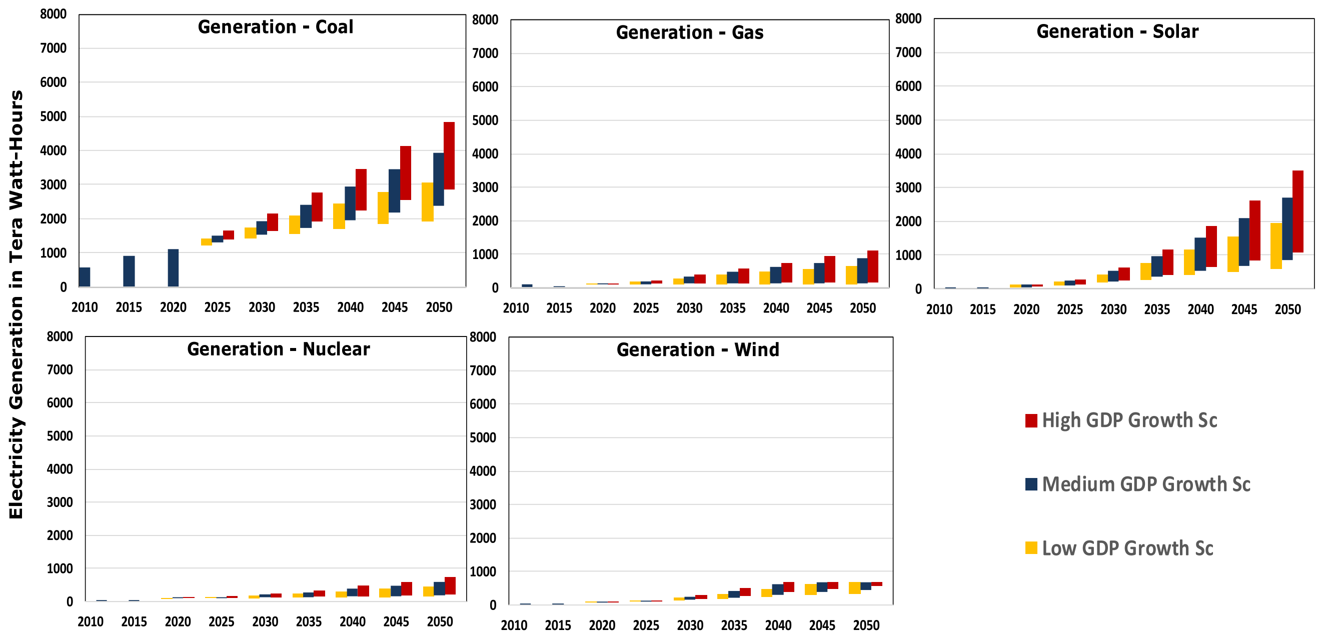

Fig. 3. Electricity generation range by technology across scenarios.

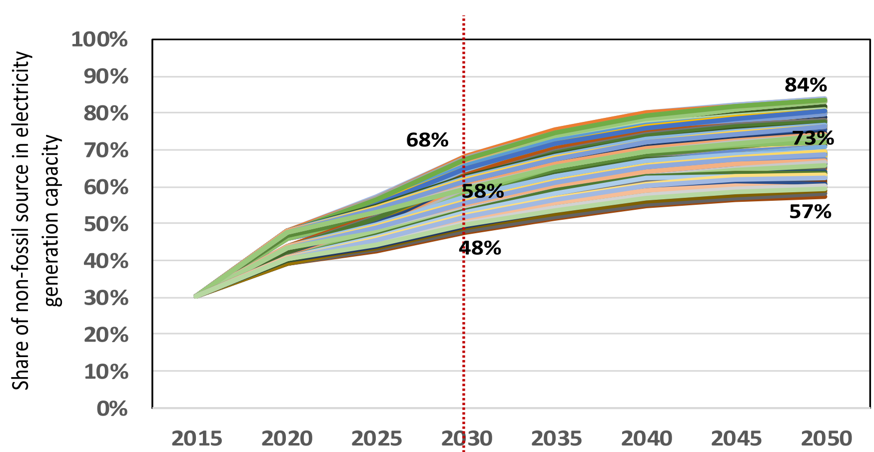

Fig. 4. Share of non-fossil energy in India's electricity generation capacity.

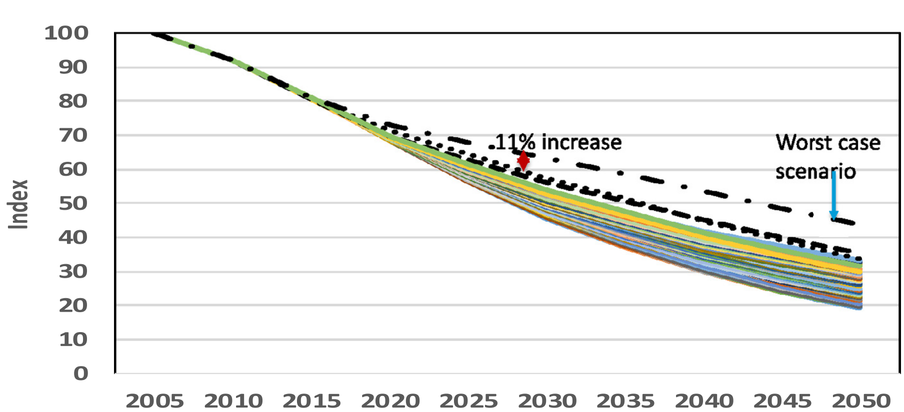

Fig. 5. Decline in energy sector-related EI of GDP across scenarios.

opments in the electricity generation sector. Between 2030 and 2050, there is also a positive impact of energy efficiency improvements, and increasing electrification of end use sectors, though the share of electricity would still be low in the industrial and transportation sectors even in 2050. We do not see any substantial shift towards low-carbon fuels and electricity in the industrial and transportation sectors in the absence of dedicated decarbonisation-focused interventions (Fig. 2b). The contribution of the transportation sector is largely through energy efficiency gains at the technology level. However, as people shift towards private modes of transport with increasing incomes, the aggregate energy and EI of this sector declines at a comparatively slower pace particularly after 2030, when private vehicle ownership increases at a fast pace.

Importantly, we find that progress towards the target of lower emissions intensity of India's GDP is highly sensitive to the developments in the industrial sector. If India is able to accelerate its manufacturing sector's growth (as is the focus of current policy), but the manufacturing sector continues to be dependent mainly on fossil fuels as it is now, and the industrial energy efficiency growth is muted, India would only marginally surpass its NDC target related to the emissions intensity of GDP. We find that in the worst-case scenario, India's EI of GDP declines by only 36% (as compared to 47% in the Ref sc) between 2005 and 2030, and by 53% (as compared to 67% in the Ref sc) between 2005 and 2050. Thus, though the target would be achieved, room for enhancing this would be very limited. A detailed assessment of India's industrial sector is necessary, and such an assessment would require a much more detailed analysis at the scale of industrial sub-sectors to distinguish the different drivers of dynamics in industries.

As compared to the industrial sector, however, a higher growth in energy demand in the transportation sector does not impact the EI of GDP significantly in 2050. This is because of the low share of this sector in India's carbon dioxide emissions, at 11% in 2015, that increases to 13% in 2030. Even a 40% increase in energy and emissions from this sector in 2030, relative to the Ref sc, would increase India's overall emissions by only 5% in 2030. Consequently, fast decarbonisation of this sector with rapid penetration of electric vehicles would have a positive, yet not game changing impact on India's emission intensity of GDP. Given the relatively low share of this sector in India's emissions, we can conclude that India's EI of GDP target is not very sensitive to the rate of energy demand from this sector, though this definitely has a minor impact.

4. Discussion and conclusion: Insights related to India's NDC enhancement and mid-century strategy

Enhancing ambition is critical to meeting the goals of a well below 2 °C world, and India is expected to play an important role in this transition towards a low carbon society. Our scenario-based uncertainty assessment shows that given the current understanding of how key uncertainties related to economy, electricity generation sector, and end-use energy demand sectors evolve, India is well on the path to exceed its electricity sector NDC target of 40% share of non-fossil sources in electricity generation capacity. There is hence room to enhance this target. In the long-run, however, the level and impact of potential integration costs on solar and wind penetration need to be better understood.

Along with good progress in the electricity generation sector towards decarbonisation, there is significant progress towards India's target of reducing the emission intensity of GDP as well. This, however, is sensitive to developments in the industrial sector- mainly a rapid increase in manufacturing growth and associated energy demand, rate of industrial energy efficiency improvements, and share of electricity in industrial energy use. India needs to better understand the state of these variables before enhancing this specific target and planning for long-term decarbonisation.

We also present a potential range for the share of non-fossil sources in India's electricity generation capacity in 2050 and reduction in economy wide carbon dioxide emissions intensity of GDP between 2005 and 2050 for informing India's Mid-Century Strategy. Based on the results related to the implications of the share of electricity in the industrial sector, and the cost of variable renewable energy, including the integration cost especially for scenarios with higher penetration of solar and wind in electricity generation, we argue that the role of power sector reforms is going to be critical for decarbonisation of India's electricity generation as well as industrial energy use.

Power sector reforms are going to be critical for India's deep decarbonisation agenda. While there could be many aspects of power sector reforms and it is a detailed subject in itself, there are three critical elements in our view most relevant from the perspective of decarbonisation. First, retail power pricing structure needs to be reformed along with eliminating cross subsidy in retail power prices. Electricity pricing policies in India favour residential consumers with subsidised tariffs while penalising commercial and industrial consumers with higher tariffs for compensating for the subsidy in the residential sector. High electricity prices for the industrial sector has led to a low share of electricity in India's industrial energy use. Electricity is used by industrial consumers only where it is essential, and there is no effective technical substitute. Unless the retail pricing structure is fixed through reforms, one can expect a low share of electricity in industrial energy use, and limited progress at best towards long-term decarbonisation. Importantly, this reform also has the potential for securing financial viability of India's distribution companies that are perennially in debt, an objective being vigorously and unsuccessfully pursued by India's policy makers since years. Distribution companies need to be given real power to levy the required prices. In the process, it has to be ensured that pricing reforms do not hurt the consumers in the lowest income category and that the transition is not unjust. Second a new market design needs to be adopted to ensure that renewable energy is not penalized due to existing incentive structures in the sector. Perverse incentives and the complex political economy of this sector are already impacting the penetration of solar and wind in India, with power generation companies and distribution utilities seeing a higher penetration of these sources as a threat to their balance sheets. A key reform would have to be in terms of the market design of power sector. Currently, the two big pieces in planning for power generation and dispatch are managing base-load and peak-load. This is consistent with a power sector that relies heavily on non-variable fuels like fossils or nuclear. For a future with heavy reliance on variable renewable energy, the role of base-load in the market design has to be much lower, and effectively disappear for a future with more than 80%-90% VRE share in generation. Power companies should bid in different segments: base-load, mid-peak, peak, and super-peak- based on the economics of generation. Power generation prices, intuitively, would be highest for the super peak segment where even coal power plants can operate with low capacity factors if they are compensated adequately. A transparent market design has the potential to fix the perverse incentives that exist today against variable renewable energy. This would also imply that integration of variable RE in the grid is appropriately incentivised, and that the government is able to socialise the cost of RE integration as required for supporting VRE into the grid. The third important piece of reform is related to promoting grid-connected distributed energy. There is a significant potential for grid-connected roof-top solar in India, and the government has devised supporting policies. This, however, has not been successful yet as the idea of distributed energy hasn't mainstreamed itself in the larger community of investors and users. It is the large centralised investments that still attract investors, and residential consumers haven't been excited by the prospect of becoming prosumers. Harnessing this opportunity would imply unlocking a lot of finance that is owned by households and could be deployed through innovative business models devised by entrepreneurs. Unless the government makes distributed energy as a must-do investment by large companies, say a fixed share of their total investments, and engages with the citizens, this opportunity would never be harnessed to its potential.

The key challenges for decarbonisation can be resolved only through effective power sector reforms, and in its absence, long-term deep decarbonisation of the Indian economy would only be an ambition on paper, given that the two sectors (electricity and industry) together contribute to almost three-fourth of India's energy related carbon dioxide emissions currently.

We conclude by highlighting that given its role in global carbon emissions, India might need to take on additional burden for the benefit of the world, for the world to achieve the global target of 'well below 2 °C temperature increase'. One way to demonstrate leadership by taking additional burden for the world would be to adopt a peaking year for its power sector emissions as a part of its Mid-Century Strategy while recognising that additional efforts would be required to achieve this ambitious target even though the progress in this sector has been impressive. Enhancing mitigation ambition, where ever possible, should be a clear choice by Indian policy makers, communicating continued leadership by India in the global climate mitigation debate.

Declaration of Competing Interest

None.

Acknowledgements

We thank Dr P C Maithani (Ministry of New and Renewable Energy, Government of India), Mr Amit Kumar Kulshreshtha and Mr Ashwini Kumar Verma (National Thermal Power Corporation, India), and Mr Pankaj Batra (Central Electricity Authority, Ministry of Power, Government of India) for their inputs and comments on our work. Our research and understanding has greatly improved because of their comments and questions. We thank Dr Robert Pietzcker (Potsdam Institute for Climate Impact Research, Germany) for his detailed comments and guidance on the issue of cost of integrating variable renewable energy. Our understanding of this issue would not have been the same without Dr Pietzcker's help. We thank Prof P R Shukla (Former Professor, Indian Institute of Management, Ahmedabad, India), for his views on India's energy and climate policy and methodological approaches during many discussions, his views have shaped our understanding of India's climate policy as well as our present research work. We thank Dr Prasoon Agarwal (International Renewable Energy Agency, UAE), Dr Tilman Altenburg (German Development Institute, Germany), Mr Suman Bery (MasterCard Center for Inclusive Growth, India), Dr Navroz Dubash (Centre for Policy Research, India), Prof Amit Garg (Indian Institute of Management, Ahmedabad, India), Dr Yu Nagai (Central Research Institute of Electric Power Industry, Japan) and Prof Masahiro Sugiyama (Tokyo University, Japan) for their comments across various stages of our study. We thank Indian private sector experts from CleanMax Solar, First Solar Power India, Fourth Partner Energy, Hero Futures Energies, SunSource Energy, ReGen Powertech, ReNew Power Ventures, Suzlon Energy, and Vikram Solar for their perspectives on India's renewable growth story and future uncertainties across different discussions. We thank colleagues from the Council on Energy, Environment and Water – Kapardhi Bharadwaj, Tirtha Biswas, Kanika Chawla, Karthik Ganesan, Vaibhav Gupta, and Neeraj Kuldeep for providing relevant information and their perspectives on the developments in India's electricity and energy sectors. We thank participants of the workshop on 'Long-Term Climate Policy of Japan and Asia, Tokyo University, Japan, 14-15 December 2017' and participants of the roundtable discussion on 'Sustainable Development, Uncertainties, and India's Climate Policy, hosted by CEEW, India, 21st February 2018' for their comments on our study. We thank the following experts for providing detailed comments on our study's first draft: Anshu Bharadwaj, CSTEP, India; Sudhir Chella Rajan, IIT Chennai, India; Srihari Dukkipati, Prayas Energy Group, India; Karthik Ganesan, CEEW, India; Dr Arunabha Ghosh, CEEW, India; Yeshika Malik, CSTEP, India; Robert Pietzcker PIK, Germany; Priyadarshi R Shukla, former Professor, IIM Ahmedabad, India; Dr E Somanathan, ISI, India; Ashok Srinivas, Prayas Energy Group, India; Henri Waisman, IDDRI, France. We thank Dr Jae Edmonds and Dr Leon Clarke (Pacific Northwest National Laboratory/Joint Global Change Research Institute, USA) for access to the Global Change Assessment Model and support provided during the course of our study.

Funding: This work was supported by the John D. and Catherine T. MacArthur Foundation, USA for providing funding support for our study under Grant No. 16-1603-150739-CLS.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2021.100031.

References

[1] UNFCCC, 2016. Aggregate effect of the intended nationally determined contributions: an update. United Nations Framework Convention on Climate Change
[2] MoEFCC (Ministry of Environment, Forest, and Climate Change), 2015. India's Intended Nationally Determined Contribution: Working towards Climate Justice, New Delhi: Government of India.
[3] Republic of the Marshall Islands. Marshall Islands and 22 other countries issue Declaration for Ambition. Accessed at https://www.docdroid.net/DmkO5kd/180621-declaration-for-ambition-rmi-press-release-declaration-final-combined.pdf
[4] P.R. Shukla, S. Dhar, D. Mahapatra, Low carbon society scenarios for India, Climate Policy 8 (2008) S156–S176.
[5] P.R. Shukla, V. Chaturvedi, Sustainable energy transformations in India under climate policy, Sustain. Dev. 21 (1) (2013) 48–59.
[6] P.R. Shukla, et al., Pathways to Deep Decarbonization in India, SDSN-IDDRI, Paris, 2015.
[7] R. Mathur, India's energy challenges and sustainable development, Yojana (August 2016) (2016) 16–20.
[8] S. Byravan, et al., Quality of life for all: A sustainable development framework for India's climate policy reduces greenhouse gas emissions, Energy Sustain. Dev. 39 (2017) 48–58.
[9] Planning CommissionReport of the Expert Group on Low Carbon Strategies, Planning Commission, New Delhi, 2014.
[10] IEAWorld Economic Outlook, International Energy Agency, Paris, 2015.
[11] S. Bery, et al., Energizing India: Towards a Resilient and Equitable Energy System, Sage, s.l., 2016.
[12] NITI-IEEJ, 2017. Energizing India, New Delhi: NITI Aayog, India and IEEJ, Japan.
[13] V. Chaturvedi, P.N. Koti, R. Sugam, K. Neog, Cooperation or Rivalry? Impact of alternative development pathways on India's long-term electricity generation and associated water demands, Energy 192 (2019) 116708.
[14] D. Gupta, F. Ghersi, S.S. Vishwanathan, A. Garg, Macroeconomic assessment of India's development and mitigation pathways, Clim. Policy 20 (7) (2020) 779–799.
[15] N.D. Rao, J. Min, R. DeFries, S. Ghosh-Jerath, H. Valin, J. Fanzo, Healthy, affordable and climate friendly diets in India, Global Environ. Change 49 (2018) 154–165.
[16] TERITransitions in Indian Electricity Sector, The Energy and Resources Institute, New Delhi, 2017.
[17] G. Shrimali, Tirumalachetty & S, Renewable energy certificate markets in India—A review, Renew. Sustain. Energy Rev. (26) (2013) 702–716.
[18] K. Chawla, M. Aggarwal, Anatomy of a Solar Tariff- Understanding the Decline in Solar Bids Globally, CEEW, New Delhi, 2016.
[19] J. Jethani, Renewable Policy Framework and Wind Energy Programme in India, Ministry of New and Renewable Energy, New Delhi, 2016.
[20] A. Garg, PR. Shukla, S. Parihar, U. Singh, B. Kankal, Cost-effective architecture of carbon capture and storage (CCS) grid in India, Int. J. Greenhouse Gas Control 66 (2017) 129–146.
[21] A. Garg, Pro-equity effects of ancillary benefits of climate change policies: a case study of human health impacts of outdoor air pollution in New Delhi, World Dev. 39 (6) (2011) 1002–1025.
[22] A. Ghosh, K. Ganesan, Rethink India's Energy Strategy, Nature 521 (2015) 156–157.
[23] N. Dubash, R. Khosla, Neither brake nor accelerator: assessing India's climate contribution, Econ. Political Wkly. 17 (October, L(42)) (2015) 10–14.
[24] Kann, A. & Weyant, J. P., 1999. Approaches for Performing Uncertainty Analysis in Large-scale Energy/Economic Policy Models, s.l.: EMF Working Paper 14.6, June 1999, Stanford University.
[25] B.v.d. Zwaan, A. Seebregts, Endogenous Technological Change in Climate-Energy-Economic Models: An Inventory of Key Uncertainties, s.l, ECN - Energy research Centre of the Netherlands, 2002.
[26] W.E. Walker, et al., Defining Uncertainty: A conceptual basis for uncertainty management in model-based decision support, Integr. Assess. 4 (1) (2003) 5–17.
[27] W. Short, T. Fergusen, M. Leifman, Modeling of uncertainties in major drivers in U.S. electricity markets, s.l, Conference Paper NREL/CP-620-40451, September 2006, 2006.
[28] M. Labriet, R. Loulou, A. Kanudia, Modeling uncertainty in a large scale integrated energy- climate model, in: J.A. Filar, A. Haurie (Eds.), International Series in Operation Research & Management Science. s.l., Springer Science, 2010, pp. 51–77.
[29] J.E. Bistline, Essays on Uncertainty Analysis in Energy Modeling: Capacity Planning, R&D Portfolio Management, and Fat-Tailed Uncertainty, s.l. PhD Thesis, November 2013, Stanford University, 2013.

[30] Y. Cai, A.H. Sanstad, Model uncertainty and energy technology policy: the example of induced technical change, Comput. Oper. Res. 66 (2014) 362–373.
[31] Gillingham, K. et al., 2015. Modelling Uncertainty in Climate Change: A Multi Model Comparison, s.l.: National Bureau of Economic Research, NBER Working Paper 21637, October 2015.
[32] D.L. McCollum, et al., Quantifying uncertainties influencing the long-term impacts of oil prices on energy markets and carbon emissions, Nat. Energy 1 (7) (2016) e16077.
[33] J. Rogelj, et al., Understanding the origin of Paris Agreement emission uncertainties, Nat. Commun. 8 (2017) 15748.
[34] J.F. Clarke, J.A. Edmonds, Modelling energy technologies in a competitive market, Energy Econ. (April) (1993) 123–129.
[35] P. Kyle, S.H. Kim, Long term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands, Energy Policy 39 (2011) 3012–3024.
[36] J. Edmonds, et al., Energy and technology lessons since Rio, Energy Econ. 34 (2012) S7–S14.
[37] P.R. Shukla, V. Chaturvedi, Low carbon and clean energy scenarios for India: Analysis of targets approach, Energy Econ. 34 (2012) S487–S495.
[38] M. Hejazi, et al., Long term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework, Technol. Forecast. Soc. Change 81 (2013) 205–226.
[39] S. Mishra, et al., Transportation module of Global Change Assessment Model (GCAM): Model Documentation, s.l.: Institute of Transportation Studies, University of California, Davis, California, USA, 2013.
[40] V. Chaturvedi, et al., Capital investment requirements for greenhouse gas emissions mitigation in power generation on near term to century time scales and global to regional spatial scales, Energy Econ. 46 (2014) 267–278.
[41] H. McJeon, et al., Limited impact on decadal-scale climate change from increased use of natural gas, Nature 514 (7523) (2014) 482–485.
[42] G. Iyer, et al., Diffusion of low-carbon technologies and the feasibility of long-term climate targets, Technol. Forecast. Soc. Change 90 (2015) 103–118.
[43] V. Chaturvedi, M. Sharma, Modelling long-term HFC emissions from India's residential air-conditioning sector: exploring implications of alternative refrigerants, best practices, and a sustainable lifestyle within an integrated assessment modelling framework, Clim. Policy 16 (7) (2016) 877–893.
[44] K. Calvin, et al., The SSP4: A world of deepening inequality, Global Environ. Change 42 (2017) 284–296.
[45] V Chaturvedi, PR Shukla, K Ganesan, A perspective on the cost of nuclear energy, Resurgence of Nuclear Power: Challenges and Opportunities for Asia, Springer Nature Singapore Pte Ltd, 2017 Edited by Nanda Kumar J, G Pant, and RB Grover.
[46] P. Kyle, S.H. Kim, Long term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands, Energy Policy 39 (2011) 3012–3024.