Sustainable Development, Uncertainties, and India's Climate Policy

Pathways towards Nationally Determined Contribution and Mid-Century Strategy

Report | April 2018

VAIBHAV CHATURVEDI,
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CEEW
THE COUNCIL

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A report on 'Sustainable Development, Uncertainties, and India's Climate Policy: Pathways towards Nationally Determined Contribution and Mid-Century Strategy.'

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About CEEW

The Council on Energy, Environment and Water (http://ceew.in/) is one of South Asia's leading not-for-profit policy research institutions. The Council uses data, integrated analysis, and strategic outreach to explain – and change – the use, reuse, and misuse of resources. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public.

In 2018, CEEW once again featured across nine categories in the '2017 Global Go To Think Tank Index Report', including being ranked as South Asia's top think tank (14th globally) with an annual operating budget of less than USD 5 million for the fifth year in a row. In 2016, CEEW was also ranked 2nd in India, 4th outside Europe and North America, and 20th globally out of 240 think tanks as per the ICCG Climate Think Tank's standardised rankings. In 2013 and 2014, CEEW was rated as India's top climate change think-tank as per the ICCG standardised rankings.

In over seven years of operations, The Council has engaged in more than 180 research projects, published well over 110 peer-reviewed books, policy reports and papers, advised governments around the world over 400 times, engaged with industry to encourage investments in clean technologies and improve efficiency in resource use, promoted bilateral and multilateral initiatives between governments on more than 50 occasions, helped state governments with water and irrigation reforms, and organised more than 210 seminars and conferences.

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Anjali Ramakrishnan is a former Programme Associate at CEEW. Her research focused on climate mitigation policies, renewable energy tariffs, and integration costs. Her interests also include energy demand assessment and consumer behaviour analysis in light of the energy-climate linkages.

Prior to her association with The Council, Anjali worked with The Energy and Resources Institute (TERI) and India Infrastructure Publishing Limited in different research capacities. She worked on a range of projects from energy access in rural India, fossil fuel subsidy programme evaluations, and power sector analysis to geopolitics of energy supply in the Bangladesh–China–India–Myanmar Forum for Regional Cooperation BCIM region.

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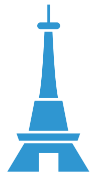
List of Abbreviations

AC	air conditioner
AME	Asian Modelling Exercise
BAU	business as usual
BCIM	Bangladesh-China-India-Myanmar
BEV	battery electric vehicles
CAGR	compounded annual growth rate
CCS	Carbon capture and storage
CEEW	Council on Energy, Environment and Water
CLEAN	Clean Energy Access Network
CSP	concentrated solar power
CSTEP	Centre for Study of Science, Technology and Policy
CUF	capacity utilisation factor
EI	emissions intensity
EIA	environmental impact assessment
EMF	Energy Modelling Forum
FCV	fuel cell vehicles
FDI	foreign direct investment
GCAM	Global Change Assessment Model
GCF	Green Climate Fund
GDP	gross domestic product
GHG	greenhouse gas
GoI	Government of India
GW	gigawatt
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HG	high cost of gas
ICCG	Initiative on Climate Change policy and Governance
IESS	India Energy Security Scenarios
IIM	Indian Institute of Management
IIT	Indian Institute of Technology
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISI	Indian Statistical Institute
LCOE	levelised cost of electricity
LED	light-emitting diode
LPG	liquified petroleum gas

MNRE	Ministry of New and Renewable Energy
NDC	Nationally Determined Contribution
NITI	National Institution for Transforming India
O&M	operations and maintenance
PAT	Perform, Achieve and Trade
PIK	Potsdam Institute for Climate Impact Research
PKT	passenger kilometres travelled
PV	photovoltaic
RE	renewable energy
SDG	Sustainable Development Goals
TERI	The Energy and Resources Institute
UE	utilisation effect
VRE	variable renewable energy
VTT	value of travel time

Executive Summary

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. In India, climate policy – framed traditionally in the context of development and poverty reduction – has been framed recently in terms of India's approach to sustainable development. Such framing is reflected in India's 'Nationally Determined Contribution (NDC)' and in domestic mitigation policies. India's NDC, now a part of the Paris Agreement, was submitted in October 2015. The underlying analysis was undertaken and completed much earlier. In addition, India, along with all other signatories, has to submit its 'Mid-Century Strategy' under the Paris Agreement for long-term decarbonisation. Together, the NDC and Mid-Century Strategy aim at achieving the long-term goals of the Paris Agreement.



Together, the NDC and Mid-Century Strategy aim at achieving the long-term goals of the Paris Agreement

Since India's NDC targets were announced, a lot has changed in the economy and in the power generation sector. Particularly, the costs of solar and wind-based electricity, which have declined substantially on the back of global developments in technology, decline in the cost of financing for renewable energy (RE) projects, as well as interventions by the Government of India (GoI) through the competitive reverse auctioning process. The cost of coal-based power generation – lowest across electricity generation technologies in the past – is expected to increase due to desulphurisation and denoxification of power plants, among other reasons. Developments in the past two years in international gas markets and nuclear energy deals have not much improved the penetration of these technologies in India's energy mix. Investors and policymakers need to deal with a host of uncertainties in deciding actions and interventions.

India's progress towards the NDC target, *'to achieve 40 percent cumulative electric power installed capacity from non-fossil-based energy resources by 2030'* depends not only on the cost of RE technologies but also on the relative costs of all key technologies in the portfolio. The cost of power generation technologies depends on the capital cost of technology, cost of finance, and the cost of operations and maintenance (O&M), including cost of human resource. Each of these, in turn, depends on a host of factors.

Solar power generation cost in India is significantly impacted by the high cost of finance, which represents the inherent risks for these projects – mainly off-taker risk, in the current scenario. Overnight capital cost is also impacted by the cost of solar panels, which is determined by global supply and demand. Currently, India imports a large share of solar panels from China. The cost of imported panels has been declining due to a glut in production and supply, it is argued, and project developers might see prices increase again. There are similar uncertainties in the variables that underlie and impact the cost of production in all power-producing technologies – nuclear, natural gas, or coal-based electricity generation.

Developments in the electricity generation sector, efficiency improvements, and energy use in end-use sectors impact India's other NDC target: *'reduce emission intensity of its gross domestic product (GDP) by 33-35 percent by 2030 from [the] 2005 level'*. It is important to understand the role of end-use sectors to appreciate the long-term evolution of India's carbon dioxide (CO_2) emissions and to devise strategies to minimise these and simultaneously address sustainable development concerns and national priorities.

In our assessment, no study in the past four or five years considers the uncertainties inherent in the evolution of key electricity generation technologies in a robust way for India

Growth rate of electricity generation and energy demand in end-use sectors could impact progress towards both these quantitative targets as a low-growth scenario might limit the opportunity for a fast transition. Economic growth is an important determinant of overall growth in electricity demand, as well as energy consumed in end-use sectors. Economic growth is impacted by a number of inter-related variables including, but not limited to, private consumption and savings, private and public investment, export competitiveness, foreign direct investment (FDI), national government policy, the governance regime, and the state of the global economy. Any combination of these factors can lead the country on to one of several different economic growth pathways and significantly impact India's long-term energy and emissions scenarios.

Several studies attempt an understanding of the challenges in India's transition towards a low-carbon pathway. However, in our assessment, none in the past four or five years considers the uncertainties inherent in the evolution of key electricity generation technologies in a robust way, or the potential impact of the cost of integrating variable renewable energy (VRE) – that is, solar and wind energy – and its implications on India's long-term electricity supply system; as well as no studies that test the impact of key uncertainties on the energy demand side, within the context of NDC. Also, there is currently no analysis of India's progress towards NDC targets and long-term emission trajectories in alignment with the Mid-Century Strategy to be submitted under the Paris Agreement.

To understand India's progress towards NDC targets our research focuses on the impact of two key uncertainties in the electricity generation sector: cost of power generation technologies and economic growth; and the impact of uncertainties related to energy efficiency and behaviour of energy demand in the end-use sectors. 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.

- How would India's electricity generation-mix evolve in an uncertain future? And how would it be impacted by the cost of integrating VRE?
- What are the implications of key uncertainties on India's progress towards the NDC target of 40 per cent share of non-fossil sources (all forms of RE and nuclear energy) in electricity generation capacity?
- In the absence of dedicated decarbonisation policies, how would India's long-term CO_2 emissions evolve? By 2030, India aims to reduce the emissions intensity (EI) of its GDP by 33 per cent to 35 per cent over 2005; how would this target be affected by its emissions and uncertainties in the end-use sectors over the long term?
- How would India's energy and emissions future be affected by a sectoral climate policy (coal cess) and by an alternative, economy-wide climate policy compatible with the '2 Degrees C target'?

- What are the insights for India's Mid-Century Strategy to be submitted under the Paris Agreement?
- How can India's climate policy be aligned with sustainable development and national priorities, including equitable access for its citizens to the global carbon space?

To answer these research questions, we use the Global Change Assessment Model (GCAM, IIM Ahmedabad version), an integrated assessment modelling framework with a detailed energy sector module used extensively for global and India-specific analysis. In the GCAM, electricity can be generated based on nine fuel types (coal, gas, oil, nuclear, solar, wind, hydro, biomass, combined heat and power [CHP]), which could be associated with multiple technologies, e.g. photovoltaic (PV) and concentrated solar power (CSP) for solar. Our assessment excludes rooftop solar, mini grids, and other decentralised electricity sources, as these are not the focus of our analysis, though their importance in providing energy access cannot be overemphasised.

Demand for electricity generation and other forms of energy is determined in end-use sectors where increases in income raise penetration of electricity-based technologies (air-conditioning, for example) and other-fuel based technologies (oil-based cars, for example). Alternative technologies compete on relative costs and efficiencies to provide energy for any given service in end-use sectors – for example, electric cars compete with oil-based cars to provide passenger transportation services in the transportation sector; and light-emitting diode (LED) bulbs compete with fluorescent and incandescent lightbulbs to provide lighting services in the buildings sector.

Within the GCAM, the share of any technology – electricity generation or end-use sector – is based on its cost relative to the cost of all other technologies. The modelling time frame is up to 2100, though we provide detailed insights related to energy systems only until 2050. For emissions and climate policy analysis, we provide CO_2 emissions pathways for up to 2100.

The value of scenario modelling-based uncertainty assessment

There could be alternative ways of modelling uncertainties. A large number of models used for energy and climate policy analysis are deterministic in nature. There are ways of using deterministic models for uncertainty assessment. The first and most basic approach is that of sensitivity analysis, wherein the parameter (or parameters) of interest is (are jointly) varied, while holding all other variables constant. A comparatively comprehensive approach is that of scenario analysis. Scenarios consist of combinations of different assumptions about possible states of the world, for example high economic growth with low energy efficiency improvements. Scenario analysis has been extensively used to inform energy and climate policy. Propagating uncertainty through a deterministic model is a more sophisticated approach to assess uncertainties, as compared to scenario analysis. The simplest approach to this involves providing joint distribution on a selection of input parameters and propagating this uncertainty through to the model output. An even more sophisticated approach, which addresses the shortcomings of deterministic models, is the modelling approach of sequential decision-making under uncertainty represented through stochastic modelling frameworks. In this approach, models determine optimal policies at more than one point in time, with learning happening based on the outcome in one period, and being used for decision-making in other periods. This approach is best suited for determining 'hedging strategies', which balance the risk of waiting with those of premature action.

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*". We use the approach of scenario analysis within a deterministic model, GCAM. This is a useful approach, apt for our purpose, which requires 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 combinations 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 India specific literature.

There are several uncertainties related to the cost of technologies in the electricity generation sector. Be it solar-based electricity, nuclear-based electricity, or coal-based electricity, investors and stakeholders have differing opinions on the future cost trajectories for these technologies. Our research aims at deriving a robust understanding of India's electricity generation future, given these uncertainties. To incorporate these uncertainties into 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 yields 72 unique pathways, which represent permutations of underlying cost pathways for the five technologies (for a given economic growth scenario). We decided the low- and high-cost trajectories (for all five technologies) and medium-cost trajectories (for solar and wind only) of all these technologies on the basis of our assessment and with inputs from experts. These experts are officials from the Ministry of New and Renewable Energy, Government of India (MNRE, GoI) and the National Thermal Power Corporation (NTPC, a leading public-sector conglomerate); private developers of solar and wind energy power plants; and sector experts. We analyse each of these 72 unique cost pathways under three economic growth scenarios for encompassing uncertainties related to economic growth. Our analysis encompasses 216 scenarios to find key insights into the future of India's electricity generation sector in the absence of dedicated decarbonisation-related interventions and to understand their implications for India's NDC and Mid-Century Strategy. The number of scenarios is not important in itself; the uncertainty assessment is key. We use it in our aim to contribute to the literature and inform policymaking in India.

Uncertainties abound in the larger energy system. Some relate to energy prices – oil price, for example – and others to how energy demand behaves in end-use sectors. From the perspective of India's energy and emission trajectories, the electricity generation sector is critical. While for understanding the change in emission intensity, end-use sectors are also important. We analyse uncertainty in the electricity generation sector with a focus on the cost of electricity generation technologies and economic growth, for informing India's progress towards NDC target of 40 per cent share of non-fossil energy sources in electricity generation capacity. Along with the 216 scenarios described above, we also analyse uncertainties in the rate of efficiency improvement in the end-use sectors, as well as the behaviour of energy demand in India's industrial and transport sectors, for capturing these key uncertainties and informing our understanding of India's progress towards the target of 33-35% decrease in emission intensity of GDP between 2005 and 2030. Our approach is only one of several possible approaches – researchers could conceptualise other ways of analysing uncertainty; for example, as described earlier, one can undertake a probabilistic analysis of uncertainties in the electricity generation sector.

In storyline-based scenarios, like the 'high renewable' or 'high nuclear' scenario, technology penetration is exogenously pushed for achieving specified technology targets and finding its implications for electricity mix and associated emissions. These are very useful, however, we have chosen uncertainty-based scenario assessment for our analysis, as it provides a different yet complementary analytical view, and is currently missing in India-focused literature. We explore the implications of key uncertainties across technologies and economic growth for the electricity generation and end-use sectors. Through this approach, we let the model inform us about the direction in which India's electricity and energy system is moving, on the basis of economic growth, technology cost, energy efficiency, and energy demand behaviour, given our current understanding of how the key uncertainties around these will evolve in the future.

Understanding implications of integrating variable renewable energy (VRE)

As India moves towards a higher share of VRE in the grid, there could be challenges in managing the transition. Europe has the richest experience and analytical knowledge base of dealing with VRE integration. We undertake a review of papers focusing on this challenge as faced in Europe, and take inputs from European scientific expertise to develop an understanding of the long-term cost of integrating VRE in India. Through our review of the literature, we glean key insights into modelling VRE and policy responses. Our review focuses on the analysis of greenfield systems, so that the insights are applicable to any electricity system that will see significant expansion, or those that will see large-scale retirement of old stock and building of new capacity for replacing retired stock. What learnings from the European analysis are applicable for India? Of course, there cannot be a one-to-one translation of a Europe-focused analysis for India, but some broader insights can still be derived.

The cost of integrating VRE mainly comprises: (i) *grid infrastructure costs*, as additional investment into transmission grids is required to pool VRE and demand over large areas; (ii) *grid balancing cost*, arising from uncertain forecasts and the need for more flexible operation of thermal power plants; and (iii) *utilisation effect (UE)*, due to reduced utilisation of thermal power plants.

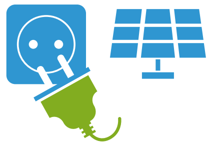
The first insight is that even under a well-planned system, UE due to reduced capacity utilisation factor (CUF) will be the dominant part of the VRE integration cost for at least up to 50 per cent VRE share.

Second, up to this share, even a significant decline in the cost of storage technology for India will not mean that the cost of integrating VRE will necessarily be small.

Third, as India's long-term plans are based mainly on solar energy, we have to understand how well solar-based generation – and also wind energy, as this has implications for the integration cost – correlates across India's geographical mass and time. Only an India-focused study can answer these questions in specific detail.

In our core set of 216 scenarios for electricity generation, we focus solely on key uncertainties in electricity generation and exclude VRE integration cost from the framework. Alongside, we present learnings from analysing the same set of scenarios after incorporating VRE integration cost into the framework. Based on learnings from European literature focused on greenfield systems that can be translated to the Indian context, we infer that the VRE integration cost should lie in the broad range of 16 per cent to 24 per cent of levelised cost of coal at 20 per cent VRE share in electricity generation and 21 per cent to 50 per cent of levelised cost of coal at 40 per cent VRE share. For our analysis of the implications of VRE integration cost, we assume an integration cost within these ranges.

We describe our approach of incorporating VRE integration cost in our India-specific modelling analysis, and highlight that this is one of the first such attempts for India in our knowledge. Our approach is basic and static across scenarios; we envisage that future research attempts will build on it. We highlight the limitations of this but irrespective of the limitations, the broad insights derived from this analysis hold well. We aim to analyse the implications of internalising VRE integration cost into total VRE generation cost for India's electricity generation future – not support or reject the argument that VRE should be taxed based on the system-wide integration cost. To mitigate climate change and achieve higher penetration of VRE, it is imperative not to tax it.



Our approach of incorporating VRE integration cost in our India-specific modelling analysis is one of the first such attempts for India in our knowledge

Who bears the cost of integration?

Our uncertainty analysis reveals that if VRE integration cost was not included in the framework – that is, budgetary support is provided for covering this cost instead of it being borne by VRE producers – India would see a rapid growth in solar energy in the short and long run, which would outpace any other competing technology (Figure ES1a). The median share of solar energy in utility-based electricity generation across our three economic growth scenarios (median value across 72 cost pathways within each economic growth scenario) ranges from 17 per cent to 19 per cent in 2030 and 42 per cent to 50 per cent in 2050. This, however, does not mean that coal-based electricity generation will peak and decline; it will grow, though much less than the growth in the past decade. Only under the most pessimistic scenario – low economic growth, along with high cost of coal, and low cost of all other competing technologies – do we see coal-based generation peaking in 2035 and then declining. All other technologies – including wind and nuclear – will have only a limited role. Electricity generation from wind energy will also see secular growth, and capacity additions will be higher than coal, but its overall potential is limited unless offshore wind (not included in our assessment) becomes cost-competitive rapidly. Gas-based electricity will not be able to play a significant role in India's power sector unless there is a significant shift in international gas market dynamics and the cost of gas-based power falls. The same can be said for nuclear energy-based power generation in India, as nuclear power plants are becoming expensive to import, and progress on domestic reactors has been slow at best.

This analysis excludes the added value of balancing and grid services that gas turbines can easily provide; therefore, the calculated values likely underestimate the optimal amount of gas power plants for scenarios with higher VRE shares.

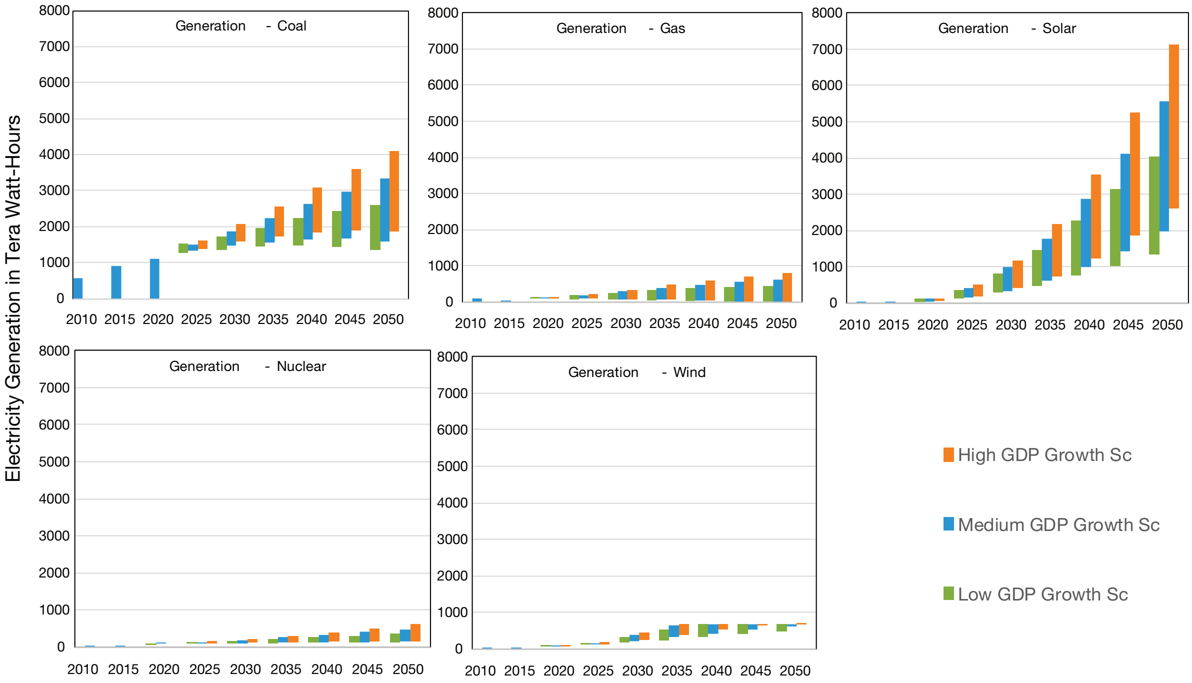
Hydroelectricity is driven exogenously in our assessment. We assume – based on the India Energy Security Scenarios (IESS) of NITI Aayog[1] – that hydro-based power will grow by 25 per cent between 2015 and 2030, and further by 40 per cent between 2030 and 2050. Hydropower is the cheapest source of power, but its growth is muted due to many social and environmental challenges. We do not see it playing a big role in meeting India's electricity needs in the long term, though it could play an important role as a storage technology for integrating a higher share of VRE in the grid. Other technologies like biomass are included in our assessment but would be marginal in the overall scenario.

1 India Energy Security Scenarios (IESS) of the National Institution for Transforming India (NITI Aayog). http://iess2047.gov.in

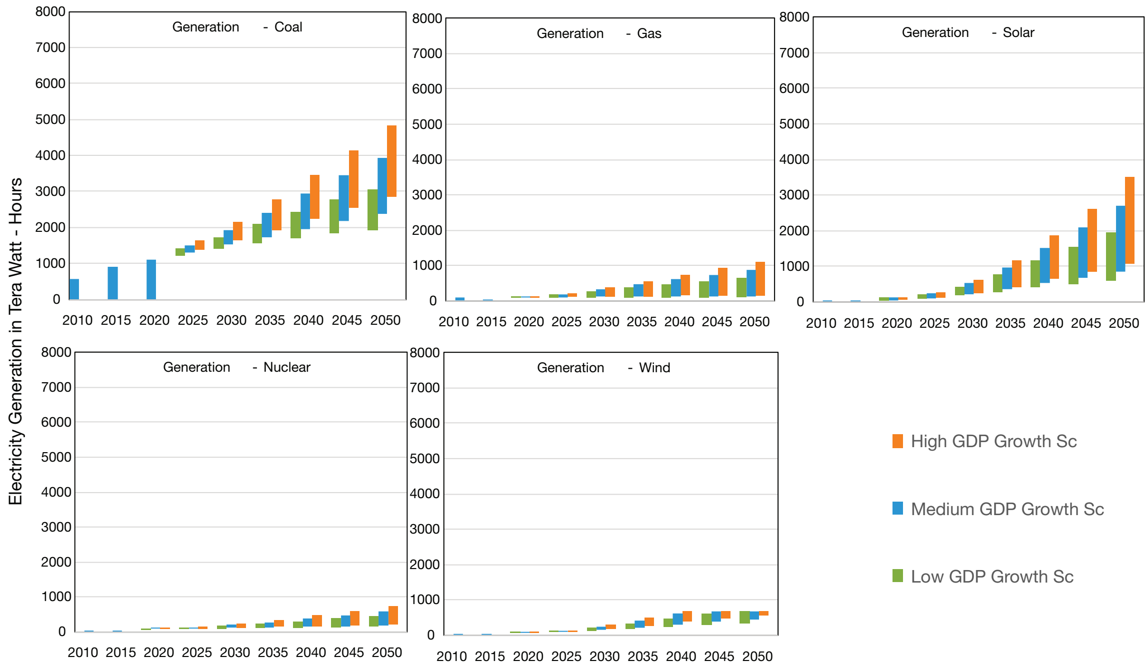
If VRE producers bore the cost of integration – though they would pass it on to consumers – coal-based electricity generation would keep on increasing in the long-run in the absence of a policy aimed at reducing coal consumption (Figure ES1b). Solar electricity would still grow significantly, though penetration would be much lower than if VRE costs were not levied on producers. The penetration of gas and nuclear technologies increases significantly under such a scenario, though in the bigger picture their role remains small, as when VRE integration cost is not levied on producers. Overall, the inclusion of VRE integration cost in the framework has important implications for the future of India's electricity generation mix.

Figure ES1: Electricity generation by key technologies (range across scenarios) – India

a) Electricity generation range by technology WITHOUT grid integration cost levied on VRE producers



b) Electricity generation range by technology WITH grid integration cost levied on VRE producers



Source: CEEW analysis, 2018

Under scenarios with high VRE share, who bears the cost of integration would be strongly influenced by market design and government policy. Our analysis shows that the share of VRE would grow much faster if the integration costs are covered through budgetary support, rather than them being borne by the producers. Increased penetration of solar and wind comes at the expense of government resources.

The *reference scenario* in our study is defined as medium economic growth, medium cost trajectory for solar and wind, low cost trajectory for coal and nuclear, and high cost trajectory for gas. In the reference scenario, if there is budgetary support for absorbing the integration cost for solar energy, the total subsidy outlay in 2015 prices would be about INR 215,000 crore (USD 33 billion) between 2015 and 2030 and over INR 3,750,000 crore (USD 575 billion) between 2030 and 2050. As compared to this, the subsidy received by power distribution companies in India, in current prices, was INR 36,758 crore (USD 5.65 billion) in 2013-14, INR 45,584 crore (USD 7.01 billion) in 2014-15, and INR 55,283 crore (USD 8.51 billion) in 2015-16. A part of the required budgetary support could be supported through dedicated taxes like coal cess. From 2010–11 to 2016–17, the coal cess collected was of the order of INR 56,600 crore (USD 9 billion). The amount collected in the next 15 years could be big enough to provide significant – if not enough – financial support to address the cost of integrating VRE. This financial support would lead to an increase in the share of VRE in electricity generation to 52 per cent in 2050 – against 30 per cent if the integration cost is levied on VRE producers.

We consider another scenario: the government bears the cost of integrating VRE only partially, producers bear no cost, and a new market design is adopted under which coal power plants bear the cost in terms of reduced CUF (UE, the largest component of VRE integration cost). In this scenario, solar-based electricity would grow significantly, and new coal additions would be severely hit by 2030 and onwards, as reduced CUF would raise the cost of coal-based electricity. This does not mean that investing in coal necessarily becomes unprofitable – only that there will be a new market design and architecture. Under this design, coal power could meet the requirements of mid-peak and peak load and would be much more expensive to produce, but still profitable. For pushing a higher share of VRE, such a market design might be imperative, but continued use of coal for power generation for meeting any market requirement would lead to continual increase in CO_2 emissions from the power generation sector. Alternatively, the role of coal-based power plants as peaking plants could also be performed by gas-based power plants, and only a detailed analysis can highlight the potential role of these competing fossil technologies under a new market design. Ultimately, the political economy of VRE integration cost, and who bears this cost, matters for the future of India's electricity generation mix.

NDC target for non-fossil energy share in India's electricity generation mix could be met as well as enhanced, but at a cost

Because of the drop in solar (and wind) generation costs, our uncertainty-based assessment finds that NDC targets would be achieved, and even exceeded. If the VRE integration cost, as assumed, is levied on producers, we expect the share of non-fossil sources in India's electricity generation capacity to be at least 48 per cent in 2030 and 59 per cent in 2050; and, if not, at least 58 per cent in 2030 and 74 per cent in 2050. If the costs of solar and wind and storage technologies drop sharply in the next decade, the share of non-fossil sources in generation capacity could be 66 per cent to 77 per cent by 2030. The strong commitment of the GoI to push RE in the Indian energy generation mix is expected to show positive results.

The increase in the share of non-fossil sources, however, comes at a cost. The decline in costs of solar-based electricity has not been driven merely by the global drop in the capital cost of solar technology; government intervention has changed the market direction. Fiscal interventions like feed-in tariffs and accelerated depreciation heavily supported the initial stages of wind energy deployment in India. The game-changing intervention, arguably, was the announcement of the targets of 100 gigawatt (GW) of solar and 60 GW of wind for 2022. This announcement signalled to investors and other stakeholders the government's long-term commitment towards enhancing the share of these technologies in India's electricity generation mix. The government has adopted several fiscal and non-fiscal measures. Two fiscal measures have been the exemption from wheeling charges and a must-run status for wind and solar power plants, along with the continuation of accelerated depreciation (at reduced rates) for wind power plants. Some major non-fiscal interventions – creation of solar parks, announcement of green highways, and refinement in contract structures – have led to a streamlined market for both technologies and, in turn, reduced risks and financing cost, particularly for solar power projects. The strong policy signal – and fiscal and non-fiscal interventions – have further led to, continued decline in the costs of these technologies. Solar and wind energy is set to gain a higher share in India's energy mix because the government has borne the budgetary and administrative burden.

The share of non-fossil energy sources in electricity generation capacity in 2030 will be much higher than 40 per cent, India's stated NDC target, because the cost of technology has declined in the past three years and the GoI has proactively set RE policies. India can raise its ambition for the 2030 mitigation target, but there will be challenges, particularly RE integration. The NDC targets related to the share of non-fossil sources as well as that of reduction in India's EI of GDP could be enhanced. However, Indian policymakers need to deal with the cost of integration (as well as other uncertainties in the end-use sectors), which our analysis focuses on. There is no in-depth, long-term, India-specific assessment, and therefore not enough credible information to conclude if the integration cost would be high or low – only much uncertainty.

Carbon dioxide emissions intensity of GDP falls rapidly under current aggressive policies, but is highly sensitive to energy efficiency improvements in the end-use sectors

Our long-term outlook shows that India's energy sector-related CO_2 emissions will keep growing as the economy becomes wealthier. Per capita emissions would still be lower than the global average, even in the long run, unless countries around the world pursue deep mitigation. In our *reference scenario*, the electricity and industrial sectors play a major role in India's energy sector-related CO_2 emissions, with respective shares of 40 per cent and 32 per cent in 2050. The share of transportation sector is lower at 19 per cent in 2050, even though CO_2 emissions from this sector grow at the fastest rate across all emitting sectors.

Though emissions grow, we find that by 2030 energy sector-related CO_2-EI of GDP reduces by 48 per cent to 54 per cent across all 216 scenarios, and by 70 per cent to 81 per cent by 2050, relative to 2005. This is due to the significant progress in the electricity generation sector, as well as strong energy efficiency improvements in the end-use sectors. This progress is only marginally impacted if the VRE integration cost (as we assume) is incorporated in the analysis. Strong fiscal and non-fiscal policies adopted by the GoI for pushing RE in India's electricity generation mix, as well as for enhancing energy efficiency in the end-use energy sectors, would lead to a higher reduction in India's EI of GDP than the NDC target. We expect India's economy to continue reaping the benefits of these interventions in terms of declining EI of GDP in the long run.

We find that our result of decline in emissions intensity (EI) of GDP is significantly sensitive to the uncertainties in the end-use sectors, particularly the industrial sector

We, however, find that our result of decline in EI of GDP is significantly sensitive to the uncertainties in the end-use sectors, particularly the industrial sector. We capture the key uncertainties in the end-use sectors: lower rate of efficiency improvements in each of the three end-use sectors, higher growth rate of energy demand in the industrial and transportation sectors, and a lower increase in electricity penetration in the industrial sector. We find that if energy energy efficiency across sectors improves at a lower rate, industrial and transport energy demand grows at a fast pace, and electricity's share in industrial energy use does not increase, the emission intensity of India's GDP will increase by 11 percentage points in 2030, relative to the reference scenario. That is, in the worst- case scenario as assessed by us, India's EI of GDP will decline only by 37 per cent between 2005 and 2030. This effect is mainly because of uncertainties related to energy growth, electricity share, and efficiency improvements in India's industrial sector. We don't find a significant impact of reduction in energy efficiency improvements in the building and transport sectors on India's EI of GDP, mainly due to the rebound effect. Higher energy efficiency in these sectors, however, is bound to improve social welfare as well as reduce the total cost of the energy supply system.

India's NDC submission pertains to GHG EI of GDP, but our analysis includes only CO_2 from energy systems and not from land-use change, or other GHGs. In our assessment, the overall GHG EI change between 2005 and 2030 could be higher by over 1-2 per cent, due to increase in hydrofluorocarbon emissions, as compared to the energy sector CO_2 EI of GDP. The energy sector is the largest contributor to GHGs, and other GHGs with a significant share are not expected to grow at a fast pace.

India could bear disproportionate responsibility for the world, but at the cost of equity

Enshrined in climate negotiations from the beginning, the principle of *historical responsibility* implies that countries historically responsible for the high growth in GHG emissions – and, consequently, for the problem of global warming and climate impacts – should bear the cost for solving it. This is reflected in the other key principle, *common but differentiated responsibility*, which is that all countries irrespective of historical responsibility for GHG emissions should share the burden of addressing climate change, but in proportionate terms. Historical responsibility, along with technical and financial capabilities, should determine the differentiated burden of mitigation across countries. These principles are the foundation of the demand from developing countries for an equitable share of the global carbon space.

As against equity-based allocation, the techno-economic analysis within GCAM-IIM shows that if India were to mitigate its CO_2 emissions to align with the '2 *Degree C temperature increase limit*', it would have a total CO_2 emission budget of 145 $GtCO_2$ between 2010 and

2100. Techno-economic analysis implies that global emission mitigation burden is distributed on the basis of cost-effectiveness criteria, that is, emissions should be mitigated where it is cheapest to mitigate. This is determined by the global distribution of cost of mitigation technologies in all supply and demand sectors across countries, and the associated mitigation potential. This does not necessarily mean that the country has to bear the mitigation cost, which can be partially or fully supported through international carbon trading, green climate fund, or any other financial transfer mechanism to India from abroad to compensate for the cost of deep mitigation. This emission budget of 145 $GtCO_2$, based on techno-economic analysis, is different from budget-based on considerations of equity and justice, which have not been analysed. The corresponding global CO_2 emission budget is 1,000 $GtCO_2$ between 2010 and 2100, as highlighted by the Intergovernmental Panel on Climate Change (IPCC).

For adhering to this national emissions budget consistent with the 2 Degrees C target, India could peak its CO_2 emissions in 2030 and then go on a declining trajectory; economy-wide emissions would need to decline at 4.5 per cent per annum between 2030 and 2100 in this case. The national CO_2 emissions budget constraint based on techno-economic analysis implies a significant near-term transformation of the energy system. India would need to take on this inequitable burden to share the global responsibility of emission mitigation. India could alternatively choose to postpone the peaking year to 2040. In that case, it would need to reduce emissions by over 13 per cent per annum to adhere to the same carbon budget. Postponing the peaking year is possible in principle, but it would require a very rapid pace of transformation beyond 2040. Indian experts and stakeholders need to discuss the implications and feasibility of this pace of transformation.

For a 2 Degrees C consistent pathway based solely on techno-economic considerations, the share of non-fossil sources in India's electricity generation capacity will need to be at least 98 per cent in 2050, and the energy sector's CO_2 EI of India's GDP needs to decline by over 90 per cent between 2005 and 2050.

Continued investments in fossil energy would lead to significant stranded assets in the future, if India takes on a disproportionate emissions mitigation burden for meeting 2 Degrees C carbon budget constraint, irrespective of whether emissions peak in 2030 or 2040. Irrespective of the peaking year, India would need to make significant efforts to bear the responsibility for mitigating CO_2 emissions, at the cost of equity in sharing the mitigation burden.

We experiment – along with an economy-wide climate policy – with a sectoral coal cess of INR 4,000/ton coal (USD 60/ton coal) starting from 2020. Such a high cess would mitigate coal use in electricity generation and resultant emissions of CO_2, but would not significantly reduce economy-wide emissions. A sectoral policy like the coal cess, however, can certainly be pursued in conjunction with other sectoral policies focused on transformations in the industrial and transportation sectors, and the cess collected could be used to fund interventions in end-use sectors.

Industrial emissions next target, scope in transportation smaller

For both mitigation pathways, given our current understanding of mitigation potential and cost of mitigation technologies, the biggest transition would need to happen in the electricity generation and industrial sectors; the role of the transportation sector would be smaller. Our current understanding about the transportation sector could change if the costs of electric vehicles decline rapidly. Regardless of the peaking year, the industrial sector will have a more important role in India's mitigation strategy than the transportation sector. Electrification of the industrial sector is key to this transition, as over 80 per cent of energy use in India's industrial sector is dependent on fossil fuels (coal, oil, and natural gas), and only dedicated interventions aimed at increasing electrification can change this significantly.

The perform, achieve, and trade (PAT) scheme is a useful beginning, but it will not significantly dent India's industrial emissions as it focuses only on industrial energy efficiency. The industrial sector must be the next focus of India's emission mitigation policy, centred largely on electricity generation and partially on the transportation sector. It is critical to devise ways for reducing the dependence of India's industrial sector on fossil energy, while ensuring that India achieves rapid growth in manufacturing and associated jobs, as well as enhancing the international competitiveness of this sector. The buildings sector will not be a big source of direct emissions in India, but efficiency improvements would play an important role in reducing electricity consumption and indirect emissions.

Is climate policy compatible with other sustainable development objectives?

India's climate policy is framed within the context of sustainable development and national priorities. For informing mitigation choices, it is important to understand the implications for energy access, jobs, industrial competitiveness, and water – among other sustainable development objectives and national priorities. To assess trade-offs between climate mitigation, sustainable development, and national priorities, we propose a 'CEEW Synergies and Trade-Off Matrix' (Table ES1).

We find that even a stringent climate policy will not impact electricity access, as incomes in urban and rural India will increase at least five or six times by 2050 relative to 2015 and raise per capita residential consumption of electricity four times in rural households and 3.4 times in urban households by 2050 relative to 2015. This implies that basic electricity-related services will be met in urban and rural areas by 2050 but leave ample room for growth in more expensive energy services like air-conditioning in rural areas. Even doubling electricity prices – due to a carbon tax – in this period will not impact electricity access, although the social welfare of low-income categories might be reduced, and will need to be analysed.

We see a beneficial situation in terms of reduced water demand at the macro level with a higher penetration of renewables, but a huge spread of solar under the stringent climate policy could pose serious challenges in arid regions of India, which also offer the best solar potential.

Requirement for land could be an impediment. We see land requirement increasing 80 per cent in 2050 under the stringent climate policy; land acquisition has always been a challenge for India. By 2050, India's population is also expected to increase at least 20 per cent, and land will become increasingly scarce in the future – requiring strategic long-term planning of land use development and management. Some of the increased demand could be accommodated in unused wastelands, but the larger issue needs to be analysed in detail.

Table ES1: 'CEEW Synergies and Trade-Off Matrix' for aligning sustainable development, national priorities, and mitigation pathways

2050							
		Reference Sc	Low Growth Sc	High Growth Sc	Coal Cess Sc	Cap 2030 Sc	
Per Capita Income	Urban	17063	13482	20109	17063	17063	USD, 2015 prices
	Rural	6332	4094	9123	6332	6332	USD, 2015 prices
Emissions	Total emissions	6785	5346	8248	4853	1663	$MtCO_2$
	Per capita emissions	4.09	3.22	4.97	2.93	1.00	tCO_2/capita
Electricity Access	Per capita urban residential electricity consumption	1.38	1.20	1.51	1.39	1.41	MWh/capita
	Per capita rural residential electricity consumption	0.46	0.34	0.59	0.46	0.46	MWh/capita
Electricity Cost	Average generation cost for new investments	2.63	2.62	2.62	2.53	2.31	INR/kWh, 2015 prices
Jobs	Total jobs related to energy generation sector	13.10	9.31	16.77	17.71	27.51	Million FTE
	Wind related jobs	0.35	0.35	0.35	0.32	0.36	Million FTE
	Ground mounted solar jobs	5.77	3.92	7.56	9.39	15.20	Million FTE
	Solar PV module manufacturing jobs	4.35	2.96	5.69	7.08	11.45	Million FTE
	Coal	2.43	1.94	2.95	0.64	0.15	Million FTE
	Gas	0.02	0.02	0.03	0.03	0.00	Million FTE
	Nuclear	0.17	0.13	0.21	0.25	0.34	Million FTE
Water	Water withdrawal-Electricity	8.28	6.69	9.92	4.23	2.13	Billion Cubic Metres
Land	Land requirement	17398	14483	19948	21735	31235	Thousand Acres
	PV	8366	5683	10950	13608	22024	Thousand Acres
	CSP	63	43	82	103	173	Thousand Acres
	Wind	8350	8255	8175	7643	8574	Thousand Acres
	Coal, oil and gas	619	501	740	382	464	Thousand Acres
Coal	Coal consumption (2021-50)	37.80	33.56	42.55	21.93	18.15	Billion Tonnes

Source: CEEW Analysis, 2018

If the stringent climate policy is adopted, there will be significant job loss in the coal sector, especially in states that depend heavily on coal for revenue and employment generation. At the macro level, this will be more than compensated through employment generation in the solar sector, but it is not necessary that the states that lose coal-based jobs and revenue will gain from the solar boom. Also, the nature of jobs and skills required will be very different;

Indian policymakers need to strategise for such a scenario. As the solar market matures, and progress occurs in automation, the quantum and nature of jobs in the sector could change. There is a significant opportunity for creating manufacturing capacity-related jobs, but it will be lost if India continues to import a large share of its solar panels.

Air pollution from thermal power plants is an important concern, but the desulphurisation and denoxification of flue gas proposed in power plants will largely address this issue. The use of coal in industries and of oil in transportation is critical from the perspective of local air pollution, and should be included in studies focusing on these sectors. We expect this to be a significant co-benefit of climate policies.

Next steps to reduce uncertainty

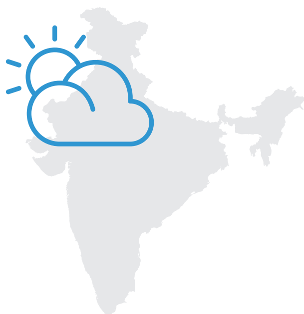
We estimate India's progress towards two key NDC targets using scenario-based uncertainty assessment. We analyse the implications on India's energy systems and emissions of a stringent climate policy that is aligned with the 2 Degrees C target, and also the synergies and trade-offs of a stringent climate policy with sustainable development and national priorities. These estimations and analyses will help inform India's Mid-Century Strategy to be submitted under the Paris Agreement.

We conclude by re-emphasising two points: First, there is a need for an India-specific study on estimating long-term VRE integration cost. Such a study should incorporate information on spatial solar and wind generation potential; its correlation across space and time; expected load curves in future years; storage costs; and potential for upcoming technologies like CSP with storage. It can inform a market design that accommodates a higher share of VRE and suggest conditions in which conventional plants can play the role required by technical constraints on the system or by policy choices.

Second, India's electricity generation sector is making significant strides towards decarbonisation, but there is not enough in-depth analysis or understanding of the potential, choices, constraints, and trade-offs in mitigating industrial emissions or of the impact on competitiveness and jobs. The next set of analyses should focus on industrial sectors; use the CEEW Synergies and Trade-Off Matrix; and inform policy on the alignment of sustainable development, national priorities, and climate mitigation goals.

1. Introduction

In October 2016, the world reached a consensus on its fight to limiting the impact of rising carbon emissions on the climate. The ratification of the Paris Agreement by 127 countries signified a collaborative willingness of signatories to work towards domestic processes, and enabled the agreement to come into force. The fundamental objective of the agreement is to limit global average temperature increase to 'well below 2 ˚C and pursue efforts to reach 1.5 ˚C', implying the need to shift from a fossil fuel-based economy to a low-carbon one. The agreement is the second big leap taken by the world towards mitigating climate change after 197 countries signed and ratified the Kyoto Protocol in 1997.



Together, the NDC and Mid-Century Strategy aim at achieving the long-term goals of the Paris Agreement

India's role is becoming increasingly important in the global climate regime. India's per capita energy consumption is very low compared to the developed world, but it is expected to grow at a significant pace, and impact global GHG emissions and climate change. Climate policy in India has always been contextualised within the framework of development and poverty reduction. More recently, it has been framed within India's approach to sustainable development, and this is reflected in India's NDC as well as domestic mitigation policies. The commitment to an internationally binding climate agreement, Paris Agreement at COP21, has showcased India's willingness to increase its efforts for mitigating global warming.

Of the eight NDC targets submitted by India for the period 2021–2030 (MoEFCC, 2015b), 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 will be subject to transfer of technology and access to low-cost international financing from Green Climate Fund (GCF). The targets for bringing the economy to a low-carbon pathway have been adopted to balance its domestic priorities along with the need to limit rise in emissions. The target of achieving 175 gigawatt (GW) of installed capacity in renewable energy (RE) by 2022 could be argued as being ambitious, but could address multiple objectives of energy access, clean energy development, and provide economic opportunities through jobs and investments. India must also submit its Mid-Century Strategy under the Paris Agreement for long-term decarbonisation. Together, the NDC and Mid-Century Strategy aim at achieving the long-term goals of the Paris Agreement.

Several studies and assessments focus on India's transition towards cleaner energy sources and decarbonisation. Some consider larger economy-wide transitions (Planning Commission, 2014; Dubash and Khosla, 2015; Ghosh and Ganesan, 2015; IEA, 2015; Shukla, et al., 2015; Bery, et al., 2016; Chaturvedi, et al., 2017; NITI-IEEJ, 2017; TERI, 2017). Others focus on challenges specific to RE (Shrimali, et al., 2013; Chawla and Aggarwal, 2016; Jethani, 2016). A few discuss climate policy within the sustainable development framework (Shukla, et al., 2008; Shukla and Chaturvedi, 2013; Mathur, 2016; Byravan, et al., 2017). These perspectives are reflected in India's NDC and domestic mitigation policies.

India's (I)NDC was submitted in October 2015, while the underlying analysis was undertaken prior to that. Since India's NDC were announced, a lot has changed in the power generation sector and in the economy. Particularly, the cost of solar and wind have declined on the back of developments in technology and interventions by the GoI through the auctioning process. The cost of coal-based power generation has increased – owing to desulphurisation and denoxification of power plants, among other reasons. Developments in international gas markets, and nuclear energy deals have not yielded positive results for India in the past two years in terms of growth in the penetration of these sources of energy.

Of all carbon dioxide (CO_2) emissions by the energy sector, a major proportion is from electricity generation. The NDC targets '40 per cent share of non-fossil energy sources by 2030'. Progress towards this target depends not only on the cost of RE technologies but the relative costs of all key technologies in the portfolio. Also, the growth of the electricity generation sector could impact the progress towards this target, as a low growth scenario might limit the opportunity for faster transition. Developments in the electricity generation sector, and efficiency improvements and energy use in end-use sectors impact India's other NDC target: '*reduce emission intensity of its gross domestic product (GDP) by 33-35 percent by 2030 from [the] 2005 level*'. It is important to understand the role of end-use sectors to appreciate the long-term evolution of India's carbon dioxide (CO_2) emissions and to devise strategies to minimise these and simultaneously address sustainable development concerns and national priorities. Our research focuses on the impact of two key uncertainties in the electricity generation sector: cost of power generation technologies and economic growth; as well as on the impact of uncertainties related to energy efficiency and behaviour of energy demand in the end-use sectors, to understand India's progress towards two key NDC targets.

The cost of power generation technologies depends on the capital cost of technology, cost of finance, and operations and maintenance (O&M) cost, including human resource cost. Each of these in turn depends on a host of factors; for example, solar power generation cost in India is significantly impacted by the cost of finance. High cost of finance for solar power projects in India represents the inherent risks for these projects – mainly off-taker risk, in the current scenario (Chawla, 2016). On the other hand, overnight capital cost is significantly impacted by the cost of solar panels, which is determined by global supply and demand. Currently, India imports a large share of its solar panels from China. It has been argued that the cost of panels has been declining due to a production glut, and project developers might see prices increasing again if the glut eases. There are similar uncertainties in the variables that underlie and impact the cost of production in all power-producing technologies – nuclear, natural gas, or coal-based electricity generation. Economic growth is impacted by a number of inter-related variables including, but not limited to, private consumption and savings, private and public investment, export competitiveness, foreign direct investment (FDI), national government policy, the governance regime, and the state of the global economy. Any combination of these factors can lead the country on to one of several different economic growth pathways and significantly impact India's long-term energy and emissions scenarios.

Since the analysis underpinning India's NDC were undertaken, almost three years have passed; it is imperative to consider again – in the light of changes in underlying assumptions – India's future energy and carbon pathways. In our knowledge, only a couple of studies have been undertaken in the recent past – TERI (2017) and NITI-IEEJ (2017). The former focuses on the electricity generation sector until 2030, while the latter is a compilation of four studies on various aspects of India's energy system and analyses scenarios for up to 2050. These studies highlight some important insights for India's energy future. In the past four or five years, several other studies have attempted an understanding of the challenges in India's transition towards a low-carbon pathway, but none– in our assessment – considers the uncertainties inherent in the evolution of key electricity generation technologies, or the potential impact of the cost of integrating variable renewable energy (VRE) – that is, solar and wind energy – and its implications on India's long-term electricity supply system; as well as no studies that test the impact of key uncertainties on the energy demand side, within the context of NDC. Also, there is currently no analysis of India's progress towards NDC targets and long-term emission trajectories in alignment with the Mid-Century Strategy to be submitted under the Paris Agreement. There is a need to assess the future pathways for India's electricity generation and end-use energy consumption sectors.

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.

- How would India's electricity generation mix evolve under an uncertain future? And how would it be impacted by the cost of integrating VRE?
- What are the implications of key uncertainties on India's progress towards the NDC target of 40 per cent share of non-fossil sources (all forms of RE along with nuclear energy) in electricity generation capacity?
- In the absence of dedicated decarbonisation policies, how would India's long-term CO_2 emissions evolve? By 2030, India aims to reduce the emissions intensity (EI) of its GDP by 33 per cent to 35 per cent over 2005; how would this target be affected by its emissions and uncertainties in the end-use sectors over the long term?
- What are the implications of a sectoral climate policy (coal cess) on India's energy and emissions future? And of an alternative, economy-wide climate policy compatible with the 2°C target?
- What are the insights for India's Mid-Century Strategy under the Paris Agreement?
- How can India's climate policy be aligned with sustainable development and national priorities, including equitable access for its citizens to the global carbon space?

In the next sections, we present a discussion on modelling uncertainties, the scenario framing and methodology; key insights from our review on the literature on VRE integration cost; results from our uncertainty assessment; the political economy of VRE integration cost; and mitigation policy scenarios. We conclude by presenting a synergies and trade-off matrix for aligning sustainable development, national priorities, and climate policy in India – and by highlighting the insights for India's Mid-Century Strategy.

2. Understanding and Modelling Uncertainties

Researchers have highlighted the importance of developing a better understanding of uncertainties in the energy and climate policy modelling analysis

Uncertainties prevail across all sectors of the economy. The context for our analysis is set in the energy and climate space, where policy makers and stakeholders need to address uncertainties at multiple levels and across different aspects. Researchers have highlighted the importance of developing a better understanding of uncertainties in the energy and climate policy modelling analysis. Zwaan and Seebregts (2002), through their focus on modelling technical change in energy models, emphasise that in modelling analysis of climate change, the presence of different kinds of major uncertainties should be appropriately recognised, classified, quantified, and reported. They also emphasise it is imperative for energy modellers to not just report single modelling results (e.g. emissions, costs, etc.), but also present an uncertainty range within which each of these findings can be expected to vary. Gillingham et al. (2015) in a detailed analysis of modelling uncertainties highlight that the economics of climate change involves a vast number of uncertainties, complicating both the analysis and developments of climate policy. The study, based on inter-model comparisons, looks at model and parametric uncertainties for population, total factor productivity, and climate sensitivity. Cai and Sanstad (2014) discuss the challenges policy makers face while understanding results from different models, leading to model-based uncertainties, and apply learnings from model uncertainty assessment in macroeconomics to energy modelling. This paper highlights that a unifying theme in macroeconomic analysis is identification of decision rules that are robust to model-based uncertainty. This could be an approach to derive robust learnings from energy models as well. Decision makers, be it policy makers or business leaders, have to deal with uncertainties, and need to devise strategies that are robust to these.

Researchers have used models to analyse uncertainties related to specific sectors and variables within the larger framework of the modelling energy systems. McCollum et al. (2016) focus on the implications of oil price for energy and carbon markets within an uncertainty framework, and highlight that this uncertainty could have a major impact on global energy systems. Interestingly, they find that whether or not gas and oil prices decouple, is the biggest uncertainty. Short et al. (2006) focus on the uncertainties in the electricity generation market. The paper highlights that one reason scenarios are developed is that the model behind scenarios cannot predict, with confidence, one or more of the market drivers. There are a host of factors - natural, social, political and technological - that are outside the models, yet are significant determinants of the future. Rogelj et al. (2017) systematically explore possible interpretations of NDC assumptions resulting in estimated emissions from 47 to 63 $GtCO_2e$ yr^{-1}, and show that this uncertainty has critical implications for the cost and feasibility of achieving the mitigation goals of the Paris Agreement. These examples illustrate the variety of issues and perspectives researchers have analysed and presented while dealing with the theme of uncertainties through energy and climate policy modelling.

Gjorjiev et al (2017) discuss an interesting aspect of the planning horizon, which has implications for the modelling methodology for incorporating uncertainties. The authors argue that long-term problems involve technology investments and capacity expansion. Models looking at these decisions with long-term impact typically analyse the expected net present value of decisions under uncertainty. On the other hand, there are models dealing with short-term issues, generally characterised by physical operations. For example, modelling intermittent renewable resources for short term intervals, say one day discretised in 48 time steps, is short-term modelling issue and provides information for a different kind of decision as compared to a long-term decision.

Walker et al. (2003) provide an extremely useful and illustrative discussion for understanding the different ways in which uncertainties can be understood and classified, within the context of modelling for decision support. They highlight that even within the different fields of decision support (e.g. policy analysis, engineering risk analysis, etc.), there is neither a commonly shared terminology, nor an agreement on generic typologies of uncertainties. There is a difference between the modellers' view of uncertainty, and the decision makers' view of uncertainty. The modellers' view is related to the accumulated impact of uncertainties on the model outcome and the robustness of insights, and conclusions of the decision support exercise; the policy makers' view on the other hand is about how to value the outcome in the context of other competing objectives, priorities and interests. We summarise the key insights from this paper below.

Walker et al. (2003), through a process of consultation and discussion, present three dimensions of uncertainties: (i) the location of uncertainty - where the uncertainty manifests itself within the model complex; (ii) the level of uncertainty - where the uncertainty manifests itself in the spectrum between deterministic knowledge and total ignorance; and (iii) the nature of uncertainty - whether the uncertainty is due to lack of our knowledge, or whether it is due to an inherent variability in the system, or the phenomena, being described. The authors argue that the ultimate goal of decision making under uncertainty should be to reduce the undesired impacts from surprises, rather than hoping to eliminate surprises or undesirable impacts

The location of uncertainty could be in the context (boundaries of the modelled system), in the model (model structure related or uncertainty due to computer implementation of the model), as well as in the inputs (description of reference system as well as the external forces that drive changes in the reference system which are either in control or not in control of the policy makers, including parameter uncertainty).

The level of uncertainty varies from deterministic knowledge to complete ignorance. Complete determinism is an ideal situation that is unattainable. Statistical uncertainties are those that can be described in statistical terms, e.g. measurement uncertainties in data due to sampling error or inaccuracies in measurement. Statistical uncertainties are also related to uncertainties in measuring probabilities in a stochastic model. Contrary to statistical uncertainty, scenario uncertainty implies that there is a range of possible outcomes, but it is not possible to formulate the probability of any one outcome occurring because the mechanisms leading to these outcomes are not well understood. The demarcation from statistical uncertainty to scenario uncertainty is essentially a shift from a consistent continuum of outcomes expressed stochastically to a range of discreet possibilities, where an option to be evaluated has to be chosen without assigning any likelihood to it. Scenarios can be manifested, among other ways, as a range in outcomes due to a combination of different underlying assumptions. Finally, there is uncertainty due to ignorance. This could be reducible through conducting further research, could be ignorance where neither research or knowledge can provide sufficient knowledge.

The nature of uncertainty could be epistemological due to the imperfection of our knowledge which can be reduced through more research. Or it could be because of inherent variability due to either inherent randomness of nature, variability in human behaviour, the chaotic and unpredictable nature of societal and institutional processes, or technological surprises with new developments or breakthroughs in technologies.

Ultimately, Walker et al. (2003) suggest that modelers should consider the key uncertainties they want to model and capture within the framework of harmonised typologies as presented by them. This would help in identifying, prioritising, and communicating uncertainty to improve the model-based decision support.

There could be various approaches to modelling uncertainties. Kann and Weyant (1999) present a very useful discussion on the variety of approaches to perform uncertainty analysis in large scale models. They suggest that the variation in results from different models can be attributed to: (a) different assumptions about the process exogenous to the models; (b) different assumptions about process endogenous to the model and their internal dynamics; (c) difference in value judgements; and (d) different approaches for simplifying the model for computational ease. A mix of these underlying factors leads to variations in results across models, and these should be better understood through an uncertainty assessment.

Kann and Weyant (1999) suggest that stochastic dynamic optimisation theoretically represents the most comprehensive approach of analysing uncertainties in the given context of energy modelling, but this approach usually does not pass the test of practicality. This has motivated other types of uncertainty analysis to inform decision making. The simplifications as compared to stochastic dynamic optimisation include reducing model detail, restricting how uncertainty is modelled, or restricting how optimal choices are made. Other researchers also argue that stochastic models are better than deterministic models to understand uncertainties better, especially when a hedging strategy needs to be devised.

A large number of models used for energy and climate policy analysis are deterministic in nature. Kann and Weyant (1999) discuss ways of using deterministic models for uncertainty assessment. The first and most basic approach is of sensitivity analysis, where in the parameter (or parameters) of interest is (are jointly) varied, while holding all other variables constant. A comparatively comprehensive approach is that of scenario analysis. Scenarios comprise combinations of different assumptions about possible states of the world, for example, high economic growth with low energy efficiency improvements. Scenario analysis has been extensively used to inform energy and climate policy. Propagating uncertainty through a deterministic model is an even more sophisticated approach to assess uncertainties. The simplest approach to this involves providing joint distribution on a selection of input parameters and propagating this uncertainty through to the model output.

A strong assumption in all the approaches for converting deterministic models to probabilistic models, as described above, is that the optimal policy is determined only once, and there is no learning happening, even though uncertainty is incorporated in the framework. A more realistic representation, as Kann and Weyant (1999) as well as Short et al. (2006), Labriet et al. (2010) and Bristine (2013) argue, is taking account of the fact that decisions are made continuously over time as long-term uncertainty reduces. This is captured in the modelling approach of sequential decision making under uncertainty represented through stochastic modelling frameworks. In this approach, models determine optimal policies at more than one point in time, with learning happening based on the outcome in one period, and being used for decision making in other periods.

For our analysis, we adopt the general definition of uncertainty as presented by Walker (2003): "*any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system*". We use the approach of scenario analysis within a deterministic model, GCAM. This is a useful approach which requires the selection of key parameters and input assumptions, and helps in understanding the robustness of model results to these key input assumptions (Kann and Weyant, 1999).

Uncertainties are present in different aspects of the energy system as well as the way the system is modelled. We focus only on some key uncertainties, inferred based on our discussions with expert stakeholders including government representatives as well as private and public-sector experts, who matter for India's NDC contributions and Mid-Century Pathway. 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 interest for a relatively robust assessment of these as compared to that available in India-specific literature. We discuss these key uncertainties in the next section on methodology. We hope to capture other uncertainties that have been excluded in the present analysis but are key for answering other research questions, in future research.

3. Scenario Framing and Methodology

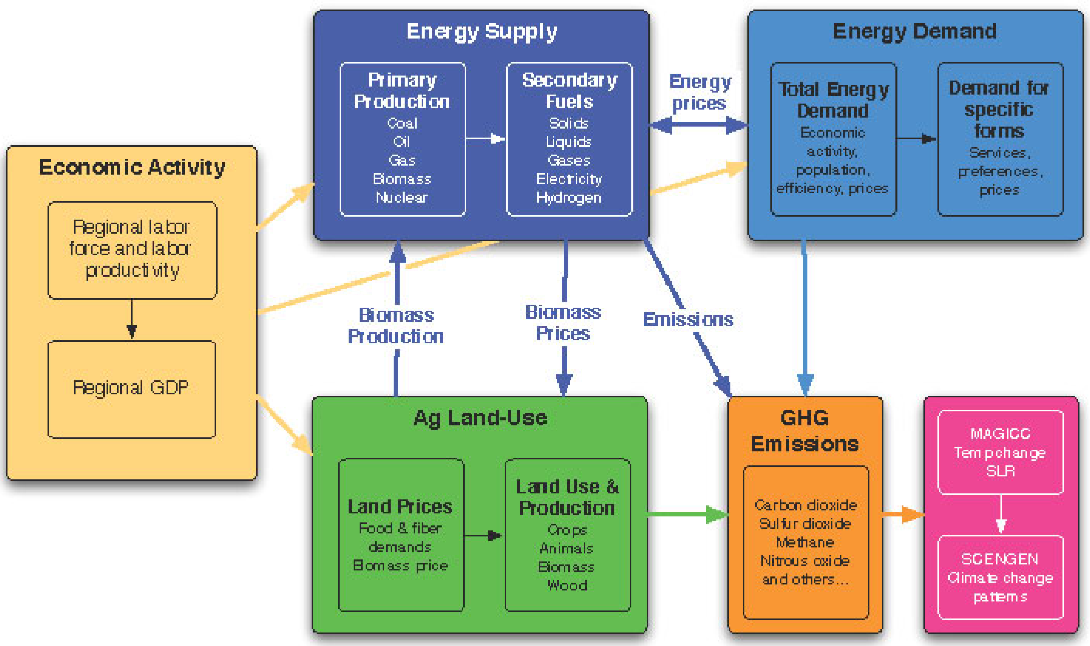
There are two pillars of our methodological approach – (i) Stakeholder engagement, and (ii) Integrated assessment modelling. We engaged with expert stakeholders from MNRE, NTPC, solar and wind power plant developers, and other policy and sector experts for informing our assumptions as well as storylines. Our framing of uncertainties is based on literature review as well as understanding based on our engagement with experts. This section presents the different aspects of our methodological approach, including modelling framework, uncertainty assessment approach, as well as climate policies among other aspects.

3.1 Modelling framework – Global Change Assessment 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.

Figure 1 presents the schematic for GCAM. GCAM is housed at the Joint Global Change Research Institute (USA), and models 32 regions of the world with India as a separate

Figure 1: Schematic representation of Global Change Assessment Model (GCAM)



Source: Joint Global Change Research Institute/Pacific Northwest National Laboratory, USA region. GCAM-IIM version was set up at IIM Ahmedabad during 2007–09, and since has been used extensively for India-specific analysis. The electricity generation sector is modelled in detailed within GCAM, as explained in Section 3.2. GCAM-IIM has a detailed representation of the building and transportation sectors, and an aggregate representation of the industrial sector. Detailed related to modelling end-use sectors in GCAM-IIM are given in Section 3.3.

The share of any given technology within GCAM is based on its cost relative to the cost of all other technologies

GCAM 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. GCAM does not model the impact of energy and climate systems on the economic variables like GDP, investments, etc. Currently, GCAM-IIMA is one of in-house models of the CEEW, India. Please refer Shukla and Chaturvedi (2012), Edmonds, et al. (2012), Hejazi, et al. (2013), McJeon, et al. (2014), Iyer, et al. (2015), Kyle and Kim (2015), Chaturvedi and Sharma (2016), Calvin, et al. (2017) among other papers for a detailed overview on the application of GCAM for analysing Indian and global energy and climate policy issues.

3.2 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 concentrated solar power (CSP) for solar. We have not included rooftop solar, mini grids or any other decentralised electricity sources in our assessment as off-grid energy is not the focus of our analysis, though their importance for providing energy access cannot be over emphasised. 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-based cars) increases as income increases. 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-based 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 demand for electricity grows in the end-use sectors, electricity generation grows to meet this demand.

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 this formulation, even if a technology has higher average cost than other technologies in the choice set, it will 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 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. For example, if in year 2030, total electricity demand is 100 units, 70 units are already generated in 2025[1], 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 will be temporarily shut down.

There are no hard constraints on any technology in GCAM in terms of either its absolute penetration, share of a given technology, or its rate of growth. However, the growth rate of any technology can be dampened if historical experience shows that there are significant non-economic barriers to the growth of this technology. The rate of growth/share is still determined by the relative costs.

In our framework, we dampen the rate of growth of nuclear energy – without putting any hard constraint on its growth rate or share – to reflect the non-economic barriers this technology faces. That is, we do not say that nuclear energy cannot grow at more than 10 per cent per year, or more than 10 GW a year, or cannot take more than 30 per cent share for a given year. In principle, in our GCAM-IIM framework with the set of assumptions we have, we can have a scenario with even more than 80 per cent-90 per cent share of nuclear energy in India's electricity generation if the relative cost of nuclear is significantly low compared to the technology that is nearest in terms of the costs. For example, a recent study (Chaturvedi et al., 2015) with higher cost of solar and a stringent climate policy target shows that the share that nuclear energy-based electricity will achieve in total electricity generation is 45 per cent in 2090, i.e., the cost difference between nuclear and competing technologies ultimately determines its share. Hydro-based electricity is modelled exogenously in GCAM as there are multiple social and environmental issues facing this technology, even though it is the cheapest from the economic perspective.

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 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.

3.3 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. Detailed theoretical formulation for the building sector as modelling in GCAM-IIM can be found in Chaturvedi et al. (2014).

1 GCAM operates in five-year time steps.

The energy demand in 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 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, 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).

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 and emissions from an aggregate industrial sector and includes energy demanded in the agricultural sector. GCAM has the capability of detailing industrial module into various industrial sectors like steel, paper, cement, etc (e.g. see Zhou et al., 2013). Disaggregating industrial demand into detailed industrial sub-sectors (e.g. steel, chemicals, etc.) is an important area of future model development and research. The 'Industry+' results denote results for both industrial and agriculture energy use. Non-electricity usage in the agricultural sector is very limited, though this sector's share in India's electricity consumption is 18 per cent-20 per cent, almost half the share of electricity consumed in India's industrial sector. We discuss the importance of industrial energy use after excluding the agricultural related energy use.

We model energy efficiency improvements in the end-use sectors with the help of exogenous assumptions, as well as endogenous price responses. We assume that average shell efficiency of residential and commercial building stock improves by 7 per cent between 2015 and 2030, and further by 10 per cent between 2030 and 2050. Appliance efficiency improves at different rates across appliances. For air-conditioners, an appliance with high energy consumption, we assume that efficiency improves at 1.45 per cent per annum between 2015 and 2030, and by 1.1 per cent per annum between 2030 and 2050. Similarly, we have technology level efficiencies for cars (four category), two-wheelers, three-wheelers, buses, and railways for meeting passenger road transportation demand. For freight sector, we have trucks (five categories) and railways. We have assumed that the aggregate energy efficiency of India's industrial energy use increases by 1.7 per cent per annum during 2020–2030, by 1.2 per cent per annum during 2030–40, and by 0.75 per cent per annum during 2040–50. At the aggregate industry sector level, our efficiency improvement rate assumption can be argued as being higher compared to what the PAT scheme aims.

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 will 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 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 will decline and the competing technology will fill the gap.

3.4 Modelling energy access

Our model has a detailed representation of energy service demands for the urban and rural residential sectors. Demands are responsive to costs as well as income. As affordability of services increase, the demand for energy services increases both in urban and rural areas. We incorporate energy access related policies in our analysis in the following way:

i. **Urbanisation rate:** The rate of urbanisation depends on the rate of economic growth. Higher the economic growth, higher is the transition towards urbanisation. We reflect this experience in our model by assuming different rates of urbanisation under the different growth rate scenarios. We assume that urbanisation rate in 2050 will increase to 51 per cent under the medium economic growth scenario, to 56 per cent under the high economic growth rate scenario, and to 46 per cent under the low economic growth rate scenario to represent the dynamics in a stylised way.

ii. **Urban rural income divide:** How energy access will evolve in urban and rural areas will depend on how per capita income grows across urban and rural households, which is linked to the growth rate of the aggregate economy. We assume that a high economic growth rate at the country level will imply that the per capita income disparity between urban and rural areas will decline at a faster rate as compared to the medium economic growth rate, which in turn will be higher than a low economic growth rate. The rate at which this disparity decreases will impact the rate of energy access in rural and urban households. The per capita urban and rural income assumptions across the three economic growth scenarios are presented in Appendix 1. Thus, our three economic growth scenarios do not just analyse the impact of the higher level economic growth rate and urbanisation rate, but also of differing levels of energy access in urban and rural areas. As compared to our assumption, data from the past three decades in India will show that even though the average per capita incomes have risen in India with economic growth, income disparity has increased between urban and rural areas (instead of decreasing as we have assumed). This is a failure of Indian economic policy which has been not able to address the growing urban rural divide. Our assumption in a way only reflects the scenario in which Indian policy makers are successful in decreasing the urban rural income gap. Our framework is capable of modelling increasing inequality in incomes as well. As energy access in itself is not the focus of this analysis, we have chosen a stylised representation of this issue, which can be argued as an optimistic assumption of the state of urban rural divide in India's future. There could be alternative ways of modelling energy access. We present one stylised way to incorporate the impact of varying income levels on access.

Our approach in a way focuses primarily on the demand side based on the logic that even if electricity is brought to a household (which is a supply side perspective), the level of consumption will largely be determined by the household income.

iii. **Clean cooking access:** The Indian government has embarked on an ambitious programme to provide clean fuel, mainly LPG to Indian households. We assume that under the medium growth scenarios, biomass will be entirely replaced by alternative cooking fuels by 2040 in the medium GDP growth scenario, 2030 in the high growth scenario, and 2050 under the low growth scenario.

iv. **Efficient lighting:** With a thrust on the LED programme, we assume that the penetration of LEDs increases at a fast pace. Incandescent bulbs will be phased out from Indian households by 2030 across all scenarios. The incandescent bulbs will be replaced by LEDs as well as CFLs. A recent report highlights that LEDs have mostly replaced CFLs in India rather than incandescent bulbs (Chunekar et al., 2017). Our assumption in a way reflects that Indian policy makers undertake strong regulatory steps to stop the sales of inefficient incandescent bulbs, as the LED focused policy in itself might not be successful in replacing incandescent bulbs in India.

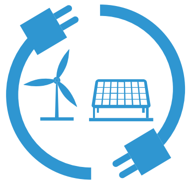
Whether the transitions in efficient lighting, clean cooking, or industrial and transportation sector efficiencies will happen as per the timelines that we have assumed is open to debate, as these depend on many factors. Our effort is not to present our assumptions as the 'best' assumptions but reflect policy developments in the Indian energy sector in our modelling analysis. We have chosen a stylised way to do this.

3.5 Framing uncertainties 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 depends not only on the cost of RE technologies, but the relative costs of all key technologies in the portfolio. Also, how big the electricity generation sector grows could impact the progress towards this target, as a low growth scenario might limit the opportunity for a faster transition. Our research focuses on these two key uncertainties- cost of power generation technologies, and economic growth, for understanding India's progress towards this NDC 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) 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 Annexure 1.

We assess the key uncertainties in the demand sectors- rate of energy efficiency improvements, as well as the rate of energy demand growth for the industrial and transportation sectors- to understand India's progress towards the NDC target related to the emission intensity of GDP.

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.



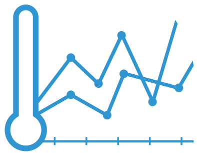
As India moves towards a higher share of VRE in the grid, there could be challenges in managing the transition

'Storyline-based scenarios' versus 'uncertainty assessment'

Scenarios could be formulated in different ways. Many studies formulate scenario based on storylines e.g. high renewable scenario, high fossil scenario, 2 Degrees constraint scenario, etc. Our scenarios are not determined explicitly by such storylines. However, it should be highlighted here that this span of scenarios encompasses many such technology-focused storylines. The scenarios with low cost of solar and wind and high cost of coal, gas and nuclear corresponds to a high renewable scenario storyline, while that with low cost of coal and gas and high cost of other technologies corresponds to a high fossil scenario storyline. The scenario with a low nuclear cost and high cost of all other technologies corresponds to a high nuclear scenario storyline. Rather than analysing storyline-based scenarios like 'high renewable energy', or 'high nuclear' scenario where the technology penetration is exogenously pushed for achieving specified technology targets and finding its implications for energy and emissions, we focus on exploring key uncertainties across technologies and economic growth, and let the model inform us about the direction in which India's electricity and energy sector is moving, given our current understanding of how these key uncertainties will evolve in the future. Storyline-based scenarios are very useful, but uncertainty-based scenario assessment provides a different analytical view which is currently missing in the India-focused literature. Instead of giving explicit targets to different technologies, our analysis is based on economics of relative technology costs.

3.6 Incorporating the cost of integrating variable renewable energy (VRE)

As India moves towards a higher share of VRE in the grid, there could be challenges in managing the transition. The current share of VRE in generation is 6 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. We undertake a review of papers focusing on this challenge as faced in Europe and take inputs from European scientific expertise to develop and understanding of VRE integration cost for India, as this region has the richest experience and analytical knowledge base of dealing with the VRE integration issues. Our literature review focuses on the analysis of greenfield systems, so that the insights are generally applicable to any electricity system that will see significant expansion in the future, or those that will see large scale retirement of old stock and building of new capacity for replacing the retired stock. We highlight the key learning for us in section 4 devoted to the issue of VRE integration cost. We present the underlying logic that will impact the cost of VRE generation. For our core set of scenarios, we focus only on the key uncertainties and exclude the integration cost from the framework. We then run all the scenarios again after incorporating the cost of VRE integration, and compare this with our core set of scenarios to understand the implications of including VRE integration cost on India's electricity generation future. We also test the budgetary implication of government support for VRE integration cost. Our assumption on VRE generation cost has been given in the Appendix 1, Table 1.3, along with the generation cost of all technologies. The limitation of our approach for including VRE integration cost in the assessment and its implications for the results is presented in Section 3.9.



We construct alternative scenarios that are consistent with achieving the 2° C temperature increase limit by 2100

3.7 Modelling climate policies

Along with presenting an uncertainty-based assessment for the electricity generation sector, we also model dedicated climate policies. The climate debate is a long-term debate. And the Mid-Century Strategy to be submitted under the Paris Agreement are to be aligned with the goals of the agreement. A carbon dioxide budget of 1000 $GtCO_2$ is available for the world between 2010 and 2100 for meeting the 2 Degrees C goal, and even lower for a 'well below 2 Degrees C goal'. We construct alternative scenarios that are consistent with achieving the 2 Degrees C temperature increase limit by 2100. The emission budget for India is based on techno-economic analysis undertaken within the modelling framework of GCAM. As per modelling-based techno-economic analysis, India will be able to emit 145 $GtCO_2$ of cumulative carbon dioxide emissions between 2010 and 2100 under the global 2 Degrees C pathway. There could be alternative pathways to achieving this carbon budget. As India's NDC is already on the table for 2030, we first test a scenario in which India peaks its carbon dioxide emissions in 2030, and reduces emissions at a rate that is consistent with the national carbon dioxide budget of 145 $GtCO_2$ between 2010 and 2100, and hence with the 2 Degrees C target. In this scenario, India's carbon dioxide emissions decline at a uniform rate between 2030 and 2100, by when these are almost zero. We also test an alternative scenario in which India peaks and then reduces its energy sector-related carbon dioxide emissions in 2040, while adhering with the same national carbon dioxide budget of 145 $GtCO_2$ between 2010 and 2100, as in the case of 2030 peaking scenario. We present the implications for both these scenarios for India's energy systems for 2050, which is aligned with the Mid-Century Strategy time frame. We do not include carbon capture and storage (CCS) in our assessment, so our mitigation pathways do not include negative emissions. Along with the economy-wide climate policy, we also test the implication of a sectoral policy- a high coal cess. The existing coal cess of INR 400/ton of coal is already included in our assessment and is reflected in our assumption on coal-based electricity generation cost.

3.8 Defining scenarios and modelling timeframe

Defining reference scenario

The focus of our electricity sector-related analysis is uncertainty assessment. As such we do not focus on any specific scenario and we are more interested in the median values as well as the ranges coming out of the uncertainty assessment. In addition to the uncertainty analysis, we also estimate the budgetary requirement if the government bears the cost of integrating VRE in the grid. We also test out the implications of three dedicated climate policies. For analysing both the budgetary implications as well as climate policies, we need a scenario as the reference scenario against which we measure the implications of climate policies. We define the scenario with medium economic growth (MedGr), medium costs for solar and wind (MS_MW), low costs of coal and nuclear (LC_LN), and high cost of gas (HG) as our reference scenario (MedGr_MS_MW_LC_LN_HG OR MedGr_RefCosts). The reference scenario has been chosen on the basis of our own assessment of technology cost and economic growth pathways, and which of these is more likely as compared to others. However, the choice of the reference scenario is mainly to present a counterfactual against which the impact of alternative scenarios can be measured. Through the reference scenario, we focus on the role of energy use in the end-use sectors, the implications of emissions mitigation policies, as well as the political economy of distribution of VRE integration cost. The climate policy scenarios that we analyse have been detailed and defined in Section 7, wherein we discuss their implications for India's energy and carbon dioxide emissions.

Defining economic growth-related scenario sets

As we undertake an uncertainty-based assessment, we have a set of 72 unique pathways representing different cost combinations of underlying key technologies for any given economic growth rate. We use terms- 'high economic growth scenario set', 'medium economic growth scenario set', and 'low economic growth scenario set' to collectively denote the 72 cost pathways within any given economic growth trajectory. So, the median value of any given variable (e.g. share of solar-based electricity) under the medium economic growth scenario set refers to the median value of this variable across the 72 cost scenarios within the medium economic growth trajectory.

Modelling timeframe

Climate change and global warming are issues that need to be analysed at the decadal scale. GCAM operates up to 2100 in five-year time steps for understanding the impacts of regional and global long-term energy and carbon emissions pathways. This informs the amount of cumulative emissions that the world will emit under any given scenario, and what it means for global radiative forcing and temperature increase. GCAM has been used extensively for informing the debate on global carbon space for achieving 2 Degrees C temperature increase limit, a target adopted by the world prior to the Paris Agreement, for which analysis of global emissions pathways for up to 2100 is required.

For achieving long-term climate goals, near-term changes are required in the way the current energy system is operated. We run the model for up to 2100, but focus only on the pathways up to 2050 for the energy systems analysis as this is the time frame relevant for our discussion on NDC and Mid-Century Strategy. We present the results for our uncertainty analysis for up to 2050. For modelling stringent climate policies that are consistent with a 2 Degrees C goal, we do the carbon budget related analysis by analysing carbon dioxide emissions pathways for up to 2100, while presenting the energy system related implications for 2050.

GCAM focuses on the long-term pathways and is suited for policies that could influence these pathways. It does not explicitly model grid balancing related aspects as that would require a model with hourly resolution and much finer representation of the grid both on the supply- and demand-side.

3.9 Limitations

We highlight three limitations of our analysis. All of our limitations also point towards some key future areas of research.

1. **Off-grid and decentralised grid-based electricity:** Off-grid and decentralised grid based electricity is important from the perspective of providing electricity access for millions currently lacking access to basic electricity services, but it could potentially also provide an architecture that is different from the current architecture of centralised grid-based electricity generation. Our analysis focuses on centralised utility-based generation and the key technologies for the electricity generation mix. Large scale renewable with low cost local storage could provide a fillip to the decentralised grid scenario if a supportive policy architecture is designed, and if these off-grid technologies and decentralised grids are able to deliver the energy services as required by consumers. Our modelling framework, and most other similar frameworks, is not designed to analyse the potential for decentralised grids, and hence we exclude these from our analysis.

2. **Static representation of integration cost:** The cost of integrating VRE should be dependent on the share of VRE, and hence should differ across scenarios on the basis of the share of VRE across each scenario. In our assessment, for a given scenario, the integration cost increases with the share of VRE across years. We, however, levy the same integration cost exogenously for any given year across scenarios which can be termed as a limitation of our analysis of the impact of VRE integration cost. The integration cost that we have levied corresponds more with the median value of VRE share in electricity generation in our results rather than maximum and minimum shares across scenarios. In absence of detailed India-specific information, we have chosen to proceed with this rudimentary exogenous approach. In terms of the results, this would simply mean that the range of VRE based electricity generation (across 216 scenarios) that we get in our results when VRE integration cost is levied on VRE producers would be higher as compared to the results one would get if the integration cost is endogenously modelled based on the share of VRE in electricity generation. Modelling of this issue needs to be based on an endogenous representation. But the larger insights from our analysis are robust, due to the detailed uncertainty-based assessment.

   In our scenarios with VRE integration cost, we present our assumptions of total cost for VRE (levelised cost of electricity plus VRE integration cost) as the range within which we capture uncertainties related to both aspects. We believe our span of 216 scenarios with VRE integration cost included in the framework is able to capture the underlying uncertainties on the technology costs, as well as uncertainties related to VRE integration cost even if we do not specifically model it. This is one of the first attempts in our knowledge for India to have an analytical understanding of VRE integration cost based on modelling research and guidance from European expertise on the subject. We present our analysis based on VRE integration cost (along with the technology cost) as a first step towards a much better and deeper understanding of VRE integration cost and its impact on India's long-term electricity generation. Our larger objective is to highlight the implications of incorporating this cost in modelling-based assessments, and our analysis is a first step in the direction of more refined and robust studies on this issue.

3. **Non-CO_2 emissions:** The GHG debate includes all the non-CO_2 GHGs along with carbon dioxide. Also, there are carbon dioxide emissions from non-energy sectors like land-use. Our assessment focuses only on the carbon dioxide emissions from India's energy sector. We emphasise here that the non-CO_2 gases are also important for understanding of India's overall contribution to global warming and mitigating these to achieve climate goals. Other GHGs having a significant share in India's emissions are methane and nitrous oxide, both largely dependent on the agriculture. We do not expect these to grow as fast as energy sector-related carbon dioxide emissions.

4. A Deeper Understanding of VRE Integration Cost for India

4.1 Learning from literature

India-specific studies on the issue of VRE integration cost are limited (e.g. see Phadke, et al., 2016; NREL-USAID, 2017). Most recently, the Central Electricity Authority, Ministry of Power, GoI has undertaken a detailed study on grid integration cost based on data available from Indian states (CEA, 2017). These studies provide very useful information on the integration cost. However, these studies focus only on the short run for meeting India's RE targets. The important question is- If India wants to design an electricity system with a high share of VRE in the long term, say at least 50 per cent-60 per cent in electricity generation in 2050, what could be the cost and optimal design of such a system? There is a dearth of India-specific studies from the long-term grid integration perspective, which is an important gap as interventions have to be devised and implemented in the near term for aligning with the long-term policy objective. The long run, i.e. next 25–30 years, offers ample flexibility for designing the grid in an appropriate way that meets the desired policy goals as there is room for strengthening the grid, incorporating new technologies, as well as managing demand-side responses through real time data and price driven market structure.

In Europe (and few other countries as well) however, there are a bulk of studies trying to understand issues related to the system-wide cost of VRE integration (Agora Energiwende, 2015; Brouwer, et al., 2014; Bruninx, et al., 2015; DeMeo, et al., 2007; Gross, et al., 2006; Heptonstall, et al., 2017; Hirth, 2012; Hirth, et al., 2015; Holttinen, et al., 2013; Holttinen, et al., 2011; IEA, 2014; Michael and Kirby, 2009; Milligan, et al., 2011; Pudjianto, et al., 2013; Roy, 2015; Sijm, 2014; Ueckerdt, et al., 2013; Scholz, et al., 2017). Of all the studies, two studies particularly stand out- Hirth et al. (2015) and Scholz et al. (2017). Hirth et al. (2015) undertake a review of 100+ studies, as well as present results from their own analysis. The studies reviewed in this analysis generally do not assume a flexible system and are more focused on understanding the current cost of integrating VRE for European countries. Independent analysis undertaken in this study however does assume a greenfield system and that thermal capacity will adjust in the long run. Also, the analysis focuses mainly on the wind technology which is argued to be cheaper for Europe in terms of its integration cost. The Scholz et al. (2017) analysis undertakes an optimisation-based approach and tests the VRE integration cost for a wind range of VRE share as well as for varying mixes of solar and wind for a larger interconnected grid in the EU region.

Some important learning can be derived from these studies. First- the VRE integration cost consists of three components- *grid infrastructure costs* as additional investment into transmission grids is required to pool VRE and demand over large areas, *grid balancing cost* arising from uncertain forecasts and the need of more flexible operation of thermal power plants, and *UE* due to reduced utilisation of thermal power plants. Scholz et al. (2017) also discuss the *curtailment effect* at very high shares of VRE which signifies that due to a variety of reasons, not all VRE that is produced can be used at shares higher than 60–70 per cent of VRE. Studies show that at least till 40 per cent-50 per cent VRE share, the UE dominates the total integration cost. Beyond this curtailment and storage costs start increasing.

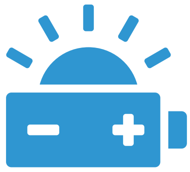
There is a substantial difference in the results of the two studies. The Hirth et al. (2015) study estimates integration costs of 25–35€/MWh at 30 per cent-40 per cent wind share in electricity generation under the assumption that the baseload price is 70€/MWh. The Scholz et al. (2017) study reports much lower total cost of integration of 12–15€/MWh for a system with 40 per cent-60 per cent VRE (even mix of wind and solar), about half the value in the Hirth et al. (2015) study.

The main reason for the lower costs in Scholz et al. (2017) is the different size of the studied regions. The studies cited by Hirth et al. (2015) cover only small to medium-sized countries/states (Germany, California), or strongly limit the amount of grid expansion when looking at larger areas like central Europe. As weather patterns are well-correlated on spatial scales below 500–1000 km, it is more likely that a certain weather (e.g., low wind) is dominant for the whole area of a small state – which means that a lot of backup is required. On the other hand, if wind and solar generation is pooled over a larger region such as all of Europe or India, it is much more likely that in one part of the region there is one weather situation (e.g., high wind) and in another part there is a different situation (e.g., low wind). This means that for the whole system, there is less over- or under-production from VRE. Put differently, the integration of VRE requires more flexibility and is costlier if it is attempted at small spatial scales instead of larger scales. However, larger scales in itself would not lead to lower integration cost. It is the correlation between solar (or wind) generation across the larger area that matters. E.g. for India, if generation based on solar is highly correlated across states and across seasons, the cost of integration will be higher compared to the cost when correlation is less.

In contrast to the Hirth et al. (2015) study, the study by Scholz et al. (2017) analyses an EU-wide optimised system with high shares of wind and solar, and allows the model to freely invest into long-distance transmission grids. It finds that substantial transmission grid expansion is a comparatively cheap integration option that reduces total integration costs to the stated values of 12–15€/MWh at 40 per cent-60 per cent VRE. Given the large expanse of India, transmission grid expansion will likely also play a key role for India to keep VRE integration costs low.

Another difference is that Scholz et al. (2017) also assume the availability of CSP in southern Europe at affordable costs. CSP with thermal storage and gas or hydrogen co-firing has the potential of becoming a dispatchable source of technology, which can be useful to manage the grid with high shares of variable renewables.

Interestingly, both the studies highlight that storage costs are a small component of the total VRE integration cost up until VRE shares of roughly 50 per cent. The analysis for a well-planned and implemented flexible electricity system shows that even if the cost of storage technologies declines significantly in the future, thermal or hydropower technologies will likely still play a role in the next decades. As the share of VRE increases in the grid, there could be many time slices with high VRE generation (relative to demand) leading to low electricity prices. An increasing number of such time slices due to increasing penetration of VRE will shift the technology choice towards mid-load and peaking plants with low capital intensity which can respond more flexibly to uncertain prices, implying that combined-cycle or even open-cycle gas turbines could replace nuclear and coal due to their low capital intensities[2]. This might increase the total system cost, but this is the cost of achieving the government policy target of integrating higher VRE in the generation mix. This is akin to saying that cost of electricity generation will increase under a carbon-constrained scenario due to a carbon tax. Generally, there will always be a cost of achieving policy objectives, and these costs should be acceptable to the society if one deems the policy objective a worthy goal.



Storage costs are a small component of the total VRE integration cost up until VRE shares of roughly 50 per cent

Along with learning key insights for modelling VRE and policy responses to deal with grid integration cost, in our VRE integration cost specific literature review the question we ask is – what learning from the European analysis are applicable for India? Our literature review focuses on the analysis of greenfield systems, so that the insights are generally applicable to any electricity system that will see significant expansion in the future, or those that will see large scale retirement of old stock and building of new capacity for replacing the retired stock. Of course, there cannot be a one-to-one translation of the Europe-focused analysis for India, but some broader insights can still be derived. As per the literature on integrating VRE, the VRE integration cost consists mainly of three components- *grid infrastructure costs* as additional investment into transmission grids is required to pool VRE and demand over large areas; *grid balancing cost* arising from uncertain forecasts and the need of more flexible operation of thermal power plants; and *UE* due to reduced utilisation of thermal power plants. First insight is that even under a well-planned system, UE due to reduced CUF will be the dominant part of the VRE integration cost for at least up to 50 per cent VRE share. Second, up to this share, even a significant decline in the cost of storage technology for India will not mean that the cost of integrating VRE will be necessarily small. Third, as India's long-term plans are based mainly on solar energy, we have to understand how well solar-based generation correlates across India's geographical mass and time, though the same is also required for wind energy, as this has implications for the integration cost. Of course, only a detailed India-focused study can give us specific answers to these questions.

Based on learnings from the European literature focused on greenfield systems that can be translated to the Indian context, we infer that the VRE integration cost could lie in the broad range of 16 per cent to 24 per cent of levelised cost of coal at 20 per cent VRE share in electricity generation, and 21 per cent to 50 per cent of levelised cost of coal at 40 per cent VRE share. For our analysis of the implications of VRE integration cost, we assume an integration cost within these ranges. The UE component of integration cost depends on the capital cost of the conventional based-load power plants, and on the extent of decline in their average utilisation factor at higher shares of VRE. For example, at a levelised capital cost of 2.1 INR/kWh, this range is from INR 0.74 – 2.1/kWh-VRE. At a lower levelised capital cost of INR 1.5/kWh, the range is from INR 0.52 – 1.5/kWh-VRE. Table 1 presents the comparison for results of the two studies and CEEW's assumptions of VRE integration costs.

2 This effect is mirrored in the recent downfall of the four incumbent German utilities: the new coal power plants built over the last decade are – partly due to high VRE in-feed – unable to recover their very high investment costs. Accordingly, the utility companies have been crushed by their debt and have been forced to sell off their assets under price to maintain their liquidity. This impact however might not happen for India as Indian grid will grow significantly, and there is enough flexibility in the system to plan for a new order in India's electricity generation systems.

Table 1: CEEW assumptions for cost of VRE integration

VRE share in generation		0%	5%	10%	15%	20%	25%	30%	35%	40%
Hirth et al. (2015)	Levelised capital cost of thermal with 0% VRE share- Euro/MWh					33		33		33
	Levelised cost of thermal generation with 0% VRE share- Euro/MWh					70		70		70
	Total integration cost (Euro/ MWh- VRE)							25		35
Scholz et al. (2016)	Utilisation effect (Euro/MWh-VRE)					8-12				10-13
	Total integration cost(Euro/ MWh- VRE)					11-17				15-20
Integration cost as a percentage of LCOE of thermal generation						16%-24%		35%		21-50%
CEEW Median Scenario Assumptions	LCOE of coal in India (INR/ MWh)- new stock	350	351	352	353	354	355	356	357	358
	Cost of VRE integration new stock (INR/MWh-VRE)	0	0	70	75	80	90	100	110	110
	Marginal VRE integration cost as a percentage of coal LCOE	0%	0%	20%	21%	23%	25%	28%	31%	31%

Source: CEEW analysis

Note: Numbers from Scholz et al. (2016) have been derived from the graph given in the paper. This paper presents numbers for up to 100 per cent VRE share. CEEW assumptions are given in terms of marginal integration cost;, the average integration cost will be lower. 1 Euro = 79 INR.

A more intuitive way to understand the UE is to directly look at the potential decline in average CUF. We explain this with the help of a hypothetical illustration- If the levelised capital cost is INR 2.1/kWh, and at 30 per cent VRE share the CUF of a new coal power plant declines from 85 per cent to 60 per cent[3], the new cost will be INR 2.97/kWh, an increase of INR 0.87/kWh. However, if the levelised capital cost is INR 1.5/kWh, and at 30 per cent VRE share the CUF of coal power plant declines from 85 per cent to 60 per cent, the new cost will be INR 2.12/kWh, an increase of INR 0.62/kWh. The total cost including balancing and infrastructure cost will be higher. In terms of levying this cost on VRE producers within the model, cost has to be converted in terms of INR/kWh-VRE, which will need to be derived based on other assumptions.

4.2 Should VRE integration cost be internalised by VRE producers?

Integration costs occur with all technologies. What is important is to find out why VRE technologies are being introduced despite increasing costs. If move towards VRE is due to government policy, the purpose of such policy and benefiters should be identified to make sure that integration costs are allocated among the stakeholders in a way that achieves the policy objectives while not excessively burdening any stakeholder. If the integration costs are due to imperfections in the market structure, the market structure needs to be reformed.

3 This is for new investments. For a given reduction in the CUF of the coal fleet, CUF of new investment will need to decline at a higher rate.

The first issue to understand before answering this question specific to VRE is if the total system cost to deliver a particular level of electricity will increase in case the share of VRE is increased through a policy push. As literature suggests, there are many factors that will determine this outcome and only an India-specific analysis can provide an answer for India. If, however, a higher penetration of VRE does increase system cost for delivering a targeted level of electricity, who should bear this cost? The answer depends on the policy objective we refer to.

'India has not been a part of the GHG emission problem, but will be a part of the solution, without compromising on the developmental objectives'

A scenario with an explicit carbon constraint as the primary policy objective

Under a scenario with an explicit carbon constraint, the priority is to increase the share of VRE as well as any other zero carbon fuel across the supply and demand sectors of the economy. If minimising carbon emissions is the objective function, it is imperative to view integration costs not as the responsibility of the VRE producers only, but as a cost that is borne by the society. Under such a scenario, it is perhaps not prudent to levy an integration cost on the VRE producers. In essence, any cost to achieve the carbon constraint should not be viewed as an 'increase' relative to a no constraint scenario, but rather as an imperative to achieve the carbon mitigation objective. However, if this constraint is not the sole or primary objective, the argument could be different.

A scenario with deep emissions mitigation not being the most important priority

This is the case where development priorities like primary health, primary education, and basic energy service are considered at least as important, if not more, as the objective of emissions mitigation. The GoI has played an active role in international climate negotiations at Paris, and has put forward NDC, which shows that it is also actively thinking about climate policy. India's climate policy has been contextualised within the development and poverty alleviation framework, sustainable development, and national priorities. Given the competing budgetary and resource allocation demands, the objective function is not solely to minimise carbon dioxide emissions at the country level, but to maximise developmental outcomes while minimising carbon dioxide emissions. India's stated perspective on the issue can be summarised as: 'India has not been a part of the GHG emission problem, but will be a part of the solution, without compromising on the developmental objectives'. As a concrete example, the objective function would be to achieve a targeted level of energy access, and achieve this in a way that minimises the cost burden (to ensure affordability) while also looking for opportunities for minimising carbon dioxide emissions. Under such a scenario, the extent to which VRE share would increase would not be dictated solely by the carbon constraint but will also be significantly influenced by the objective of achieving a given level of energy access (say 5,000 kWh electricity consumption/capita/year in 2050) while minimising the total system cost for the same to ensure affordability. In case higher VRE share leads to a higher system cost, the society needs to decide who should bear this cost- the VRE producers, the government, or end consumers. At this point while this report is being written, who bears the integration cost under this scenario is an open question that the stakeholders within India need to decide given India's national circumstances and priorities.

India as a society has not accepted any absolute carbon constraint yet and who should bear the integration cost is an open question at best. Our analysis tests one set of 216 scenarios with a notional integration cost on VRE producers, while our core set of scenarios does not include the VRE integration cost in the framework. The objective of this modelling choice is to highlight the future of India's electricity generation sector even if an integration cost is levied on VRE producers and inform the debate on this issue. We are of the firm opinion that to achieve the objectives of emission mitigation as well as the Paris Agreement, it is imperative to promote VRE in as many ways as possible, and levying the integration cost on VRE producers might only impede the growth of VRE.

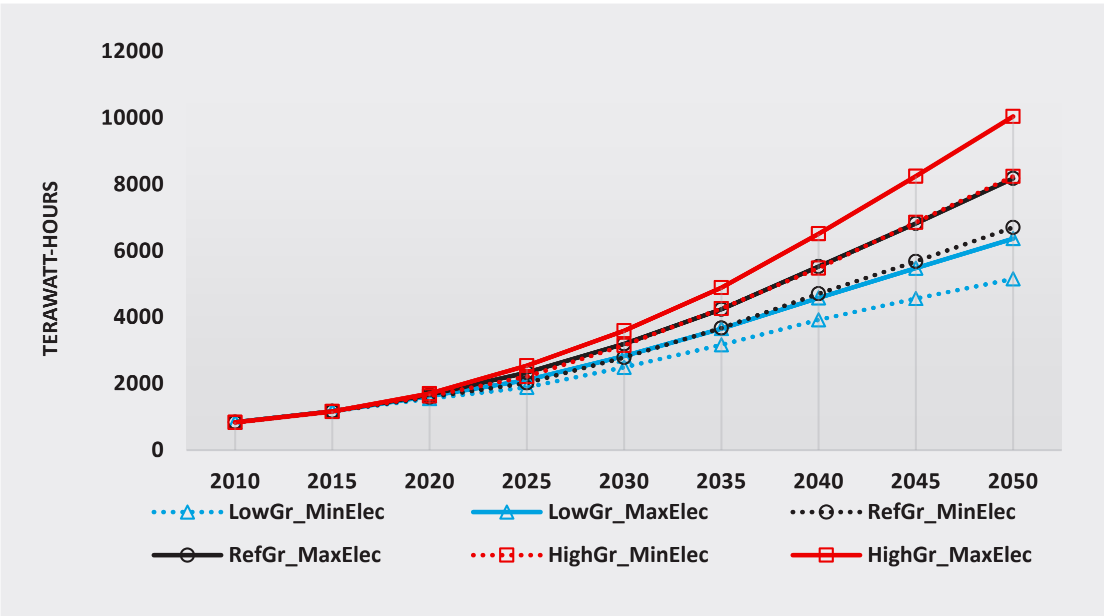
Our argument only highlights that the extra costs due to higher penetration of VRE exists at a system level, and simple use of LCOE to show that VRE is getting cheaper is misleading. Beyond that, how to make use of it for policy making is still up for debate.

5. Outlook for India's Electricity Generation

5.1 Growth in electricity generation and capacity

India's electricity generation is bound to grow at a fast pace, driven by increasing incomes and government policy focused on increasing electricity access. Electricity demand will depend on both the rate of growth as well as the cost of electricity. Figure 2 shows the minimum and maximum utility-based electricity generation across the 72 cost pathways within each of the three economic growth rates, in our core set of scenarios.[4] As per our analysis, median estimates for India's utility-based electricity generation in 2030 range from 2,671 TWh under the low economic growth scenario set to 3,350 under the high economic growth scenario set. In 2050, the median value of electricity generation ranges from 5,705 TWh to 9,111 TWh under the low and high growth scenario sets. For the range of technology cost uncertainties included in our study, the impact of technology cost over the median values is 15 per cent-16 per cent. Our estimates for 2030 appear to be higher than the estimates in India's Draft Electricity Plan (CEA, 2016). We do not model rooftop solar or 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 demand is met through such off-grid sources. Also, our numbers do not include captive electricity generation by Indian industries,

Figure 2: Utility-based electricity generation without grid integration cost (range across economic growth scenarios) – India



Source: CEEW Analysis, 2018

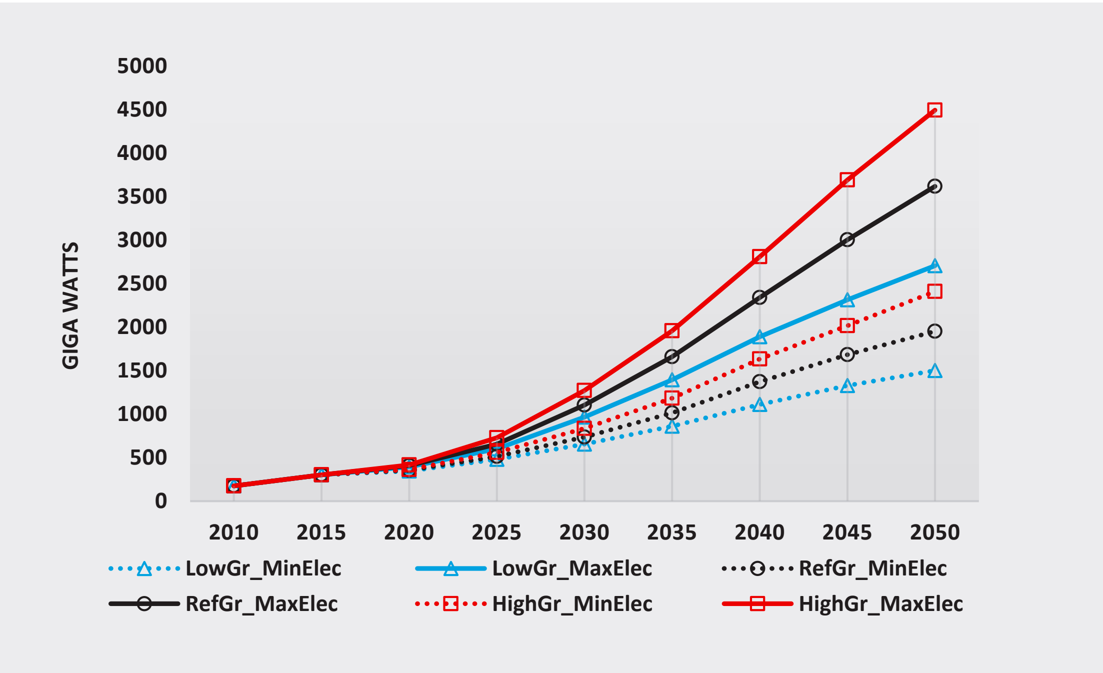
4 By core scenario set, we mean the set of scenarios in which integration cost is not levied.

which we expect to be low in the future compared to the scale of India's electricity generation system.

Inclusion of integration cost reduces the electricity generation because the end-use sectors are price sensitive. If integration cost is levied on VRE producers, the average cost of producing electricity increases, which when passed on to the end-use consumers decreases its demand in the end-use sectors and consequently the generation.

The generation capacity[5] in the future however will also be dependent on the fuel mix of electricity. A solar and wind-based scenario will have much higher capacity owing to the low CUF as compared to fossil or nuclear dependent scenario. The median capacity in 2030 in our medium growth scenario set is 856 GW, which increases to 2,669 GW in 2050. In 2050, 80 per cent of this capacity is based on VRE (solar and wind), which corresponds to 39 per cent in terms of share of solar and wind in electricity generation (median values of the medium economic growth scenario set). Figure 3 gives the range of generation capacity across cost pathways within each of the three GDP growth rates. The minimum and maximum generation capacity in 2030 across our 216 scenarios range from 655 GW to 1,271 GW, the maximum value reflecting a higher share of VRE under a high economic growth rate scenario.

Figure 3: Utility-based electricity generation capacity without grid integration cost (range across economic growth scenarios) – India



Source: CEEW Analysis, 2018

Our uncertainty analysis reveals two important insights at the higher level. Actual electricity consumption is determined not just by the economic growth rates, but also by the average cost of electricity. As our model incorporates the shift in fuel demand in response to prices, we see that even for a given economic growth rate, electricity consumption changes by 15 per cent-17 per cent due to change in average electricity cost. We see a reduction in electricity consumption due to higher cost not just in the residential and commercial sector, but also in the industrial sector. Whether the extent of this reduction is 10 per cent or 20 per cent

5 Generation capacity mentioned in this report pertains only to utility-based generation. Captive generation capacity has not been analysed in this study, and will be additional to the numbers presented here.

will of course depend on many factors including real world behaviour as well as the way we model this behaviour. The key insight, irrespective of the specific number, is that electricity price matters for consumption, and the cost of underlying technology mix hence is also an important variable that policy makers and planners need to assess.

In 2030, lower economic growth leads to a 10 per cent reduction in electricity consumption compared to reference growth scenario, while a high growth leads to an increase by 12 per cent

As compared to technology cost, economic growth certainly has a higher bearing on the level of electricity consumption in the economy. In 2030, lower economic growth leads to a 10 per cent reduction in electricity consumption compared to reference growth scenario, while a high growth leads to an increase by 12 per cent. Respective changes in 2050 relative to reference growth scenario is 22 per cent on either side, i.e. a wide range of 44 per cent across the range of high and low economic growth. The extent of impact due to variation in economic growth as compared to the variation in technology cost in our results are driven by the uncertainty range included in both of these variables. E.g. a higher range in terms of technology cost pathways will show higher impact of technology cost on the variation in electricity generation. However, we believe that the ranges considered in our analysis for both economic growth as well as technology costs capture the uncertainties in these variables to the best of our current knowledge as these assumptions have been developed based on inputs from expert stakeholders. This result highlights the point that technology costs do matter, but it is the rate of growth that will play a decisive role in determining the level of electricity demand and consumption in the Indian economy.

Along with electricity price and economic growth, energy efficiency improvements in end-use sectors are also important. Efficiency improvements for end-use sectors are included in our assessment as explained in the methodology section, and we also test sensitivity around this variable.

5.2 Evolution of electricity generation mix and generation technologies

Our uncertainty analysis helps us in presenting a robust picture of the future of key electricity generation technologies in India's power generation mix, given the current understanding of how some key variables may evolve in the future. Figure 4a shows the growth of electricity generation based on five key electricity generation technologies across all scenarios, when grid integration cost is *not* levied on VRE producers. Figure 4b compares this with the outlook when grid integration cost *is* levied on VRE producers.

The literature and discussion on modelling the future of India's electricity generation sector available as of now does not include the implications of VRE integration cost. Our results (Figure 4a) comparable to this discussion show that when the integration cost is not included in the assessment framework, the rate of growth in solar energy is high in the near and long term. Along with solar, coal will also be a technology with a significant share in India's electricity generation future, but the high share of coal-based generation will be largely due to stock that is already in place, as against new generation capacity. The best case scenario for coal is a growth of 6.5 per cent per annum in coal-based electricity generation between

2020 and 2030. Growth in the worst case scenario during this time period is 2.1 per cent per annum, reflecting a scenario with low economic growth, high cost of coal, and low cost of all competing technologies, after which coal-based generation will be largely stagnant in the future. In the best case scenario for coal during 2030–50, coal-based electricity generation grows by 3.5 per cent per annum.

Based on the median numbers from our analysis we do not see peaking happening in coal-based electricity generation at least for up to 2050. In our medium economic growth scenario set, median coal-based capacity addition is 40 GW during 2025–30, which declines to 32 GW during 2045–50. Even under the most pessimistic scenario, i.e. low economic growth, high cost of coal-based generation and high low cost of all competing technologies, we see 10 GW of capacity addition in coal-based power generation during 2045–50 (Figure 5a), but this would be less than capacity that will need to be retired during this period and hence coal-based electricity generation still declines under the most pessimistic scenario. Higher cost of coal (INR 4.25/kWh, against INR 3.5/kWh) reduces the range of potential capacity addition by 10–17 GW during 2025–30, and 6–25 GW during 2045–50, across all scenarios of economic growth and technology cost. Even though we do not see peaking happening, the rate of growth in required coal power capacity additions appears to decline in the near and long term. In the absence of a dedicated policy to reduce coal use, we do not see coal consumption in India's electricity generation sector peaking any time even by 2050.

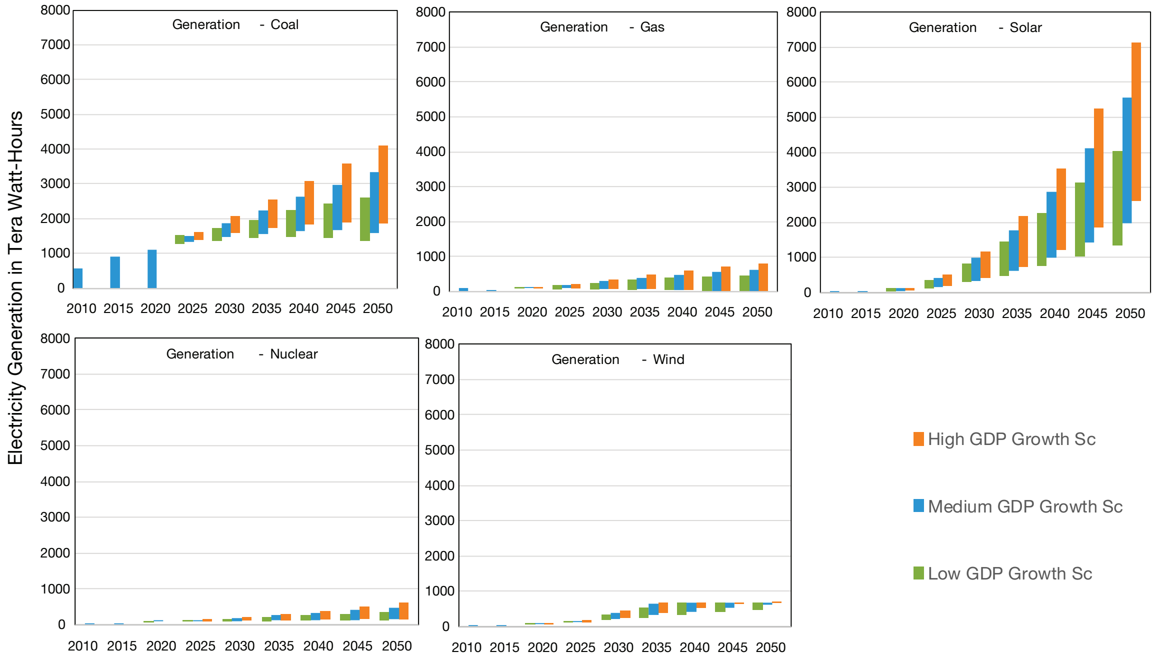
We find that the penetration of solar energy will grow at a fast pace and this is highly sensitive to its cost. In the best case scenario (high economic growth, low cost trajectory for solar, and high cost trajectory for all other technologies), solar-based electricity generation in India grows to 1,170 TWh in 2030 and 7,120 TWh in 2050. As against this, in the worst case scenario (low economic growth, high cost trajectory for solar, and low cost trajectory for all other technologies), solar-based electricity generation is limited to 281 TWh in 2030 and 1,325 TWh in 2050. The penetration of solar electricity generation is very sensitive to cost. For a given economic growth rate, solar-based electricity generation in India increases by two and a half times in 2050 if the cost of solar is low (INR 1.4/kWh) in comparison to the high cost scenario (INR 2.4/kWh). The growth in electricity generation means significant pace of capacity addition for solar as well. Even under the highest PV cost and low economic growth scenario, we see capacity addition of 91 GW during 2025–30, and 161 GW during 2045–50. Median capacity additions in our medium economic growth scenario set stand much higher at 190 GW and 567 GW for the two-time periods respectively. Our scenarios without integration cost in a way implicitly mean that the costs of solar and storage for integrating it decline at a fast pace.

In our medium cost trajectory, the average cost of solar-based electricity declines to INR 2.5/kWh by 2030 and further to INR 1.9/kWh in 2050. In the optimistic scenario, we assume the cost to fall to INR 2/kWh and INR 1.4/kWh by 2030 and 2050 respectively. As in these results the VRE integration cost is not levied on solar producers, the best case scenario in a way also presents the implications of sharp decline in the cost of storage technologies along with the cost of solar panels. The INR 2/kWh in 2030 and INR 1.4/kWh in 2050 as the cost of solar energy in the best case reflect that significant advancements have been made in the storage technologies along with declining cost of solar panels and cost of borrowing. In absence of any additional integration cost, this is a significant pace of decline and this increases the pace of solar-based capacity additions significantly, as shown in Figure 4a.

Within our range of scenarios, we also capture some storyline-based scenarios. Appendix 2 presents the electricity generation mix for the scenario with 'low fossil cost and high non-

Figure 4: Electricity generation by key technologies (range across scenarios) – India

a) Electricity generation range by technology WITHOUT grid integration cost levied on VRE producers

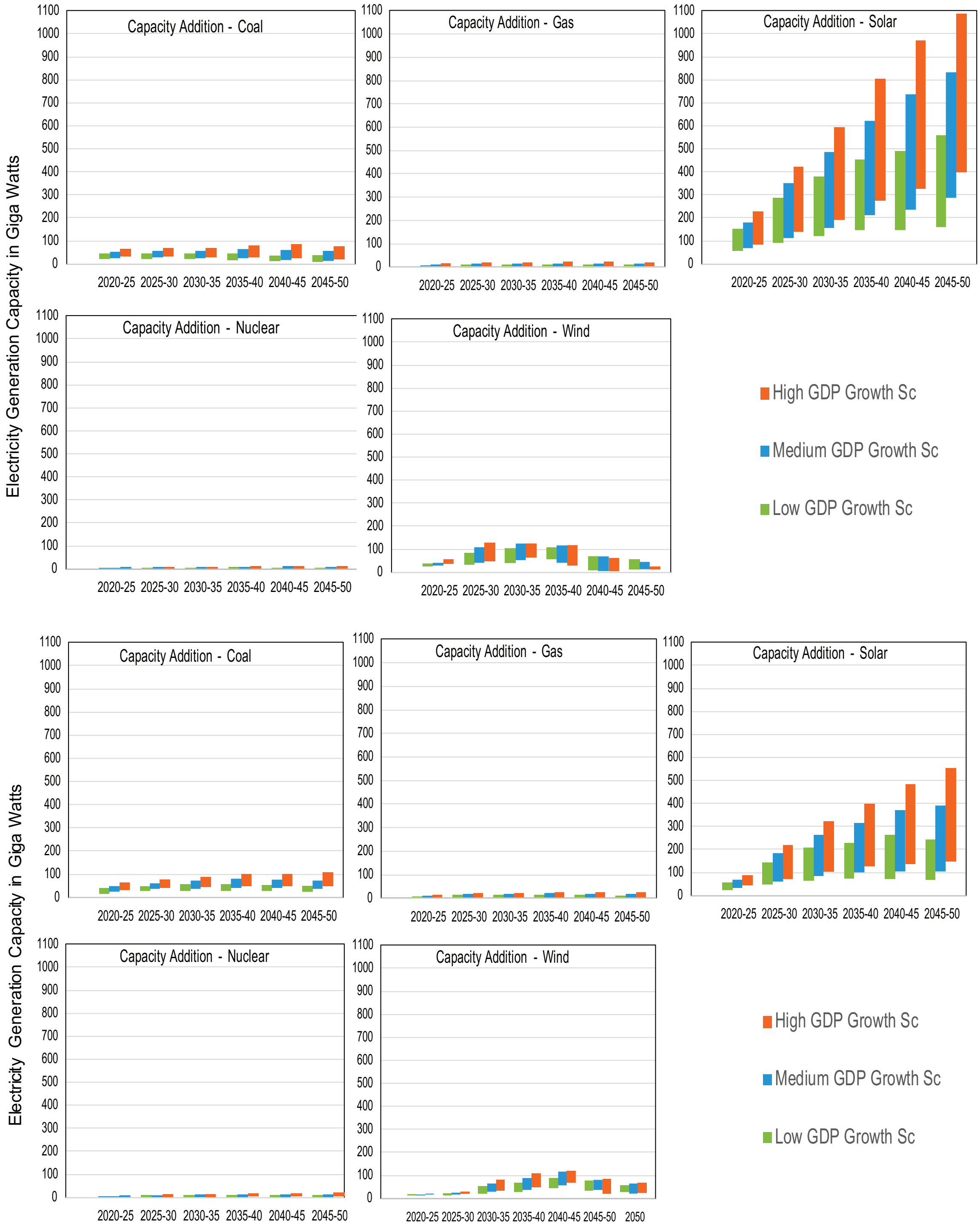


b) Electricity generation range by technology WITH grid integration cost levied on VRE producers

Source: CEEW Analysis, 2018.

fossil cost', 'high fossil cost and low non-fossil cost', as well as what we present as our reference scenario, which is defined in section 2.8. The results, as expected, show the very different electricity generation profiles for India for up to 2050, depending on the underlying relative costs. Any of these could be a potential future, given the underlying developments in the cost trajectories of various technologies. The utility of uncertainty assessment is to step away from looking into any one of these possible futures and derive conclusion based on

Figure 5: Electricity generation capacity additions by key technologies (range across scenarios) - India



Source: CEEW Analysis, 2018

these. The profiles of various electricity generation technologies, when presented based on cost and economic growth related uncertainties, help us in a robust understanding of future evolution of the electricity generation sector.

Penetration of both gas and nuclear on the basis of cost competition is relatively low, even in the long run (Figures 4a and 5 a). In the short run, we do not see a high increase in the penetration of nuclear energy in India's power generation mix even under the low cost scenario (3.95 INR/kWh, representing a mix of imported and domestic nuclear power plants (NPPs)). Penetration of NPPs is very sensitive to the cost of generation, and cost might be an impediment to India's high nuclear energy ambition. Our assessment finds that if the average cost of nuclear-based electricity increases to INR 5.5/kWh (2015 prices) or more, there is effectively no capacity addition irrespective of economic growth trajectory or the cost of competing technologies as included in our assessment. If the average generation cost is lower at INR 4/kWh or below, we see capacity addition 5–8 GW during 2025–30 and 4–9 GW during 2045–50 across all economic growth and technology cost scenarios (Figure 5a). Going by the developments at the international level, costly imported NPPs might have only a limited role even in the long run. This could change if India is able to reduce the cost significantly either through local manufacturing or through successful scale up and commercialisation of domestic technology. On the basis of economic analysis, we see India's target of 63 GW being achieved only by 2050, and only under the most optimistic scenario i.e. high economic growth, low cost of nuclear electricity, and high cost of all other competing technologies, unless nuclear energy is propelled by a carbon tax or other subsidy mechanisms.

A continuation of high gas prices will have a significantly negative impact on gas power generation in India. Even under a high economic growth scenario set, median gas capacity increases only to 27 GW in 2030 and stays stagnant thereafter if high prices persist. Recent developments in international gas markets offer some hope. A glut, reflected in reduced gas prices will provide fillip. Reduced gas prices will lead to a significant increase in the share of gas-based power capacity. If average gas-based power production prices reduce to INR 4/kWh, median capacity under the medium economic growth scenario set increases to 43 GW in 2030 and 75 GW in 2050. In the larger scheme however, gas will still play a small role even if gas prices decline. It should be noted that the current analysis does not include the added value of balancing and grid services that gas turbines can easily provide. It is therefore likely that the calculated values underestimate the optimal amount of gas power plants for scenarios with higher VRE shares. Gas could have a larger role to play under the carbon-constrained scenario where it will play a role in conjunction with VRE.

Growth in wind power will witness an increasing trend. Even under the most pessimistic scenario, wind power growth continues and capacity additions increase year on year. After solar, wind-based capacity additions will grow at the fastest rate, even higher as compared to coal. In our medium growth scenario, median wind-based capacity addition is 101 GW between 2020 and 2030, and 216 GW between 2030 and 2050. Comparative numbers for coal-based capacity addition are 75 GW and 146 GW. Overall wind potential, assumed at around 310 GW in our study, limits the growth of this technology in the long term. Low CUF means that electricity generation based on this newly added capacity will still be much lower compared to that from coal.

We have not endogenously modelled hydro-based electricity in our assessment, though it is included in our framework and is driven exogenously. Based on IESS scenarios of NITI Aayog, we have assumed that hydro-based power will grow by 25 per cent between 2015 and 2030, and further by 40 per cent between 2030 and 2050. Hydropower is the cheapest source of power, but its growth is muted due to many social and environmental challenges. We do not see it playing a big role in meeting India's electricity needs in the long-term future, though it could play an important role as a storage technology for integrating higher share of VRE in the grid.

Implications of levying VRE integration cost on VRE producers

The key results and insights discussed earlier focus on the scenario when the integration cost is not included in the assessment. When the integration cost is included in the framework over and above the generation cost of solar and wind technologies, the pace of capacity additions in solar and coal changes significantly, though the broader outlook remains the same. We find that levying an integration cost of INR 0.70/kWh in 2025 increasing up to INR 1.10/kWh in 2050 will reduce the electricity generation from solar energy by 50 per cent or more across scenarios (Figure 4b). As solar and wind lose due to levying of integration cost, coal gains from this intervention. Most importantly, coal-based electricity generation keeps growing at the rate of 1.6 per cent per annum between 2030 and 2050 instead of stagnating even in the worst case scenario.

Though the rate of capacity additions in solar will decline if VRE integration cost is levied on producers, we still see a rapid deployment of solar-based power generation capacity (Figure 5b). Solar-based capacity addition under the most pessimistic scenario is 47 GW during 2025–30 and 67 GW during 2045–50, and much higher in the scenarios with lower cost of solar-based electricity. In terms of the role of nuclear and gas-based electricity, we see a negligible change by 2030 irrespective of whether VRE integration cost is levied on solar and wind or not. Between 2030 and 2050, however we do see an increase in the penetration of these technologies when VRE is taxed. In our medium economic growth scenario, median nuclear-based capacity across all 72 cost scenarios is 41 GW in 2050 when VRE cost is levied as against 31 GW when VRE cost is not levied. Respective numbers for gas-based electricity are 53 GW and 41 GW for 2050. Still in the larger picture, their share is much lower compared to both solar and coal-based electricity.

Irrespective of whether integration cost is included in the assessment or not, we find that the 50 GW of under construction capacity of coal, which is expected to come online by 2019, will lead to overcapacity for up to 2025. Though under a high economic growth scenario 235 GW in 2025 will not be an over capacity. Figure 5 presents the capacity addition for key technologies across our scenarios. With the 50 GW of new coal-based capacity, India will not need any new coal power plant up to 2025 if the average GDP growth rate between 2015 and 2025 is below 8 per cent, unless old plants are retired. For an average economic growth rate of 8.5 per cent and above in this period, India might need additional coal capacity.

If the total coal-based capacity is 235 GW by 2025, in all probability it will have to run at a lower CUF, as we do not see the aggregate demand in 2025 at a level where all the electricity generation from fossil as well as non-fossil sources will be absorbed. This also gives an opportunity for rationalising electricity pricing structure. If pricing reforms are undertaken, we can see an uptake in electricity consumption in the industrial sector. This potential opportunity needs to be analysed in detail, which is beyond the scope of present work. However, the analysis does point towards such an opportunity wherein coal power producers do not lose on their investments due to lower utilisation as enough power demand is not realised, as well as India's industrial sector gains if electricity pricing reforms happen.

We can say with a high degree of confidence that how big the per unit cost of integrating VRE will be, as well as who bears this cost will have important implications for how the mix of technologies in the electricity generation sector spans out in the future. Still, we do not see an absolute decline in coal-based electricity generation, and we see a significant increase in solar-based electricity generation even in the most pessimistic scenario. How a higher share of VRE increases the system-wide cost averaged over units of total electricity produced across all technologies, and how this increase in cost (if any) is distributed across VRE producers, the government, or the end consumers does matter, but it does not alter the broader character of India's electricity generation future, which is going to go the solar way in the near and long- term future.

Sensitivity Analysis of VRE integration cost

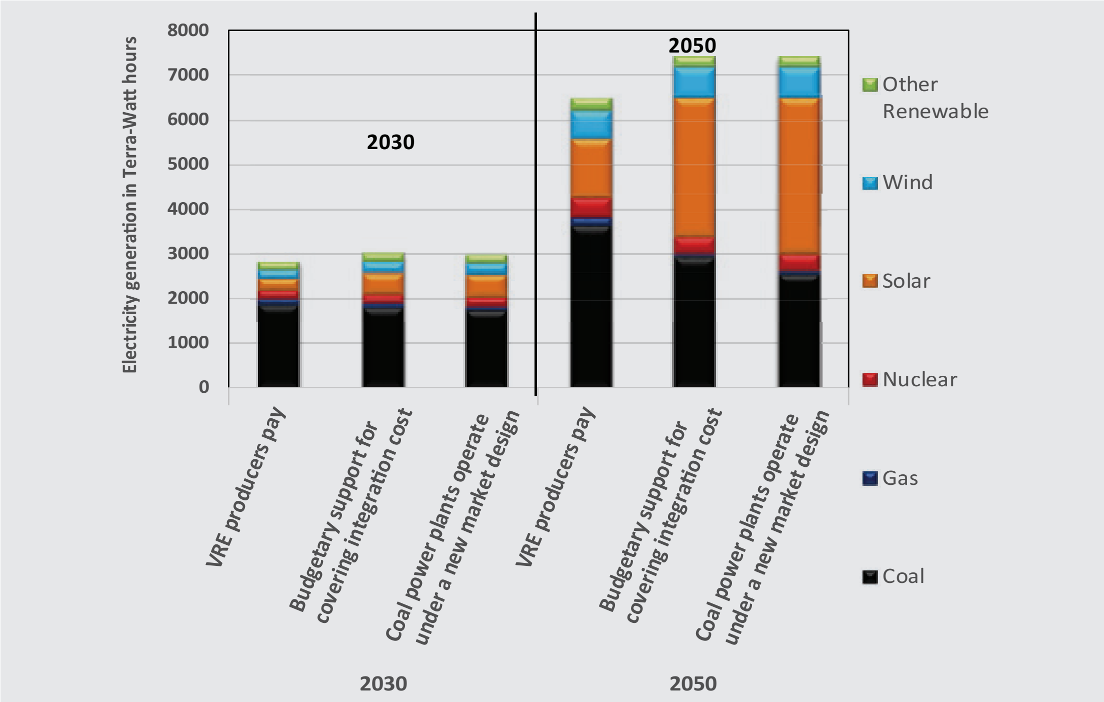
Our analysis assumes the cost of integration based on what is currently being experienced in India, along with the insights from European studies, as well as inputs from key experts. It is important to highlight that this variable is important, and we would be able to make a robust assessment only on the basis of a detailed India-specific analysis. In absence of a detailed India-specific analysis, we also undertake sensitivity analysis on VRE integration cost to see if our key insights change due to this variable. We experiment with the VRE integration cost assumption that is higher than the VRE integration cost we have assumed for 2030 and beyond to see if our results change significantly. Results are presented in Appendix 3, and Table 1.3 in Appendix 1 compares the VRE integration cost assumption that we have used for our analysis against that used for the sensitivity analysis. We see that if in the long term, VRE integration cost increases by 40 paisa (INR 1.5/kWh as against INR 1.1/kWh), we do see a change in the quantitative results. However, we do not see a change in the magnitude and direction of our results, and the key insights in terms of how we expect India's electricity generation mix to evolve. Our insights from the uncertainty analysis hence are robust

5.3 Political economy of VRE integration cost and market design

The evolution of shares of various technologies is also a matter of the political economy of VRE integration costs and how these are distributed. We have presented our outlook for the future of India's electricity generation sector both with and without grid integration cost being included in the assessment. The set of scenarios with no integration cost represents a future in which the government is ready to provide budgetary support for covering the integration costs, whatever these may be. The government might choose to bear the cost of integration for pushing VRE, or it might favour a market design in which coal power plants operate at a lower CUF and are used for mid-peak and peak load requirements which increases their cost of production i.e. coal power producers bear this cost reflected in higher cost of coal-based electricity as the CUF declines. The third scenario is that the VRE producers internalise the cost of integration which is represented by our second set of scenarios with integration cost included in the assessment. Without any government action, the integration costs will be borne by all generating capacity, albeit at different shares. Exploring how the current market design will distribute integration costs will require research using detailed investment and dispatch modelling.

While we present in detail the implication of VRE integration cost on India's electricity generation future if the government pays or the VRE producers pay, what is also important to assess is what does this mean in terms of the budgetary outlay if the government is ready to provide the budgetary support. We analyse and present the budgetary support, for our reference scenario as defined in section 3.8, that will be required to support a higher penetration of VRE if the government is ready to provide this support. We also compare the electricity generation under three scenarios- when VRE producers pay for integration cost, when government provides budgetary cost for covering VRE integration cost, and an illustrative scenario wherein the coal power plants operate under a new market design in

Figure 6: Political economy of VRE integration cost and market design



Source: CEEW Analysis, 2018

which the CUF of new (to be built) coal-based power plants is reduced for meeting mid-peak or peaking requirement. In this illustrative scenario, we reduce the CUF of new investments in coal-based power plants to 75 per cent in 2030, and reduce it across all future years up to 60 per cent in 2050 and compare this with our reference scenario. In both these scenarios, the VRE producers do not bear the cost of integration. This lets us test the scenario when the government only partially bears the integration cost, VRE producers bear no cost and a new market design is adopted under which coal power plants bear the VRE integration cost in terms of reduced CUF (*UE, the largest component of VRE integration cost*). The economic growth and technology cost assumptions remain same across all three scenarios. If new investments are still made, this means that these power plants are profitable even if they operate at a higher price point.

Figure 6 shows the electricity generation mix under these three scenarios. The results for the first scenario when VRE producers pay show implications of a scenario where the integration cost has been internalised. Our second scenario shows implications of government intervention, when the government provides budgetary support for covering the cost of VRE integration instead of the VRE producers or coal producers. As the cost of integrating solar and wind is borne by the government, we see a significant increase in their share. In this scenario, the government will need to bear a significant outlay, totalling INR 215,000 crores (USD 33.1 billion) between 2021–30, and over INR 3,750,000 crores (USD 577 billion) between 2030 and 2050. As compared to this, the subsidy received by power distribution companies in India, in current prices, was INR 36,758 crores (USD 5.65 billion) in 2013-14, INR 45,584 crores (USD 7.01 billion) in 2014-15, and INR 55,283 crore (USD 8.51 billion) in 2015-16 (PFC, 2016). This budgetary burden however propels the share of solar and wind to more than 52 per cent in electricity generation by 2050, compared to 30 per cent when VRE integration cost is levied on VRE producers. A part of this subsidy can be supported through dedicated taxes like coal cess. The coal cess collected from 2010–11 to 2016–17 was of the order of INR 56,600 crores (USD 9 billion). The amount collected in the next 15 years will be big enough to provide significant (if not enough) financial support to address the VRE integration cost.

The government will need to bear an outlay totalling INR 215,000 crore (USD 33.1 billion) between 2021–30, and over INR 3,750,000 crore (USD 577 billion) between 2030 and 2050

When we move from this scenario to a scenario where the electricity generation system works under a different market design, we see that the generation mix is very similar compared to the second scenario, though coal use reduces further compared to the reference scenario. In this scenario, we assume that the average CUF of new coal power plants will keep on declining, as these would be allocated for meeting mid-peak and peaking requirements. This however does not mean that coal-based generation is losing money. This implies that there will be a new market design and architecture. Under this design, coal power could meet the requirements of mid-peak and peak load, hence will be much more expensive to produce, but will still be profitable. For pushing a higher share of VRE, such a market design might be imperative, but continued use of coal for power generation for meeting any market requirement will lead to continuous increase in carbon dioxide emissions from the power generation sector. Alternatively, the role of coal as peaking plants can also be performed by gas-based power plants, and only a detailed analysis can highlight the potential role of these competing fossil technologies under a new market design.

Table 2: Cumulative VRE integration cost across scenarios (billion US$, 2015 prices)

	2021-25	2026-30	2031-40	2041-50
VRE Producers Pay	3.8	13.9	8.7.4	21.1
Governement Pays	7.6	26.6	163.5	413.9

Note: The per unit integration cost is assumed to be the same, only the number of units of VRE generation is almost double when VRE integration costs are not borne by the producers.

Source: CEEW Analysis, 2018

A similar discussion is also presented in Annaluru and Garg (2017), who argue that the most carbon and cost-efficient path to integrate VRE into India's grid would be to operate existing coal power plants as peaker plants instead of base load plants. The political economy and how the VRE integration costs will be distributed is a political choice. This choice does have important implications. If the government wants to move towards an alternative market design and structure, then coal power plants would have to work under entirely different market conditions, and VRE would take on a high share in India's grid. If, on the other hand, the integration cost is internalised, coal power producers would still have some share in new investments even up to 2050. In such a scenario, the government would have to provide additional incentives to propel VRE to a higher share in the generation mix if that were the desired policy objective. Ultimately, political economy of VRE integration cost, and who bears this cost, matters for the future of India's electricity generation mix.

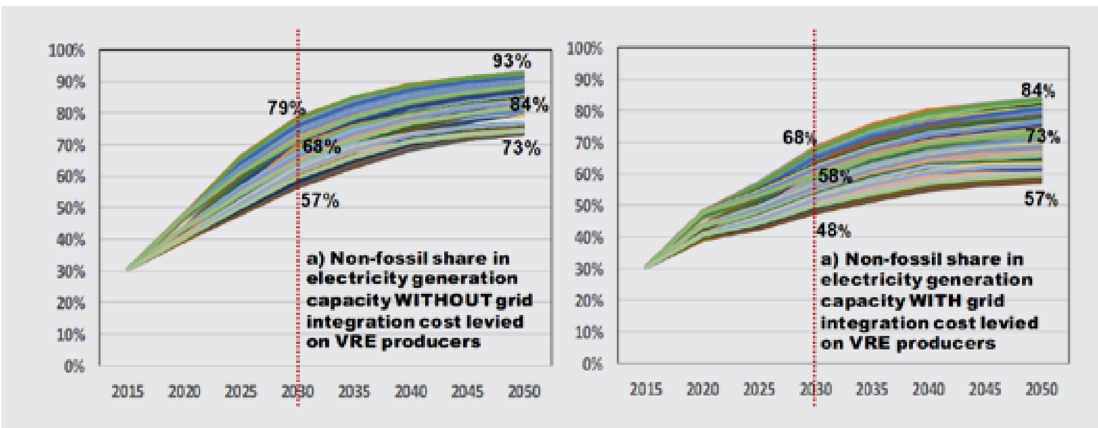
5.4 Progress towards NDC target of non-fossil share in electricity generation mix

Our scenario set explores the uncertainty in technology costs and economic growth, rather than a dedicated carbon policy. The uncertainty approach is important for answering open questions like – Will India achieve its NDC targets or not? Open questions such as this are not questions related to a policy instrument and the wider scenario set spanning some key uncertainties helps us in deriving a robust answer to such questions.

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 (Figure 7a). Even under the most pessimistic scenario, we find that the share of non-fossil in generation capacity will be at least 57 per cent in 2030 across 216 scenarios. Under the most favourable scenario representing low cost of solar, wind and nuclear and high cost of coal and gas, and high economic growth, this share could increase to 79 per cent (Figure 7a). If, however, a detailed assessment finds that there will be additional system-wide costs for integrating a higher share of variable renewable energy and if this cost is levied at least partially on VRE producers, the share of non-fossil will come down significantly. We find that if an integration cost of INR 0.70 – 0.75/kWh-VRE is levied from 2025 onwards, the combined share of solar and wind is reduced by 9 percentage points by 2030, compared to scenario when this cost is not levied. Still, the least share of non-fossil in generation capacity that we get in 2030 is 48 per cent. We expect a strong commitment by the Indian government to push RE in the Indian energy generation mix to show positive results.

The increase in the share of non-fossil sources, however, comes at a cost. The decline in costs of solar-based electricity is not merely driven by the global drop in the cost of this technology. Interventions by the GoI have changed the direction of the market. Wind energy deployment in India was heavily supported in its initial stages through fiscal interventions like feed-in tariffs and accelerated depreciation. The game-changing intervention, arguably, was the announcement of targets of 100 GW of solar and 60 GW of wind for the year 2022. This announcement was a strong policy signal to investors, as well as other stakeholders, regarding a long-term and credible government commitment for enhancing the share of these technologies in India's electricity generation mix. After this announcement, a host of fiscal and non-fiscal measures have been adopted by the government for moving towards this commitment. Two fiscal measures have been exemption from wheeling charges, and a must-run status for wind

Figure 7: Share of non-fossil energy in India's electricity generation capacity



Source: CEEW Analysis, 2018

and solar power plants, along with continuation of accelerated depreciation (at reduced rates) for wind power plants. Creation of solar parks, announcement of green highways, refinement in contract structures, etc. have been some major non-fiscal interventions, which have led to the creation of a streamlined market for both these technologies. This has, in turn, resulted in reduced risks and lower cost of financing, particularly for solar power projects. The strong policy signal, combined with on-ground fiscal and non-fiscal interventions, have created a push for further and continued decline in the costs of these technologies. The budgetary and administrative burden borne by the government has ensured that the market is set to move in the direction of high share of solar and wind in India's energy mix.

Our uncertainty assessment shows that due to decline in technology costs in the past three years, and due to the Indian government's proactive RE policies, India will at least exceed its stated NDC target of raising the share of non-fossil energy sources in electricity generation capacity to 40 per cent by 2030. This gives India space for enhancing its ambition for the 2030 mitigation target. This, however, will come with its own set of challenges, particularly RE integration. Our analysis focuses on the critical issue of integration cost. The NDC targets, related to the share of non-fossil sources as well as that of reduction in India's EI of GDP, could be enhanced. However, Indian policymakers need to deal with 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.

6. Outlook for India's Long-Term Energy Sector Carbon Dioxide Emissions

6.1 Long-term carbon dioxide emission trajectories for up to 2100

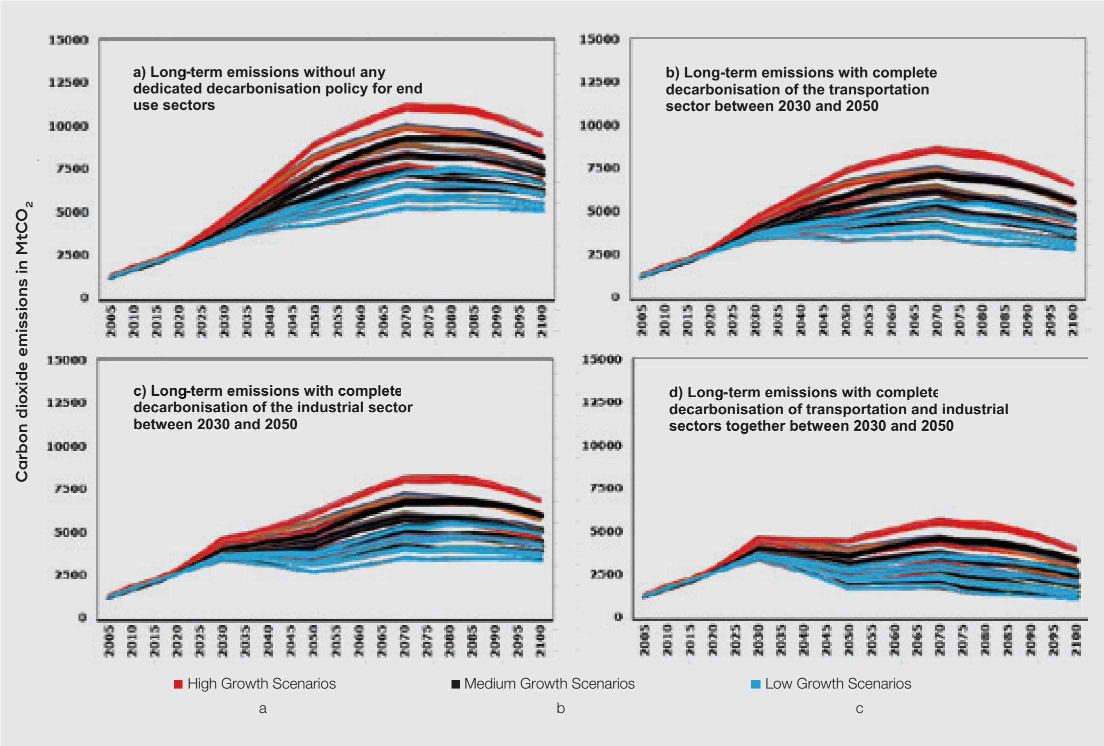
Emissions and climate change debate is a debate that takes a long-term, century long, view of the issue as climatic change happens at decadal scale. At the same time, actions need to be undertaken in the near term to ensure that we are on a trajectory that is consistent with the long-term pathway for achieving climate policy objectives. Under the Paris Agreement, NDCs focus on targets for 2030, and the Mid-Century Strategy on targets for 2050. All these submissions and commensurate actions need to be consistent with the global emission pathway for achieving 'well below 2 Degrees' goal, which is a target for the end of century.

Our uncertainty analysis presented till now focuses on the electricity generation sector which is a major source of India's carbon dioxide emissions. However, the role of other sectors-buildings, industrial, and transportation, is also critical in the emissions debate. Each of these sectors needs to be analysed in detail for devising sector-specific interventions, which is outside the scope of this study. We do, however, provide some critical high-level insights for energy and emissions from India's end-use sectors. Our modelling analysis and model time horizon extends up to 2100. While we present results for the electricity generation sector for up to 2050, we present India's potential long-term trajectories for up to 2100, and then analyse what interventions would be required for both 2030 as well as 2050 to remain on a path that is consistent with a global 2 Degrees C mitigation pathway.

Will the significant progress in India's electricity generation sector translate in terms of stabilisation of carbon dioxide emissions in absolute terms? We present long-term emission results across 216 scenarios. It should be highlighted here that this set of scenarios only explores the uncertainties in the evolution of the electricity generation sector. Changes in end-use sectors like industry and transportation reflect improvements in energy efficiency, as well as some shift in fuel mix due to change in average cost of electricity across scenarios. We hence present four panels, showing the impact in terms of decarbonisation of industrial and transportation sectors, as well as long-term emissions if there is no dedicated attempt to decarbonise these sectors.

We present results in four different panels in Figure 8. Panel 'a' reflects emission scenarios wherein no dedicated decarbonisation interventions are undertaken in the industrial and

Figure 8: India's long-term energy sector carbon dioxide emissions



Source: CEEW Analysis, 2018

transportation sectors. Panel 'b' reflects emissions across scenarios when the transportation sector is completely decarbonised between 2030 and 2050, panel 'c' does the same for the industrial sector, and panel 'd' assumes complete decarbonisation between 2030 and 2050 for both these sectors together. The range across scenarios reflects the implications of our uncertainty analysis for emissions from the electricity generation sector as well as for emission trajectories due to changes in the energy use and mix in end-use in response to changes in electricity prices. This juxtaposition shows some interesting insights.

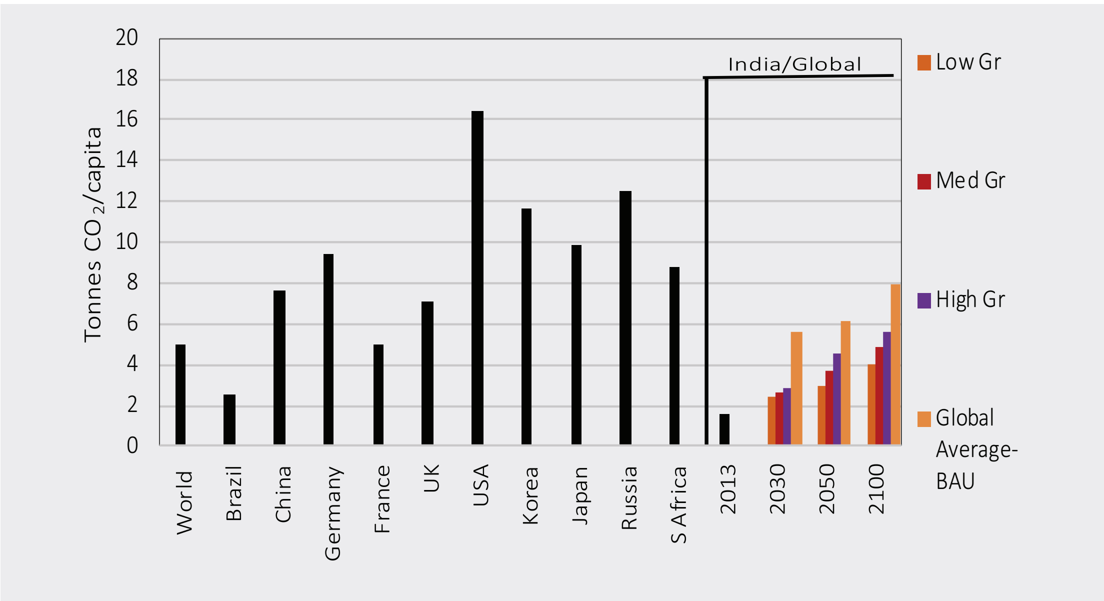
Panel 'd' shows that if the industry and transportation sector were completely decarbonised by 2050, then India's long-term emission trajectory would largely stabilise beyond 2050. This reveals that emissions from other carbon dioxide emission sectors, mainly the electricity sector will show only a small increase post 2050. The increase between 2050 and 2070 is due to increase in electricity sector emissions, which increase under most of the scenarios for up to 2070, and then a decline to 65 per cent-75 per cent of the 2050 level by 2100. A 25 per cent higher share of non-fossil in electricity generation by itself reduces economy-wide emissions by 16 per cent to 17 per cent. For deep mitigations in this sector, only a dedicated carbon policy, like a carbon tax or an emission cap, would be able to help.

Panel 'a' shows the implication of scenarios where the industry and transportation sectors are not decarbonised. We see that in absence of dedicated policies focused on carbon dioxide mitigation in these sectors, India's emissions would keep on increasing at least till 2065 after which these will stabilise and finally decline under both the high and medium economic growth scenarios. The level of income and consequently emissions in 2050 is much lower in the low economic growth scenario set compared to the medium and high economic growth scenario sets. Because of the lower base, the post 2050 growth rate (for both GDP and emissions) under the scenario which has lower growth rate till 2050 could be expected to be higher as compared to the post 2050 growth rates of the other two economic growth scenarios. Total emissions keep increasing across scenarios up to 2065 because emissions from electricity generation, industrial energy use, and transportation sector all increase. Industrial sector energy use is dominated by fossils, and in transportation sector also emissions increase as we do not see a significant shift towards electricity-based vehicles unless there is a significant drop in their cost.

In terms of per capita emissions, however, India's emissions will be lower than the global average per capita emissions in the reference scenario, not just up to 2050, but also up to 2100, even under a high GDP growth rate scenario (Figure 9). Our reference scenario does not include dedicated decarbonisation policies by nations across the world. If other countries achieve deep decarbonisation targets, and India does not, then this result will not hold. For example, if the EU region achieves a decline in carbon dioxide emissions of even 70 per cent by 2050 as compared to 1990 levels, its per capita emissions will be below 2.9 tCO_2 in 2050.

In terms of per capita emissions, however, India's emissions will be lower than the global average per capita emissions in the business-as-usual (BAU) scenario, not just up to 2050, but also up to 2100

Figure 9: India's long-term per capita carbon dioxide emissions across scenarios



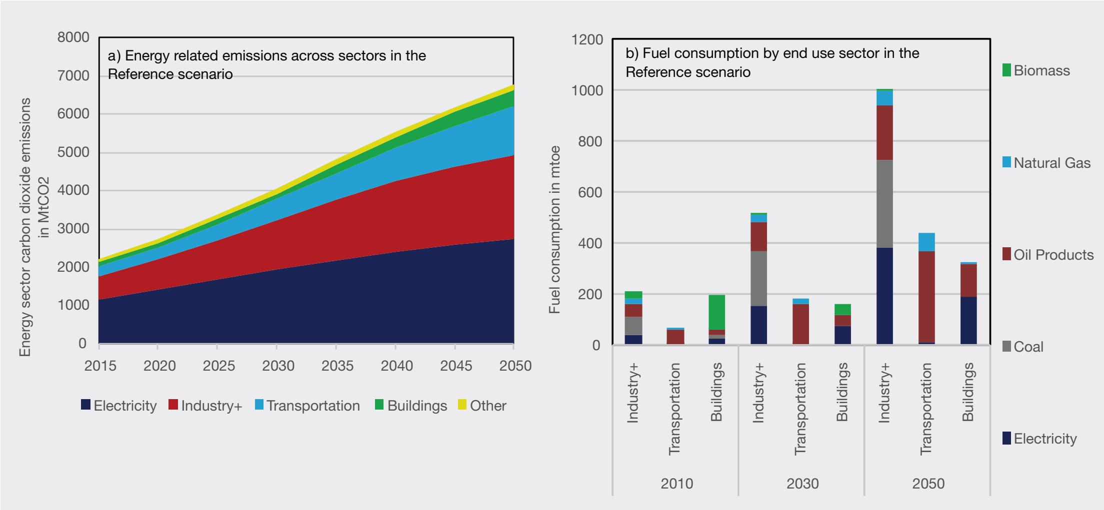
Source: CEEW Analysis, 2018

6.2 Role of end-use sectors in India's energy and emissions

Carbon dioxide emissions are a consequence of fossil fuel consumption in different sectors. Our assessment focuses on uncertainties related to the electricity generation sector, which is a major source of India's carbon dioxide emissions. Fuel consumption also happens in the end-use sectors, and understanding the uncertainties related to growth of energy and consequent emissions in end-use sectors is also very important. We present results from our reference scenario (Section 3.8) to understand the role of end-use sectors in India's energy and emissions debate. We present our results for up to 2050.

We find that electricity sector will continue to play a major role in India's energy consumption related carbon dioxide emissions (Figure 10a). As shown in Figure 4, coal-based electricity

Figure 10: Fuel consumption and associated emissions across sectors



Source: CEEW Analysis, 2018

generation will continue to play an important role in India's electricity generation in absence of any dedicated climate policy. Apart from the electricity generation sector however, we find that the industrial sector will be a big source of India's carbon dioxide emissions.

Figure 10b shows the evolution of fuel mix across end-use sectors in India. Our results for 'Industry+' include energy and emissions from both the industrial and agricultural sector. The consumption of fossil fuels in India's agricultural sector is very low, though this sector consumes 18 per cent to 20 per cent of India's electricity generation, which is reflected in our results. India's industrial sector's energy mix is predominantly based on fossil fuels which account for more than 80 per cent share, with electricity accounting for rest of the share. We find that commercial energy consumption in India's industrial sector (excluding agriculture) increases by over 5.7 per cent compound annual growth rate (CAGR) between 2015–30, and at 3.4 per cent CAGR during 2030–50. We do expect shift towards electricity – by 4 percentage points between 2015 and 2030, and further by 9 percentage points between 2030 and 2050. We can conclude that in the absence of a dedicated policy for increasing the share of electricity in India's industrial sector, we will see it depend largely on fossil fuels, mostly coal and then oil, though the share of electricity will increase compared to the current level.

Apart from electricity generation sector and industrial sector, another important end-use sector in terms of direct emissions is the transportation sector. This sector witnesses the fastest growth in final energy consumption across sectors. As people become wealthier, the ownership of cars increases and the share of public transportation in India's passenger transportation service decreases. Even though technology efficiency increases at the vehicle level, overall growth in passenger service demand as well as move towards private ownership of vehicles increases energy consumption in India's transportation sector manifolds. The share of this sector in India's commercial final energy consumption in 2050 is 24 per cent. This leads to an increase in the share of direct emissions from the transportation sector from 11 per cent in 2015 to 19 per cent in India's total energy sector-related carbon dioxide emissions in 2050.

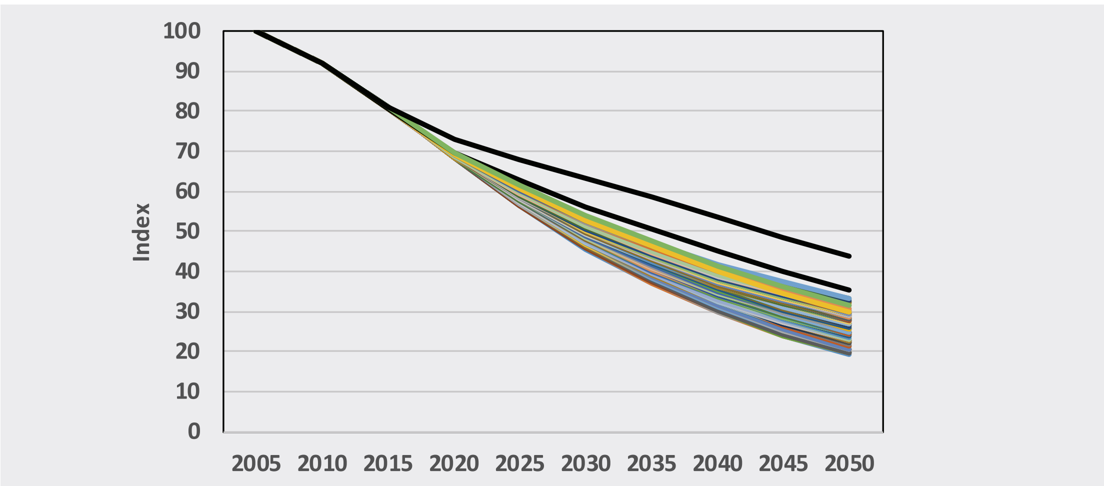
Direct emissions from India's buildings sector are largely because of the use of fuel for cooking, which is dependent on traditional biomass or LPG. All other key services are mainly dependent on electricity. Though water and space heating might also be dependent on non-electricity sources to some extent, the penetration of these is very low. Overall, the impact of this sector in India's carbon dioxide emissions is largely through electricity consumption, as one-third of India's electricity is consumed in this sector. As in the reference scenario coal forms an important part of India's electricity generation even in 2050, indirect emissions due to electricity consumption in the building sector are equal to over 900 $MtCO_2$. This is after significant energy efficiency improvements in appliance use as well as building envelop across the next few decades.

6.3 Progress towards NDC target of reduction in EI of India's GDP

One of the targets of India's NDC is reduction in India's EI of GDP by 33 per cent to 35 per cent between 2005 and 2030. EI reduction is not only due to the electricity generation mix moving towards RE, but also due to significant energy efficiency improvements in the end-use sectors. We find that EI of GDP reduces by 48 per cent-54 per cent across all 216 scenarios by 2030, and by 70 per cent-81 per cent by 2050, relative to 2005 (Figure 11). This, however, could change significantly, by up to 11 percentage points by 2030, due to some key sensitivities in the end-use sectors explained later. As our analysis focuses only on the carbon dioxide emissions from energy systems, CO_2 from land-use as well as other GHGs are excluded in our analysis.

A large part of this reduction can be attributed to the developments in the electricity generation sector. We do not see any substantial shift towards low-carbon fuels and electricity in the industrial and transportation sector in absence of dedicated decarbonisation-focused interventions (Figure 10). 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 lower pace particularly after 2030, when private vehicle ownership increases at a fast pace.

Figure 11: Decline in energy sector-related EI of GDP across scenarios



Source: CEEW Analysis, 2018

Strong fiscal and non-fiscal policies adopted by the GoI for pushing RE in India's electricity generation mix would lead to a higher reduction in India's EI of GDP as compared to the NDC target, even if decarbonisation in the industrial and transportation sector were marginal. As mentioned earlier, fiscal and non-fiscal support provided by the Indian government for the RE sector – as well as interventions for enhancing energy efficiency of industrial and buildings sector, including appliance efficiency standards – all have led to a significant progress in reducing the EI of India's economy. We expect India's economy to continue reaping the benefits of these interventions in terms of declining EI of GDP in the long run.

The impact of energy efficiency improvements, electricity penetration, and energy demand growth in the end-use sectors on EI of India's GDP: Exploring key uncertainties

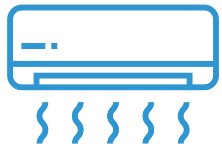
Our results reflect an aggressive rate of energy efficiency improvements, as envisaged by policy makers, across all the three end-use sectors that we model, i.e. buildings, industry and transport between 2010 and 2050. Along with significant energy efficiency improvements, we also assume a higher share of electricity generation in India's industrial sector in the long run, an increase of four percentage points between 2015 and 2030, and further by nine percentage points between 2030 and 2050, based on the belief that a large part of new industries being set up will use electricity- based operations to the extent possible given the operational constraints. The rate of energy efficiency improvements, along with a higher penetration of electricity in India's fossil dependent industrial sector, leads to the significant decline in emission intensity of GDP between 2005 and 2030, and further, as shown in our results. However, there are big questions around the rate of efficiency improvements that India will actually achieve across sectors in the future, as well as the rate of electrification in the industrial sector. Over these uncertainties, there is a big uncertainty related to the growth of energy demand in the fossil intensive industrial and transportation sectors. The Government of India has been pursuing aggressive policies for accelerating the share of manufacturing in India's GDP. If this happens, energy demand will also accelerate for meeting a higher growth rate of the manufacturing sector. Similarly, a higher rate of growth in transportation services is another big uncertainty that needs to be understood.

We capture these uncertainties through running three separate scenarios for lower rate of efficiency improvements in each of the three end-use sectors, one scenario with a higher growth rate of energy demand and a lower increase in electricity penetration in the industrial sector, one scenario with a higher growth rate of transportation energy demand, and an integrated scenario will all of these uncertainties together[6]. The integrated scenario presents the worst-case scenario, as assumed by us, where in efficiency improvements in the key technologies and fuels across all end-use sectors happens at a slow rate, energy demand grows at a faster rate in the industrial and transportation sector, and the share of electricity in industrial energy consumption grows only marginally.

In the building sector, the low efficiency scenario is represented with a lower rate of efficiency improvements in the air-conditioning and HVAC technologies, which will be the largest consumers of electricity in the future in India's building sector. Along with the air-conditioning technologies, we also assume a lower rate of building envelop efficiency improvement in our sensitivity scenario, which also directly impacts the demand for electricity for cooling. For all other electricity and non-electricity based technologies in this sector, efficiency improvements as assumed by us are already small in the reference scenario, so we don't change these.

6 Please refer Appendix 4 for energy efficiency assumptions in the end-use sectors across BAU and sensitivity scenarios

For the transportation sector, we assume a lower rate of efficiency improvements in oil and natural gas based cars, and oil based two and three wheelers. For all other technologies the rates of efficiency improvements in the reference scenario are already low, so we do not change these. In the reference scenario, transportation energy demand grows at 5.2 per cent CAGR between 2015 and 2030, and at 4.6 per cent CAGR between 2030 and 2050. In the sensitivity case, the respective CAGR numbers for transportation energy demand are 6.2 per cent and 5.5 per cent respectively for 2015-30 and 2030-50.



We find that a lower rate of efficiency improvements in the air-conditioning technologies and building envelop has a negligible impact in terms of India's economy wide emissions

For the industrial sector, the rate of efficiency improvements in the reference scenario are assumed at 1.8 per cent per annum between 2015 and 2030, and then 0.95 per cent per annum between 2030 and 2050, reflecting an aggressive push by the government on improving the energy efficiency of the industrial sector. For testing the sensitivity of this, we assume a much lower rate of efficiency improvement of 0.70 per cent between 2015 and 2030, and then 0.60 per cent between 2030 and 2050.

Energy demand in the industrial sector will grow at an even higher rate, compared to the reference scenario, if the objectives of the 'Make in India' policy are achieved. In the reference scenario, we find the industrial sector's energy demand grows by 5.7 per cent CAGR between 2015 and 2030, and by 3.4 per cent CAGR between 2030 and 2050. We test a sensitivity to this, with a 6.5 per cent CAGR between 2015 and 2030, and 4.4 per cent CAGR between 2030 and 2050 in energy demand in the industrial sector. In this scenario, we also assume a lower penetration of electricity in the industrial sector. We assume that electricity's share stays at the same level between 2015 and 2030 (compared to four percentage points increase in reference scenario), and increases by only 2 percentage points (compared to nine percentage points in the reference scenario) between 2030 and 2050.

We find that a lower rate of efficiency improvements in the air-conditioning technologies and building envelop has a negligible impact in terms of India's economy wide emissions. EI of GDP declines by only one percentage point in 2050, relative to the reference scenario, and 0.2 percentage points in 2030. This is largely because the share of these technologies in India's emissions in 2050 will be 6-7 per cent, and with cooling technology efficiency that is 35 per cent lower than the reference scenario in 2050, we do not see a significant change in economy wide emissions. Moreover, in our model results we also see that with lower efficiency, people start using lesser service as cooling services become more expensive, reducing the impact of lower efficiency on the increase in electricity consumption. Together, these factors lead to a negligible impact of lower efficiency improvements in building envelop and cooling technologies on the emission intensity of India's GDP. This does not imply that efficiency improvements are not important. There are significant positive impacts of higher energy efficiency improvements in terms of social welfare as well as cost of emission reductions. Relative to the 2005 value however, even a lower rate of efficiency improvements has a significant positive impact of reducing the emission intensity of GDP. The impact of different rates of efficiency improvements on economy wide emissions is however very low in our results. For all other building sector technologies, we have assumed a lower rate of efficiency improvements in the reference scenario itself.

We find, similar to the results of the building sector, that even halving the rate of efficiency improvements in oil-based cars, two wheelers and three wheelers has only a marginal impact on economy wide emissions. For all other transportation technologies in the passenger and freight sectors, we have already assumed a low rate of efficiency improvements in the reference scenario. The economic behaviour in response to lower energy efficiency improvements is similar to that explained for the building sector.

We find a significant impact of lower rate of efficiency improvements in the industrial sector on India's aggregate emissions. If aggregate energy efficiency of the industrial energy use increases by 0.95 per cent CAGR between 2015 and 2030, instead of 1.8 per cent CAGR as assumed in the reference scenario, the EI of GDP increases by five percentage points in 2030, and further four percentage points in 2050, relative to the reference scenario.

We also find that the EI of India's GDP is sensitive to the way energy demand and its mix evolves in India's industrial sector. At present, fossil sources meet almost 80 per cent of industrial energy demand, and electricity's share is less than 20 per cent. In our reference scenario results, the share of electricity increases by four percentage points between 2015 and 2030, and further by nine percentage points between 2030 and 2050. The industrial energy consumption increases by 5.7 per cent CAGR between 2015 and 2030, and by 3.4 per cent CAGR between 2030 and 2050. If, however, the growth rate of industrial energy consumption increases by even 0.8 per cent per annum over the reference scenario, and the share of electricity stays similar instead of increasing by thirteen per cent points by 2050 and the sector is still mainly dependent on fossil fuels, the EI of India's GDP could end up being higher by three per cent points in 2030, and five per cent points in 2050.

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 per cent in 2015, that increases to 13 per cent in 2030. In our higher energy demand sensitivity case, energy demand for meeting transportation sector needs in 2030 increases by 17 per cent relative to the reference scenario. Even if transportation sector emissions increase by 20 per cent relative to the reference scenario in 2030, it would increase India's overall carbon dioxide emissions in 2030 only by 2.5 per cent or so, relative to the reference scenario in 2030. A 40 per cent increase in energy and emissions from this sector in 2030, relative to the reference scenario, would increase India's overall emissions by only 5 per cent in 2030. 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.

The pessimistic scenario, that combines all these sensitivities in one scenario, leads to a significant increase in the EI of India's GDP. We find that in the worst-case scenario, India's EI of GDP declines by only 37 per cent (as compared to 48 per cent in the reference scenario) between 2005 and 2030, and by 56 per cent (as compared to 70 per cent in the reference scenario) between 2005 and 2050. Rate of growth in energy demand, efficiency improvements, and share of electricity are three key sensitivities in India's Industrial sector that will have significant implications for the change in India's emission intensity of GDP. 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.

The role of non-CO_2 gases

The role of non-CO_2 gases, as well as CO_2 from non-energy sectors is also important in overall EI of GDP. The land-use change sector, mainly agriculture and livestock, is a big source of these emissions. Though we have not looked at these emissions in details, our understanding is that the change in land-use related non-CO_2 and CO_2 emissions is very low at best. One set of GHGs that is bound to grow at a fast pace is hydrofluorocarbons (HFCs), which are short lived gases and are also known as super greenhouse gases. India is currently moving away from hydrochlorofluorochloro (HCFCs) consumption as per Montreal Protocol HCFC management guidelines and the large HCFC consumption sectors are currently moving towards HFCs, which will increase India's GHG emissions. As per the Kigali Agreement under the Montreal Protocol, India has to freeze its HFC consumption by 2028, and will need to reduce this to 10 per cent of baseline (2024–26) by 2031. The timelines of the Kigali Agreement imply that India's HFC emissions will increase by at least 2028 and will contribute to at least some increase in India's EI of GDP. The question is: by how much?

A detailed cross-sectoral assessment made by Chaturvedi et al. (2015), found that India's HFC emissions under the BAU would increase to 114 MtCO2-eq in 2030 and 500 MtCO2-eq in 2050. India's participation and agreement to the Kigali Amendment ensures that HFC consumption in India post 2030 will decline, which will reduce potential HFC emissions significantly by mid-century. Recent developments in the Indian market also show that at least some companies are moving towards lower GWP HFCs for some big sectors, which should further reduce HFC consumption. Based on our uncertainty analysis, median value of carbon dioxide emissions in 2030 in the medium economic growth scenario set is 3,927 Mt-CO_2. HFC emissions are based on Chaturvedi et al. (2015) are 2.9 per cent of this value in 2030. After including uncertainties in HFC emissions, GHG EI of India's GDP could be higher by 1-2 per cent in 2030 as compared to energy sector CO_2 EI of India's GDP. Given our understanding of growth in India's other non-CO_2 gases as well as non-energy related carbon dioxide emissions, we believe that decline in India's GHG EI of GDP will not be very different from the decline in CO_2 EI of GDP of India's energy sector.

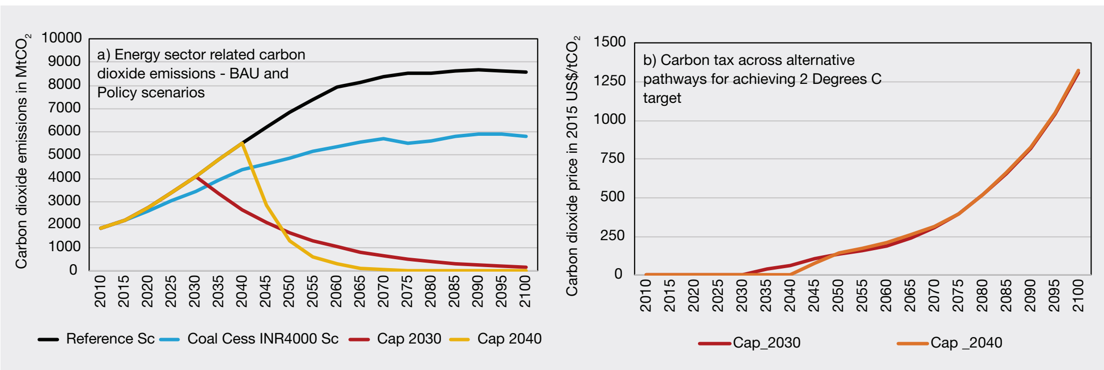
7. Implications of Climate Policies: Carbon Budget, Peaking Year, and Coal Cess

As we show, India's long-term energy sector carbon dioxide EI of GDP will keep on declining at a significant pace on the back of rapid positive developments in India's electricity generation as well as end-use sectors. Even after these positive developments, we find that India's long-term emissions will keep growing to meet the development and aspirational needs of a wealthier population. Dedicated climate policies will be required to mitigate emissions at a faster pace.

7.1 Implications of carbon budget and alternative peaking years

The principle of '*historical responsibility*' has been enshrined in the climate negotiations since the beginning. This principle essentially implies that the countries historically responsible for the high growth in GHG emissions, and consequently, for the problem of global warming and climate impacts should bear the cost for solving it. This is reflected in the other key principle of '*common but differentiated responsibility*' as well. Countries across the world, whether these have been historically responsible for GHG emissions or not, should share the burden of addressing climate change, but in proportionate terms. Historical responsibility along with technical and financial capabilities should determine the differentiated burden of mitigation across countries. These principles are the foundation of the demand from developing countries for an equitable share of the global carbon space.

Figure 12: India's long-term carbon dioxide emission pathways under alternative scenarios



Source: CEEW Analysis, 2018

As against an equity-based allocation, the techno-economic analysis within GCAM-IIM shows that if India were to mitigate its CO_2 emissions to align with the '2 *Degrees C temperature increase limit*', it would have a total CO_2 emission budget of 145 $GtCO_2$ between 2010 and 2100. Techno-economic analysis implies that the global emission mitigation burden is distributed on the basis of cost-effectiveness criteria, that is, emissions should be mitigated where it is cheapest to mitigate. This is determined by the global distribution of cost of mitigation technologies in all supply and demand sectors across countries, and the associated mitigation potential. This does not necessarily mean that the country has to bear the mitigation cost, which can be partially or fully supported through international carbon trading, green climate fund, or any other financial transfer mechanism to India from abroad to compensate for the cost of deep mitigation. This emission budget of 145 $GtCO_2$, based on techno-economic analysis, is different from budget-based on considerations of equity and justice, which have not been analysed. The corresponding global CO_2 emission budget is 1,000 $GtCO_2$ between 2010 and 2100, as highlighted by the Intergovernmental Panel on Climate Change (IPCC). The emission budget would be even lower for a 'well below 2 Degrees C' goal.

Can India push the peaking year to a future year (beyond 2030) and still achieve the carbon budget constraint?

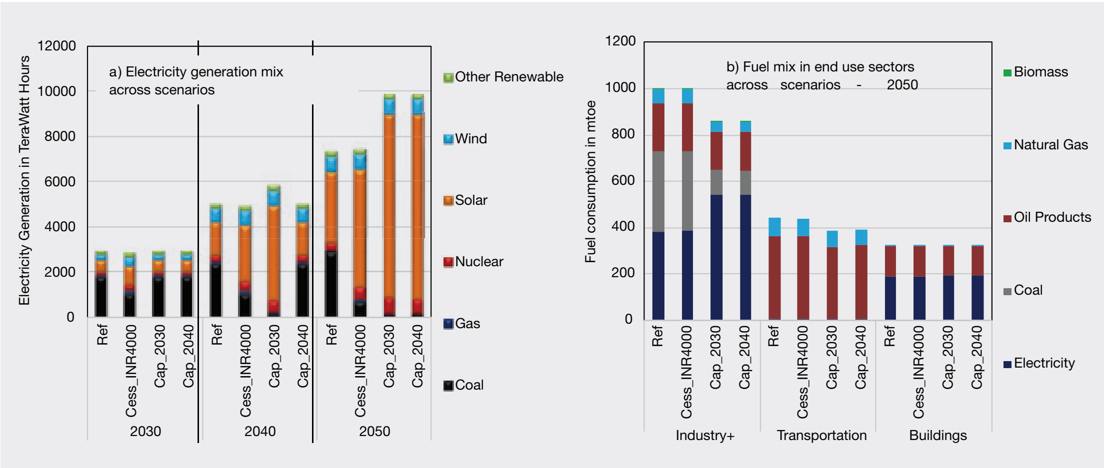
The climate debate is a long-term debate. NDC and 'Mid-Century Strategy' to be submitted under the Paris Agreement are to be aligned with the long-term goals of the Paris Agreement. We construct alternative scenarios that are consistent with achieving the 2 Degrees C temperature increase limit by 2100. There could be alternative pathways for achieving the 145 $GtCO_2$ carbon budget between 2010 and 2100. As NDC targets are on the table for 2030, we first test a scenario in which India peaks its carbon dioxide emissions in 2030, and reduces emissions at a rate that is consistent with the national carbon dioxide budget of 145 $GtCO_2$ between 2010 and 2100, and hence with the 2 Degrees pathway. In this scenario, India's carbon dioxide emissions decline at a uniform rate between 2030 and 2100, by when these are negligible. We depict this scenario with Cap_2030 sc.

In the debate of the peaking year, the interesting question is - can India push the peaking year to a future year (beyond 2030) and still achieve the carbon budget constraint? For analysing this question, we also construct an alternative scenario wherein Indian carbon dioxide emissions peak at 2040 (as an experiment) and then decline at a uniform rate so as to meet the same carbon budget constraints as in the case of 2030 as peaking year. We depict this scenario with Cap_2040 sc. We test these dedicated emission mitigation policies on our reference scenario as defined earlier.

The first interesting insight is that postponing the peaking year to a later date is definitely one possibility, but the rate at which transformation of the energy systems is required beyond 2040 to meet the carbon dioxide budget is very high. Under the 2030_Cap sc, the rate at which India's energy sector-related carbon dioxide needs to decline is 4.4 per cent between 2030 and 2050, which under the 2040_Cap sc, the rate of decline in carbon dioxide emission is 13.4 per cent per annum between 2040 and 2050. Undertaking a transition at such a fast pace could be challenging. This insight is not just true for up to 2050, it is true even beyond 2050 up to the end of century. The average rate of decline between 2050 and 2100 will have to be 4.5 per cent when emissions peak in 2030, versus an average decline rate of above 14 per cent when these peak in 2040. In case it is possible to peak before 2030, then the average rate of required transformation over the long run is even slower. But significant actions will be required in the near term, almost immediately, for peaking prior to 2030. The national carbon dioxide budget constraint based on techno-economic analysis does imply significant transformation of the Indian energy system in the near term. India would need to take on this disproportionately inequitable burden to share the global responsibility of emission mitigation.

Secondly, the level of emissions, as well as the state of energy systems in 2050 would need to be very similar under both Cap_2030 sc and Cap_2040 sc. This is evident from Figure 12a and Figure 13, as we see that the emission pathways for both the scenarios intersect in 2050. Beyond this year, energy systems will have to change very rapidly when peaking year is 2040 instead of 2030, as highlighted earlier, as the emission pathway as highlighted in Figure 12a will need to be followed.

Figure 13: Fuel mix in electricity generation and end-use sectors across policy scenarios



Source: CEEW Analysis, 2018

Thirdly, the implicit value that needs to be put on carbon dioxide will be higher the later the peaking year at least until 2070. Figure 12b shows the carbon tax that will be required for achieving the rate of desired transition across the century in both the peaking scenarios. Peaking at 2030 level and then declining emissions for meeting the 145 Gt-CO_2 carbon budget implies a carbon tax of USD 40/tCO_2 in 2035 and USD 133/tCO_2 in 2050 (in 2015 prices). We see that carbon tax is higher by 5 per cent in 2050 and by 12 per cent in 2065 to achieve the faster rate of transition if peaking happens at 2040 level. The speed at which energy system transformation will be required under the Cap_2040 scenario to achieve the same carbon dioxide budget as under the Cap_2030 scenario will be possible only if a higher negative value is placed on carbon dioxide emissions, which signifies additional burden on the economy in the given period.

The aim of 2030_cap policy is to ensure that overall emissions peak at 2030 level, and then decline in a way that is consistent with the 2 Degrees C target. We see an increase in electricity generation in the end-use sectors (Figure 13b), which is imperative to reduce overall emissions, as also discussed by Shukla, et al. (2015). In this scenario, overall electricity generation increases by 16 per cent in 2040 and 33 per cent in 2050 as compared to the reference sc as fuel mix in the end-use sectors has to shift towards electricity. A bulk of increase for meeting the stringent carbon constraint is in solar energy, due to its low cost in 2050. Our assumption of INR 1.9/kWh (and no integration cost) in 2050 reflects a scenario when solar energy with storage will decline to this value and that there will not be any additional burden due to intermittency related costs. With this cost, solar energy outperforms any other competing energy source, and corners a share of 81 per cent in 2050 under this scenario, compared to 43 per cent under the reference sc. The share of nuclear energy in electricity generation increases only to 7 per cent as compared to 5 per cent under the Ref sc in 2050[7]. Wind energy will achieve the potential of 300 GW by 2040 even under the reference sc based solely on market dynamics, so it does not gain much due to a strong climate policy, unless significant off shore potential is also available at competitive costs.

In our mitigation scenarios, we do not consider CCS for electricity generation. However, if CCS were considered, we expect to see an increase in coal-based electricity generation in 2050, compared to non-CCS sc. CCS could also reduce the near-term burden as it allows for negative emissions (biomass with CCS) in the long run. Current estimates of CCS costs add 57 per cent to the capital cost of non-CCS power plants. It is interesting to note that even with this significant cost increase, CCS becomes an economically viable option if carbon is explicitly valued as a negative externality.

There could be alternative energy system configurations for achieving the Cap_2030 sc. Our analysis presents one such pathway for meeting this constraint based on least cost approach which takes into account the relative costs of competing technologies in the electricity generation sector, as well as improvements in end-use efficiencies and the costs of technologies in the buildings, industry, and transportation sector. Given our current understanding of how these variables will evolve in the future across key energy sectors, our modelling analysis presents the following results for the transition to a pathway consistent with 2030 peaking and 2 Degrees temperature increase limit:

1. The share of non-fossil in electricity generation (as against electricity generation capacity) increases to 97 per cent in 2050, as compared to 55 per cent in the reference scenario
2. The share of electricity in the industrial sector increases to 54 per cent in 2050, as compared to 29 per cent in the reference scenario
3. Final energy demand in the industrial and transportation sectors reduces by 15 per cent-20 per cent by 2050, relative to the reference scenario.

The transformations in our results happen mainly in the electricity generation and the industrial sectors. The role of significant transformations in the transportation sectors appears limited in our results. This shows that in principle, even if the cost of electric vehicles remains high and we see a limited decarbonisation in the transportation sector, India can still peak at 2030 level and reduce overall carbon dioxide emission at 4.4 per cent per annum up to 2050 through a strong focus on the electricity generation and industrial sectors.

However, it is important to highlight here that these results are an outcome of our existing understanding of how technology costs and other parameters evolve in the future across sectors. In the current debate in India, we do see significant policy ambition for the transportation sector, especially a thrust on increasing the share of electric vehicles, though as of now it is not backed by any strong policy instrument. There could be some disruptive innovations and rapid decline in the cost of electric vehicles on the back of government policies and investment in research and development. If the cost of electric vehicles comes down significantly and at a fast pace, the burden on the electricity and industrial sectors will definitely decline with higher decarbonisation in the transportation sector.

7 If the cost of integrating VRE is included in the framework and is levied on VRE producers, we will see at least a doubling of nuclear energy under the Cap_2030 scenario.

We see the industrial sector as a sector where a lot of research needs to be undertaken for a better understanding of technical and economic opportunities for electrification, efficiency improvements, and a structural shift towards less energy intensive sectors. Also, any impact on industrial competitiveness and on jobs due to impacts of energy prices and decarbonisation needs to be assessed before any strategy for this is detailed. Ultimately, an economic evaluation of alternative pathways with different levels of mitigation across the major sectors should be undertaken for finding the most cost-effective solution suited for India, which also ensures that there is no conflict with India's national priorities and sustainable development.

Irrespective of the peaking year, it is clear that significant efforts would need to be undertaken by India to bear the responsibility for the world for mitigating carbon dioxide emissions, and this would be at the cost of equity in the sharing of the mitigation burden.

The sectoral policy of a high coal tax does have a significant impact on the electricity generation sector but fails to have a significant dent in India's long-term emissions

7.2 Implications of a high coal cess

Along with the economy-wide mitigation policies that are consistent with a global 2 Degrees C target, we also test a sectoral mitigation policy. We analyse the implications of a higher cess on coal for the electricity generation sector- INR 4000/ton coal from 2020 onwards. This level of tax is very high and we aim to compare its implications with the economy-wide climate policy. We depict this scenario with CoalCess_INR4000 sc. There are many and varying estimates of the impact of coal cess on final electricity generation prices (PTI, 2015). In our analysis, the cost of coal-based electricity generation increases by INR 2.43/kWh under the Cess_4000 sc, as compared to the reference scenario which already includes the impact of existing coal cess of INR 400/ton coal. The tax rate we have chosen is to illustrate the implications of a high coal cess policy, and should not be read as our suggestion.

As expected, the sectoral policy of this stringency does have a significant impact on the sector, but fails to make a significant dent in India's long-term emissions. The share of coal-based electricity generation declines to 38 per cent in 2030, and further to 10 per cent in 2050 (Figure 13a), though this is still higher than what would be the case under Cap_2030 sc for achieving 2 Degrees C target. This policy however does not have any impact on the energy use in the end-use sectors (Figure 13b), and only a limited impact on the economy-wide carbon emissions (Figure 12a), as overall emissions will keep increasing. A sectoral policy like the coal cess, however, can certainly be pursued in conjunction with other sectoral policies focused on transformations in the industrial and transportation sectors, and the cess collected could be used to fund interventions in the end-use sectors.

7.3 Insights for Mid-Century Strategy

All signatories to the Paris Agreement need to submit Mid-Century Strategy for decarbonisation, for linking NDC to the goals of the Paris Agreement. There are some interesting insights for mid-century pathways from our analysis. We see a significant progress in the electricity generation sector for up to 2030 even in absence of any dedicated decarbonisation policy.

However, between 2030 and 2050 we see that a significant increase in the share of non-fossil energy in India's generation capacity is critically dependent on whether the cost of integrating variable renewable energy is significant, and if this is passed on to the VRE producers. When VRE is not taxed due to the integration cost, median share of non-fossil energy sources in India's electricity generation capacity increases from 68 per cent in 2030 to 85 per cent in 2050 in the medium economic growth scenario set. The comparative values when VRE is taxed are 58 per cent in 2030 and 73 per cent in 2050. For a 2 Degrees C consistent pathway, this will have to increase to 98 per cent by 2050. To what extent will VRE integration cost impede further penetration of VRE sources will depend on the cost of integration, and more importantly on who bears the cost.

The energy sector CO_2 EI of GDP will decline at least by 56 per cent between 2005 and 2050, even under the most pessimistic scenario, and by 80 per cent if there are rapid improvements in energy efficiency across sectors, increase in share of electricity in the industrial sector, and significant decline in the cost of solar and wind technologies; and if VRE integration cost is not levied on VRE producers. For a 2 Degrees C consistent pathway, the EI of India's GDP needs to decline by over 90 per cent between 2005 and 2050.

Our sensitivity analysis of VRE integration costs (please refer Appendix 3) strongly supports this insight. As we have highlighted earlier, estimates of VRE integration cost vary with underlying capital cost of thermal technologies, as well as the extent to which CUF of thermal will be reduced to accommodate higher VRE under a novel market architecture, among other factors like cost of storage. Our scenario analysis highlights that it is critical to understand VRE integration cost for India-specific circumstances. If this cost were significant, this could be a big impediment to increasing the share of VRE in India's grid in the long run.

Another important insight from our results is the criticality of emissions mitigation in India's industrial sector. As per our estimates, industrial sector contributed to 25 per cent of India's emissions in 2015. This sector has a high dependence on fossil fuels, more than 80 per cent. The share of electricity is very low. As per the IESS energy calculator of NITI Aayog, the share of electricity in industrial energy consumption was at 16.2 per cent in 2012. Though we do expect some increase in the share of electricity, we can see that the industrial sector in the long run will still be largely fuelled by fossil sources, unless dedicated policies are in place to avert this.

Mitigating emissions in the industrial sector is complicated. Any policy intervention entails cost, and the cost for India's industrial sector might be its impact on competitiveness and jobs. India is seeking to increase its manufacturing base and its share of exports in global markets, so any policy intervention should dovetail with these objectives. It is critical to understand the energy and emissions profiles of industrial sectors (steel, cement, etc.); analyse decarbonisation pathways for energy-intensive sectors; highlight impacts and trade-offs in terms of growth, competitiveness, and jobs; and devise appropriate response strategies.

8. Sustainable Development, National Priorities, and Climate Policy

India's climate policy has always been framed within the context of poverty alleviation and development. More recently, it has been framed within the context of 'sustainable development goals (SDGs)'. Climate policy also needs to be aligned with national priorities like 'Make in India'. The narrative has started getting prominence in at least the last decade, with few studies also framing the issue analytically and contributing to better understanding of the alignment of mitigation pathways with sustainable development pathways (Shukla, et al., 2008; Shukla and Chaturvedi, 2013; Mathur, 2016; Byravan, et al., 2017). Developing on the analysis undertaken by researchers in the past, we emphasise that the synergies and trade-offs need to be understood in concrete and quantitative terms. We propose a **'CEEW Synergies and Trade-Off Matrix'** for better understanding the alignment of mitigation pathways with sustainable development as well as national priorities. An illustrative matrix schema for year 2050 is presented in Table 3. The idea of such a matrix is to understand whether dedicated emissions mitigation policies will have an impact on sustainable development and national priorities.

For this illustration, we have chosen some key development goals as well as national priorities such as electricity access, electricity generation cost, energy sector jobs, impact on water, and impact on coal sector. We look at all these variables along with total emissions across scenarios to better understand the trade-offs.

We explain the trade-offs with the help of one of the most important policy variables - electricity access. Electricity access has been a focus of the Indian government policy since long, and has received renewed thrust under the new government (Balachandra, 2011; Ahmed, et al., 2014; Aklin, et al., 2016; Rao and Pachauri, 2017). The big question we ask is: Would electricity access be impacted because of deep decarbonisation policies? One of the important concerns of stakeholders in developing countries has been that the cost of emissions mitigation policies will make energy more expensive, which could lead to reduction in purchasing power of consumers, and impact their affordability of energy services.

The CEEW Synergies and Trade-Off Matrix reveals that if India aims at limiting carbon dioxide emissions at 2030 level, there will be no impact as far as electricity access is concerned. Per capita residential electricity consumption increases by over four times in rural households between 2015 and 2050, reaching level higher than that in urban areas currently.

Similarly, per capita electricity consumption increases by 3.4 times between 2015 and 2050. This implies that basic electricity-related services are met both in urban as well as rural areas by 2050, though there is still ample room for growth in the more expensive energy services like air-conditioning in rural areas.

It is interesting that the marginal cost of electricity generation (averaged across technologies) decreases under the stringent climate policy, a finding that could be argued as being counter intuitive. Under the Cap_2030 scenario, most of the electricity production shifts to solar, which is cheapest in the mix. As coal becomes more expensive because of a carbon tax, and solar becomes relatively cheaper (compared to the relative cost under the reference sc), coal use in electricity generation is almost eliminated by 2050 if the carbon budget constraint under the 2 Degrees C target is to be adhered to. Electricity generation is entirely based on solar, which reduces the average generation cost based on new installed capacity. This does not mean that there will not be any cost for the electricity generation system. The cost will have to be borne in terms of stranded assets. E.g. If any coal-based capacity is installed in 2030, with a technical lifetime of 50 years, this capacity will have to be stranded by 2050, i.e. after operating for only 20 years. The cost of stranded capacity is not included in our assessment, but is important to understand this cost and plan accordingly. It is hence critical to ensure that a long-term policy signal is provided to investors for making decisions that do not lead to long-term lock-ins and stranded capacity. The earlier such a signal is provided, the better for investors and the economy.

On the other hand, even if the generation cost increases in 2050 in case the cost of solar and wind is high due to intermittency cost, it would not impact household electricity consumption as per capita income increases by 4–5 times in urban and rural households between 2020 and 2050. In our model, penetration of household appliances increases with increasing affordability, which is a function of per capita income and appliance ownership cost (Refer Chaturvedi et al., 2014). With increasing incomes hence, even a 20 per cent to 25 per cent increase in the cost of electricity would not matter a lot as this does not impact affordability in a big way. Even if appliance energy use is price elastic in our framework, the higher level of incomes dampen the impact of any increase in electricity costs in the long-term future. However, there might be low-income groups even in 2050, for whom increased prices might make electricity unaffordable. The government will need targeted subsidy policies to ensure that the economically weaker sections are not impacted by rising energy prices in case of a stringent climate policy.

Another important policy concern is in terms of the impact on energy sector jobs. We see that as the jobs coefficient of the wind and solar sectors is higher than that for coal, gas as well as nuclear (Rutovitz and Atherton, 2009), the potential for job generation related to the electricity generation sector is very high under the climate policy scenario. A large part of the job potential exists in the manufacturing of solar panels in India. If this is not tapped, jobs generated will be lower. However, in-situ jobs related to installation are in itself a significant potential and will be able to compensate for potential job losses in the fossil sector. With progress happening in automation as the market matures, the quantum and nature of jobs in the solar sector could also change. The cost of mitigation will be borne disproportionately by the coal sector across the supply chain, from coal mining to coal-based power generation. Coal sector will see significant job losses if the stringent climate policy is adopted, and this will be more for states that are heavily dependent on coal for revenue as well as employment generation. At the macro level, this will be more

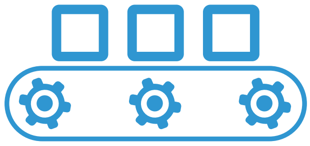
Table 3: CEEW Synergies and Trade-Off Matrix for aligning sustainable development, national priorities, and climate policy

2050							
		Reference Sc	Low Growth Sc	High Growth Sc	Coal Cess Sc	Cap 2030 Sc	
Per Capita Income	Urban	17063	13482	20109	17063	17063	USD, 2015 prices
	Rural	6332	4094	9123	6332	6332	USD, 2015 prices
Emissions	Total emissions	6785	5346	8248	4853	1663	$MtCO_2$
	Per capita emissions	4.09	3.22	4.97	2.93	1.00	tCO_2/capita
Electricity Access	Per capita urban residential electricity consumption	1.38	1.20	1.51	1.39	1.41	MWh/capita
	Per capita rural residential electricity consumption	0.46	0.34	0.59	0.46	0.46	MWh/capita
Electricity Cost	Average generation cost for new investments	2.63	2.62	2.62	2.53	2.31	INR/kWh, 2015 prices
Jobs	Total jobs related to energy generation sector	13.10	9.31	16.77	17.71	27.51	Million FTE
	Wind related jobs	0.35	0.35	0.35	0.32	0.36	Million FTE
	Ground mounted solar jobs	5.77	3.92	7.56	9.39	15.20	Million FTE
	Solar PV module manufacturing jobs	4.35	2.96	5.69	7.08	11.45	Million FTE
	Coal	2.43	1.94	2.95	0.64	0.15	Million FTE
	Gas	0.02	0.02	0.03	0.03	0.00	Million FTE
	Nuclear	0.17	0.13	0.21	0.25	0.34	Million FTE
Water	Water withdrawal-Electricity	8.28	6.69	9.92	4.23	2.13	Billion Cubic Metres
Land	Land requirement	17398	14483	19948	21735	31235	Thousand Acres
	PV	8366	5683	10950	13608	22024	Thousand Acres
	CSP	63	43	82	103	173	Thousand Acres
	Wind	8350	8255	8175	7643	8574	Thousand Acres
	Coal, oil and gas	619	501	740	382	464	Thousand Acres
Coal	Coal consumption (2021-50)	37.80	33.56	42.55	21.93	18.15	Billion Tonnes

Note: Employment coefficients for coal, gas, and nuclear have been taken from (Rutovitz & Atherton, 2009), and for solar and wind have been taken from CEEW (2017).

Source: CEEW Analysis, 2018.

than compensated through employment generation in the solar sector, but it is not necessary that the states that lose coal-based jobs and revenue will be the ones to gain from the solar boom. Also, the nature of jobs and kind of skills required will be very different and Indian policy makers needs to strategise for such a scenario. With progress happening in automation as the market matures, the quantum and nature of jobs in the solar sector could also change with time. Thus, at the economy level, the opportunities for job creation will be significant under the decarbonisation scenario, but there will be difficult choices to be made at sectoral levels for any transition.



With progress happening in automation, as the market matures, the quantum and nature of jobs in the solar sector could also change

India is a water scarce country, and there is increasing pressure on India's water resources. Though as of now electricity sector-related water withdrawals are small as compared to the total water demand across sectors, but high growth in water withdrawals for thermal cooling is expected with increasing electricity generation. The draft notification by the Indian government seeks to limit the water withdrawals from electricity generation plants (MoEFCC, 2015a). Studies have highlighted the importance of this issue for India, as well as estimate future water requirement for electricity generation across different scenarios (Bhattacharya and Mitra, 2013; Chaturvedi, et al., 2017; Srinivasan, et al., 2017). This will put increasing marginal pressure on India's water resources. The CEEW Synergies and Trade-Off Matrix, however, shows that at the level of the economy, the pressure on water resources will be reduced under the mitigation scenario. Water withdrawals will reduce by 75 per cent as more and more solar and wind come into the grid, as these technologies have a lower water footprint. Water, however, is a very local issue, hence even if the macro picture were positive, dynamics as the local level could be very different. For example, the arid state of Rajasthan has high potential for solar energy, but is one of the most water-scarce regions of India. Even a little additional demand for water for cleaning solar panels could be a challenge for such a region. This will be more so for CSP technology, which has a higher water footprint as compared to photovoltaic (PV) based electricity. Future analysis needs to go spatial to understand the trade-offs of climate policy with water withdrawals.

Land required for setting up electricity generation plants will increase under climate policy. Land acquisition is a big challenge in India, and we see this growing in the future with a higher share of solar, which has a higher land footprint. Requirement for land could be an impediment as we see land requirement increasing by 80 per cent under the stringent climate policy in 2050, relative to the reference sc. By 2050, India's population is also expected to increase by at least 20 per cent, and land will get increasingly scarce in the future unless land-use development and management is strategically planned for in the long term. Some of the increased land requirement could be accommodated in unused wastelands as well as in desert regions, but this issue also needs to be analysed in detail.

Air pollution from thermal power plants has also been a very important concern, however with the proposed flue gas desulphurisation of power plants, we are of the opinion that this issue will be largely addressed. Coal use in industries as well as oil use in transportation are however very important from the local air pollution perspective, and should be included in studies focusing on these sectors. We expect this to be a significant co-benefit of climate policies.

9. Concluding Summary and Insights

Together, the NDC and Mid-Century Strategy aim at achieving the long-term decarbonisation goals of the Paris Agreement. Since India submitted its NDC, a lot has changed. We attempt to understand the implications of these changes, especially for India's progress towards achieving NDC and long-term decarbonisation targets, within an uncertainty assessment framework.

We test key uncertainties in technology costs for electricity generation and economic growth. Our assessment encompasses 222 core scenarios and spans uncertainties in the electricity generation sector related to technology cost and economic growth. We test the impact of VRE integration cost and its political economy on India's electricity generation mix. Finally, in our scenarios, we also test the impact of key uncertainties in the end-use sectors for the change in India's emission intensity of GDP.

In terms of dedicated climate policies, we present the implications of a higher coal cess and scenarios with India's CO_2 emissions peaking in 2030 and 2040 and then declining to be consistent with the global 2 °C target. We undertake our analysis within the integrated assessment modelling framework of the GCAM, IIM Ahmedabad version.

Our analysis reveals the following policy insights.

Variable renewable energy (VRE) integration cost

- As the share of VRE in total electricity generation in India exceeds 15 per cent, the cost of integration and its implications could become non-trivial.
- For a robust estimation of system-wide integration cost, we need detailed, India-specific analysis for up to 2050 based on daily and seasonal load curves and supply-side VRE generation information.
- Indian policymakers and experts should deliberate on who should bear the integration cost and arrive at a consensus soon.
- Modelling frameworks and assessments must include VRE integration cost.
- The political economy of the cost of VRE integration and who bears it matters for the electricity generation mix in the future and how ambitious can India be in terms of domestic targets and international mitigation commitments.

Outlook for electricity generation sector

- Electricity generation will grow rapidly. Rising incomes will raise access to electricity and its affordability despite the rising cost of electricity generation.

- If higher penetration of solar and wind raises the system-wide cost of integrating VRE in the electricity sector, and producers bear a part of this cost, coal-based generation will keep on increasing in the long run in the absence of a policy aimed at reducing coal consumption. We assess that there will be overcapacity for the next seven or eight years.
- If VRE producers do not bear integration costs, we see a significant and rapid gain in the share of VRE in electricity generation. If coal power plants bear the cost in terms of reduced CUF, new coal additions will be severely hit by 2030 and onwards. However, this does not mean that investing in coal becomes unprofitable, only that there could be a new market design and architecture. Under this design, coal power could meet the requirements of mid-peak and peak load, and hence be much more expensive to produce, but could still be profitable. Such a market design might be imperative to raise the share of VRE, but continued use of coal for power generation for meeting any market requirement would lead to a continual increase in CO_2 emissions from the power generation sector. Alternatively, gas-based power plants can perform the role of coal as peaking plants, and only a detailed analysis can highlight the potential role of these competing fossil technologies under a new market design. Ultimately, the political economy of VRE integration cost, and who bears this cost, matters for the future of India's electricity generation mix.
- Solar-based electricity grows quickly, even under the most pessimistic scenario, and even when solar producers internalise VRE integration cost. Wind-based electricity generation will also grow quickly; however, its overall potential is limited in India.
- Gas will not play a significant role in India's power sector unless international market dynamics shift significantly and the cost of gas-based power falls. This is true also for nuclear energy-based power generation in India, but its role could be enhanced if policymakers can reduce the cost of nuclear-based electricity through interventions like domestic manufacturing.

India's progress towards NDC targets

- India is on the path to achieve, and even exceed, NDC targets, due largely to significant penetration of VRE sources, supported by strong fiscal and non-fiscal interventions by the GoI.
- India's NDC can be enhanced – if Indian policymakers can deal with the cost of integration and other costs of direct fiscal and non-fiscal support. But we do not have enough credible information to conclude if this cost would be high or low; we need in-depth, long-term, India-specific assessment.
- By 2030, we expect, non-fossil sources will garner a share of at least 48 per cent in electricity generation capacity even if VRE generation costs are levied on generators; it could exceed 65 per cent if there is a sharp drop in the cost of solar and wind-based electricity generation even though VRE integration cost is levied.
- We expect CO_2 EI of GDP (from energy systems) to decline by at least 48 per cent between 2005 and 2030 on the back of significant energy efficiency improvements. The cost of generating electricity from solar and wind sources will drop, and raise the share of VRE in electricity generation, and propel India's EI of GDP towards its NDC target. However, the EI of GDP in 2030 could be higher by 11 percentage points in 2030, if energy efficiency in end-use sectors improves at a lower rate, industrial and transportation energy demand grows at a faster pace, and electricity's share in industrial energy use does not increase.

Long-term carbon dioxide emissions and Mid-Century Strategy

- India's CO_2 emissions will keep growing even beyond 2050 in the absence of a stringent emissions mitigation policy – as the economy becomes wealthier – but will still be lower than the global average even in the long run, unless countries pursue deep mitigation.
- The electricity and industrial sectors play a major role in India's energy sector-related CO_2 emissions, with respective shares of 40 per cent and 32 per cent in 2050. Industrial emissions matter; we need to understand how we can electrify the industrial end-use sector. Currently, the share of electricity in industrial energy use is less than 20 per cent, and there is huge dependence on fossil sources, particularly coal. India's emissions mitigation policy – focused largely on electricity generation and partially on transportation – must also focus on the industrial sector.
- Carbon dioxide emissions from India's transportation sector will grow the fastest; however, its share in India's CO_2 emissions would be lower, 19 per cent in 2050, compared to other sectors.
- To be consistent with the 2 Degrees C target, India needs to cut CO_2 emissions by at least 4.5 per cent per annum post 2030 to adhere to an emissions budget of 145 $GtCO_2$, based on techno-economic analysis. Postponing the peaking year is possible, but the pace of transformation of energy systems will need to increase hugely to adhere to the same CO_2 emission budget constraint. The emission budget based on equity considerations could be much higher for India.
- If emissions mitigation in the transportation sector is minimal, the share of non-fossil sources in India's electricity generation capacity needs to increase to 98 per cent by 2050 to be consistent with the 2 Degrees C target, and the share of electricity in industrial energy use needs to increase to 54 per cent by 2050.
- For a 2 Degrees C consistent pathway, the energy sector CO_2 EI of India's GDP needs to decline by over 90 per cent between 2005 and 2050, if the carbon budget based on techno-economic analysis is to be achieved.
- Continued investments in fossil energy infrastructure is bound to lead to increase in stranded assets if a 2 Degrees C target budget constraint is to be achieved, irrespective of the peaking year.

Sustainable development, national priorities, and climate policy

- India is making significant strides towards meeting its climate commitments; and the electricity generation sector is leading the effort in meeting NDC and long-term decarbonisation targets.
- Understanding implications for energy access, jobs, industrial competitiveness, and water is important for informing mitigation choices. We propose the CEEW Synergies and Trade-Off Matrix for assessing trade-offs between climate mitigation goals, sustainable development, and national priorities.
- Under an emissions cap at the 2030 level, the marginal electricity generation cost – averaged across technologies for new investments – could increase or decrease depending on the share and cost of different technologies. By 2030, per capita rural and urban income will increase by five to six times, and even doubling the electricity price relative to 2015 – due to a high carbon tax – will not significantly impact electricity access.

- It is important to understand the impact of emissions mitigation policies on the cost structures, competitiveness, and job potential of small, medium, and large enterprises in India's industrial sector. The policy should assess the trade-offs between mitigation objectives and industrial development goals. The trade-off matrix, like the one suggested by us, should be expanded to incorporate industry sector-specific impacts.
- All assessments should incorporate some form of uncertainty.

We conclude by re-emphasising two points: First, there is a need for an India-specific study on estimating VRE integration cost. Such a study should incorporate information on spatial solar and wind generation potential; its correlation across space and time; expected load curves in future years; storage costs; and potential for upcoming technologies like CSP with storage. Such a study has the potential for informing a market design wherein a higher share of VRE can be accommodated, while also suggesting conditions in which conventional plants can play a role as required by the technical constraints on the system or policy choices.

Second, India's electricity generation sector is making significant strides towards decarbonisation, but there is a lack of in-depth analysis and understanding of the potential, choices, constraints, and trade-offs in mitigating emissions from the industrial sector. The next set of analyses should undertake a deeper evaluation of industrial sectors and inform policy based on assessment through CEEW Synergies and Trade-Off Matrix.

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Annexures

Appendix 1: GDP, Population, and Technology Cost Assumptions

Table 1.1: GDP and population assumptions

	GDP Growth				Population (Bn)
	Low	Medium	High		Total
2015-20	7.0%	7.6%	8.0%	2020	1.38
2020-25	6.7%	7.5%	8.7%	2025	1.45
2025-30	6.2%	7.2%	8.0%	2030	1.51
2030-35	5.8%	6.8%	7.5%	2035	1.56
2035-40	5.2%	6.5%	7.2%	2040	1.61
2040-45	4.7%	5.9%	6.6%	2045	1.64
2045-50	4.2%	5.5%	6.3%	2050	1.66

Table 1.2: Urban and rural population and income assumptions

	Urban Population Share			Per Capita Income (US$)-Urban			Per Capita Income (US$)-Rwal		
	LowGr	Meder	HighGr	LowGr	MedGr	HighGr	LowGr	MedGr	HighGr
2020	35%	36%	37%	3659	3674	3691	1163	1215	1257
2025	37%	38%	40%	4741	4861	5087	1486	1625	1811
2030	33%	41%	44%	6193	6417	6735	1844	2167	2573
2035	40%	43%	47%	7781	8332	9030	2286	2845	3531
2040	41%	45%	49%	9523	10824	31973	2836	3793	4927
2045	44%	43%	53%	11417	13659	15538	3438	4931	6716
2060	46%	51%	56%	13482	17063	20109	4094	6332	9123

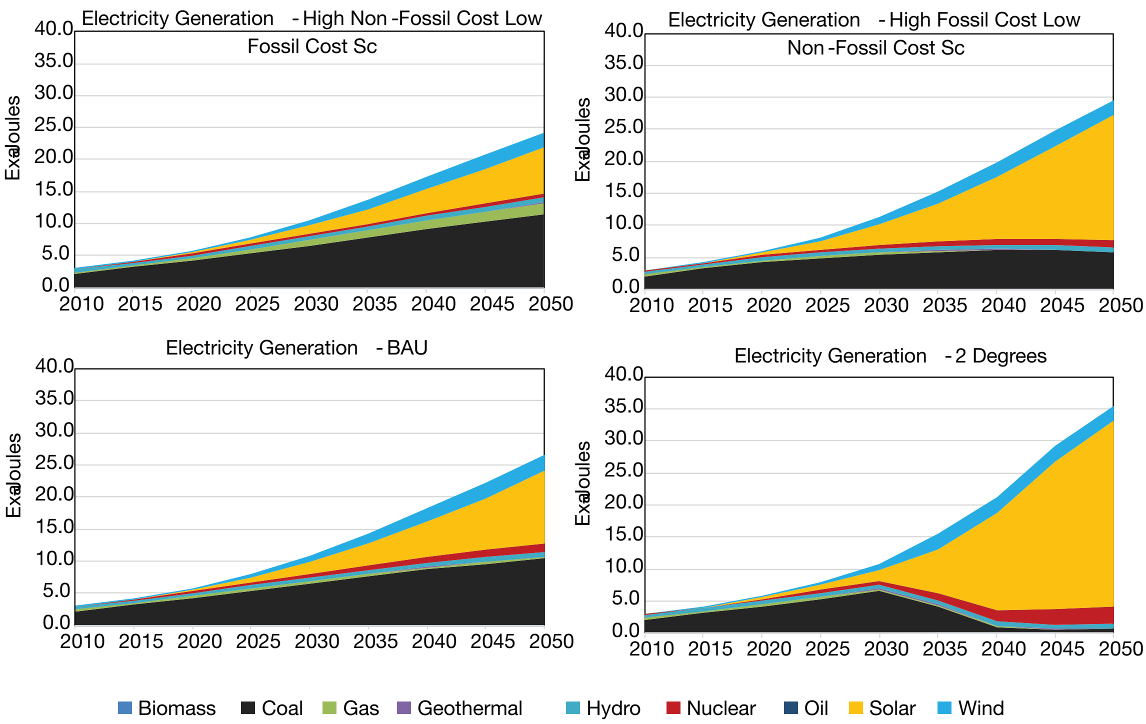
Note: Incomes are in 2015 prices

Table 1.3: Alternative generation cost pathways for key electricity generation technologies (INR/kWh)

		2020	2025	2030	2035	2040	2045	2050
Coal	High	3.49	4.25	4.26	4.27	4.29	4.30	4.31
	Low/Ref	3.49	3.50	3.51	3.52	3.54	3.55	3.56
Gas	High/Ref	7.00	7.00	7.00	7.01	7.05	7.13	7.22
	Low	7.00	4.00	4.00	4.01	4.06	4.14	4.22
Nuclear	High	3.85	5.50	5.52	5.54	5.57	5.60	5.63
	Low/Ref	3.85	3.85	3.87	3.90	3.93	3.96	3.99
Solar	High	3.1	2.9	2.7	2.6	2.5	2.5	2.4
	Medium/ref	2.7	2.6	2.40	2.3	2.2	2.0	1.9
	Low	2.3	2.2	2.0	1.8	1.7	1.6	1.4
Wind	High	3.6	3.43	3.4	3.4	3.3	3.3	3.3
	Medium/ref	3.5	3.34	3.19	3.15	3.10	3.05	3.00
	Low	3.4	3.25	3.0	2.9	2.9	2.8	2.8
VRE Integration Cost		0.00	0.70	0.75	0.80	0.90	1.00	1.10
VRE Integration Cost-Sensitivity		0.20	0.50	0.75	1.00	1.25	1.40	1.50

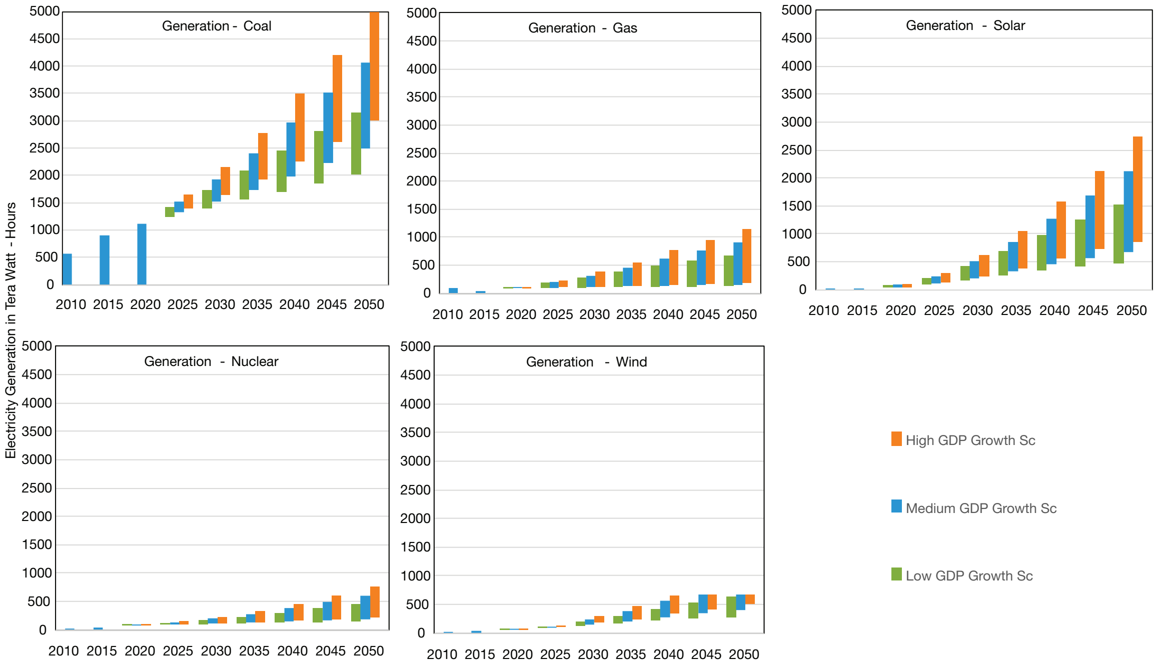
Note: Values are in 2015 prices

Appendix 2: Electricity generation mix for some key scenarios



Note: These results are without VRE integration cost

Appendix 3: Electricity generation mix across scenarios– Results from sensitivity analysis with a higher increase in the VRE integration cost



Note: Integration cost assumptions for this sensitivity are given in Appendix 1, Table 1.3

Appendix 4: Rate of change in energy efficiency across key technologies in the end-use sectors

			BAU sc		Low Efficiency sc	
	Technology	Fuel	2015-30	2030-50	2015-30	2030-50
Building sector	Commercial hvac	Electricity	1.39%	1.12%	0.39%	0.24%
	Air-conditioning (high-eff)	Electricity	1.45%	1.10%	0.51%	0.29%
	Air-conditioning (low-eff)	Electricity	1.44%	1.15%	0.33%	0.24%
	Building envelop	Electricity	0.50%	0.52%	0.07%	0.15%
	Tubelight	Electricity	0.13%	0.11%	0.13%	0.11%
	LED	Electricity	0.17%	0.25%	0.17%	0.25%
	CFL	Electricity	0.21%	0.08%	0.21%	0.08%
	Bulbs	Electricity	0.21%	0.08%	0.21%	0.08%
	Referigerator (low-eff)	Electricity	0.15%	0.26%	0.15%	0.26%
	Referigerator (high-eff)	Electricity	0.18%	0.24%	0.18%	0.24%
	Television	Electricity	0.00%	0.00%	0.00%	0.00%
	Fans	Electricity	0.00%	0.00%	0.00%	0.00%
	Other appliances	Electricity	0.16%	0.25%	0.16%	0.25%
Industrial sector	Aggregate efficiency improvement		1.80%	0.95%	0.70%	0.60%
Transport sector	Cars	Oil	0.73%	0.66%	0.13%	0.10%
	Cars	Natural Gas	0.70%	0.63%	0.13%	0.10%
	Two-Wheelers and Three-Wheelers	Oil	0.73%	0.66%	0.13%	0.10%
	Buses	Oil, Natural Gas	0.01%	0.01%	0.01%	0.01%
	Train - Passenger	Oil, Electricity	0.03%	0.03%	0.03%	0.03%
	Light frieght trucks	Oil	0.25%	0.25%	0.25%	0.25%
	Heavy frieght trucks	Oil	0.13%	0.13%	0.13%	0.13%
	Train - Freight	Oil	0.03%	0.03%	0.03%	0.03%
	Aviation	Oil	0.86%	0.48%	0.86%	0.48%
	Shipping	Oil	0.10%	0.10%	0.10%	0.10%

Image: Pexels / Atiqul Haque

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