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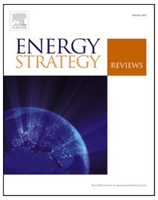

Pathways to net zero emissions for the Indian power sector

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ABSTRACT

At COP26, India has committed to achieve net zero emissions by 2070. For economy wide net zero, the power system should be first to attain it. This paper explores the role of different technologies, CO2 capture and storage (CCS), nuclear, solar PV and thermal, battery storage, pumped storage, hydro etc. along with energy efficiency in doing so by different target years, 2050 and 2060 and their economic implications.

With more intermittent renewables, the issue of balancing hourly demand-supply of both energy and power becomes critical for ensuring the feasibility of a pathway. Hourly availability of different renewable technologies is considered along with hourly variations in electricity demand.

Three scenarios are analysed, Business-as-Usual (BAU) scenario assumes current policies to continue, and two Net Zero (NZ) scenarios to achieve net zero emissions by 2050 and 2060.

Solar PV, wind onshore and offshore, battery storage are the dominant technologies in achieving net zero emissions. Solar and wind together contribute 85% and 90% of the total generation capacity in 2050 and 2060, respectively. Dispatchable technologies like Coal plant with CCS and nuclear are also important. Results specify Battery with storage hour specifications (1 h, 2 h etc.), so one can plan storage in details. Decarbonisation has significant additional cost and investment requirement over the Business-As-Usual scenario. Respective additional cumulative investment requirements (2030–60) are about 1.6 trillion USD and 1.4 trillion USD in two NZ scenarios. The required policies and measures are also discussed.

1. Introduction

Though India's per capita energy usage is less than half of the global average [1], it is the third largest GHG emitter. At COP26 in Glasgow, India made a pledge of achieving net zero emissions[1] by 2070. However, how this will be achieved, and what would be the pathway to reach the target smoothly without causing disruption in economic development or quality of life remain key' questions.

The energy system contributes 75% of India's total emissions [2]. India is in the lower rung of the development path. Per capita income was 2099 USD (current US dollar (2019)) in 2019. Soon to be world's most populous country, India faces several developmental challenges such as poverty alleviation, low standards of living, lack of access to basic necessities such as reliable electricity, basic quality housing, etc. Per capita electricity consumption is one of the lowest in the world at 972 kWh, compared to 5297 kWh in China, and 2850 kWh in Brazil.[2] There is enormous potential for growth in energy demand and energy infrastructure. In next twenty years, India needs to add power generation capacity in same amount of European Union's current power capacity [1]. Creating such large capacities will involve enormous resources, mix of technologies, that will have impact on global energy markets and GHG emissions. Although India's contribution to the global cumulative greenhouse gas emissions is low, the country is already facing the worst effects of climate change.

India's Nationally Determined Contribution (NDC) targets for 2030 include reduction of the GHG emission intensity of GDP by 33–35% from 2005 levels, increase in sequestration by forest cover by 2.5–3 GtCO2e and increase in the share of non-fossil power generation capacity to 40% by 2030 and so on [3].

India is actively implementing multiple policies and measures to grow on a path aligned with the idea of "economic development without destruction" [3] and is on track in meeting its NDC commitments.[3] Immense growth in renewables deployment has been achieved since

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[1] Achieving a balance between CO2 'sources' and 'sinks' is referred to as 'net zero' emissions [12].

[2] https://www.statista.com/statistics/383633/worldwide-consumption-of-electricity-by-country/.

[3] https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1738317.

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List of abbreviations

APS	Announced Pledges Scenario
BAU	Business-as-Usual
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
EV	Electric Vehicles
GW	Giga Watt
IRADe	Integrated Research and Action for Development
LWR	Light Water Reactor
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
MMBTU	Million British Thermal Unit
NDC	Nationally Determined Contribution
NZ	Net Zero
NZ50	Net Zero Scenario 2050
NZ60	Net Zero Scenario 2060
OPEX	Operating Expenditure
PAT	Perform, Achieve and Trade
PV	Photovoltaics
PWHR	Pressurised Heavy Water Reactor
UJALA	Unnat Jyoti scheme for Affordable LEDs for All
UNFCCC	United Nations Framework Convention on Climate Change
VRE	Variable Renewable Energy
WEO	World Energy Outlook

2015, as the total new renewable capacity has reached 100 GW in 2019[6]. Implementation of innovative policies and regulatory approaches, for example, viability gap funding, reverse auctions, etc have resulted in extraordinary cost-competitiveness of solar and the rise of utility-scale renewable power projects. India has also made significant progress on energy efficiency, implementing policies and measures like Perform Achieve and Trade (PAT) for industries, Unnat Jyoti scheme for Affordable LEDs for All (UJALA), etc. In addition, India has launched Electric vehicles (EV) programme, and National Hydrogen Mission, which have attracted huge investments from the corporate sector.

In COP26, India presented the following climate actions,[4] i) 500 GW Non-fossil energy capacity by 2030, ii) 50% of its energy requirements from renewable energy by 2030, iii) reduction of total projected carbon emissions by one billion tonnes from now to 2030, iv) reduction of the carbon intensity of the economy by 45% over 2005 levels by 2030, and v) achieving the target of net zero emissions by 2070.

India needs a stable pathway that will guide its net zero goal at the least cost without disrupting its development goals; and to inform the policy/decision makers and other stakeholders (industries) on least cost technologies, investment needs, and energy supply costs implications.

Indian power sector is the single largest GHG emitter, contributing 50% to the total CO2 emissions [2]. The objective of this paper is

- to develop long-term net-zero emissions pathways for the Indian power system (focusing on CO2).

This is the first step of efforts and will be extended to the whole energy system in the future. Several studies [4–6] have recommended prioritising the electricity sector decarbonisation as clean technologies are available and once electricity becomes clean, electrification will emerge as a crucial economy-wide tool for decarbonizing other sectors such as mobility and hard to abate sectors. Paper aims to investigate two target years 2050 and 2060 for net zero emissions as technology choice and cost implications could be different, early decarbonisation may be more expensive. The questions to be explored include:

- What technologies need to be deployed and which technology/technologies will play dominant roles in decarbonizing power system?
- What potentials for different renewable sources will be required as reliable assessment of potentials are not yet available in the country?
- What would be the economic implications of the power sector for reaching Net Zero by different years, let say 2050, or 2060 in terms of
  - o investment
  - o cost of electricity supply;
- What would be the role of
  - o storage technologies with different storage duration to ensure peak and uninterrupted operation of the power supply system in the presence of large amount of intermittent technologies as demand (energy and load) varies hourly, from day to day and month to month;
  - o technologies like carbon capture and storage (CCS) and nuclear?

Indian power system is modelled using International Atomic Energy Agency's energy planning software MESSAGE. Sensitivity analysis on the potential of CCS and deployment of nuclear is carried out, since accurate assessment of CCS has not been undertaken in India, progress of nuclear has been very slow. Sensitivity analysis is also carried out on the future cost development of renewable and storage technologies since capital costs and O&M costs of these technologies are projected to decline at different rates in different scenarios. The outputs of this paper would be useful to formulate power system development plan, technology policies (assessment of potentials, technology import, R&D, international collaboration, market development, etc.), investment planning and climate finance negotiations.

2. Literature review

This section reviews the various studies that have addressed decarbonisation pathways for the electricity/energy sector at country or regional level (e.g., EU 27) or even at the global level.

2.1. Countries/region other than India

2.1.1. China

According to the Energy Foundation report [7], electricity sector decarbonisation in China would be accompanied by increasing electricity demand driven by income growth, digitalization, and growing electrification of end-use sectors. Report analysed various scenarios that project electricity generation to reach 15,000–18,000 TWh by 2050, with renewables contributing 70% of the total. Study suggests no new coal-fired power plants without carbon capture, utilisation and storage (CCUS) and fitting viable existing plants with CCUS technology. CCUS is recognized as an important option for decarbonizing China's electricity system. However, contributions from CCUS and nuclear technology depend largely on the degree of policy support. Flexibility of the power system needs to be dealt with demand side response and deployment of storage technologies.

IEA study [5] developed The Announced Pledges Scenario (APS) to reflect China's pledge of achieving net zero by 2060. Power generation is the first sector to reach net zero emissions, as mitigation technologies are generally more advanced, and it is also the leading contributor to the decarbonisation of the Chinese economy. Emissions fall to zero before

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[4] https://www.pib.gov.in/PressReleasePage.aspx?PRID=1795071.

2055. The study recommends a massive expansion of renewable power capacity, along with flexible low-carbon resources to maintain electricity system security. Share of renewable energy sources – mainly solar PV and wind power in total generation increases from 25% in 2020 to 80% in 2060, while share of coal drops from 60% today to 5% in 2060, most of it is generated in plants with carbon capture facilities. The other main low-carbon generating technologies, nuclear and large hydro, play a strong supportive role in decarbonisation.

2.1.2. USA

The United States has set a goal for 100% carbon pollution-free electricity by 2035, and 2050 for the entire economy. Various analytical studies have focused on long-term technological transformations and associated emission reduction strategies that would be necessary to reach net-zero; many of these studies have focussed on the entire economy, while others focus on specific sectors such as electricity, industry etc [8]. Phadke et al. [9], demonstrates the technical and economic feasibility of achieving 90% clean (carbon-free) electricity in the United States by 2035 using state-of-the-art capacity-expansion and production-cost models. Existing hydropower and nuclear capacity (after accounting for planned retirements), and much of the existing natural gas capacity combined with new battery storage, would be sufficient to meet U.S. electricity demand (i.e., every hour of the year). All existing coal plants are retired by 2035, and no new fossil fuel plants are built. Generation from natural gas plants constitutes about 10% of total annual electricity generation, which is about 70% lower than their generation in 2019.

Applying U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model, a detailed capacity expansion and dispatch model of the U.S. electric sector [10], explored the roles and potential value of different low-carbon technologies; investment requirement; the economic impacts on electricity prices and energy service costs for achieving net zero emissions targets. Reducing electric sector emissions up to roughly 80% below 2005 levels by 2035 can be cost-effectively achieved with a combination of currently available technologies. Achieving reduction beyond 80% requires deployment of emerging low-carbon technologies, including natural gas or bioenergy with CCS, advanced nuclear, and long-duration storage such as hydrogen produced from electrolysis. The optimal combination of these technologies for achieving 100% reductions and the associated costs depends strongly on how the target is defined. This includes for example, provision for negative emissions to offset a positive emissions component, whereas, bioenergy with CCS could be a technology option offering possible negative emissions.

2.1.3. European Union (27 countries) region

[11] has reported a range of GHG reduction scenarios in the EU region, starting at −80% going up to −100% by 2050 compared to 1990 level. The power sector in the region has already taken important steps towards decarbonisation with the closure of most inefficient thermal generation, the growth of renewables and the contribution of nuclear capacity. The main driver of decarbonisation is electrification in all sectors. Power is nearly decarbonized by 2050 with strong penetration of renewable energy sources and support from the demand-side response, storage, interconnections, and nuclear while CCS deployment faces limitations.

[4] presents a cost-effective, feasible pathway to a net-zero Europe (27 EU countries) by 2050. With wind and solar power generation technologies are already available at scale, power would be the quickest sector to decarbonise, reaching net-zero emissions by the mid- 2040s. Since the demand for power will double due to electrification of other sectors and production of green hydrogen using electricity, sector needs to scale up renewable production rapidly providing 91% of supply by 2050 and expanding its storage capacity. Remaining electricity will come from nuclear and gas-based power plant with CCS. Solar and wind capacity additions need to be 45 GW and 24 GW per year respectively during 2030–50. The EU would also need to increase battery storage capacity to 25 GW and 150 GW by 2030 and 2050 respectively.

2.2. World

IPCC [12] reported 1.5 °C pathways of the global energy system simulated by various models. Renewables are projected to supply 70–85% of electricity in 2050 (high confidence). Shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are expected to increase in most 1.5 °C pathways. The use of CCS would allow the electricity generation share of gas to be approximately 8% of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% in electricity generation.

[6] pathway for global energy system to reach net zero by 2050 calls for annual additions of 630 GW of solar photovoltaics (PV) and 390 GW of wind by 2030 with Hydropower and nuclear technology make key foundation for transitions. Similar to other studies, it also suggests electrification with clean electricity as a crucial economy-wide tool for decarbonisation. Electricity is also essential to produce supportive energy carriers like green hydrogen, leading to increase in total electricity generation by more than two-and-a-half-times between today and 2050. With no new unabated coal plants, by 2050, almost 90% of electricity generation comes from renewable sources, with wind and solar PV together accounting for nearly 70%, remainder (10%) comes from nuclear.

2.3. India

TERI/Shell study [13] has evaluated the technology and policy options that can lead India towards net-zero emissions by 2050. However, the study presents a scenario sketch, in-depth insights are missing. The electricity system shifts to zero-carbon generation through solar and wind power. Study does not disclose the methodology used, costs implications are missing, capacity aspects are not addressed and same for the flexibility issues.

Applying Global Change Analysis Model, Chaturvedi and Malyan [14] analysed implications of energy transition in energy intensive sectors including power by developing scenarios combining various peaking year and net zero year. Coal-based power generation must peak by 2040 and reduce by 99% between 2040 and 2060; Solar-based electricity generation capacity must increase to 1689 GW by 2050 and to 5630 GW by 2070. Study mentions economic losses due to the shift in investment towards mitigation measures but does not indicate the investment and cost implications for the power sector. The impact of intermittency of such large amount of solar and wind in the power system are not analysed. It is not clear if temporal representation of electrical load and supply from intermittent sources are modelled which are important factors in power sector decision making be its technology choice or capacity planning.

[15] made a review of India's near-term (2030) and mid-century (2050) mitigation pathways from peer-reviewed 34 studies, applying model based scenario analyses especially from a sectoral perspective. Some examples are [16–24] and so on. They analysed 16 national scenarios that provided information on power sector transitions and 15 power sector scenarios (from studies addressing only power sector). While most scenarios aim to minimize emissions in 2050 [21], ensures that cumulated emissions over 2012 to 2050 within a fair share of global environmental space for India for a 1.5 °C world. Several scenarios indicate that India is likely to achieve non-fossil capacity from 45% to 59% in 2030 outstripping its NDC target. Several scenarios pointed out that achieving emission reductions (between 2 and 4 GtCO2 by 2050) need coal capacity reduction to about 160–270 GW by 2030. While most of the scenarios reported high presence of VRE (Variable Renewable Energy) sources, however, do not report storage which is very important for higher share of VRE integration. Also majority scenarios ignore electricity demand supply balancing at granular time steps which is

essential for VRE integration [15]. concludes that the further research is required to establish the feasibility of large-scale VRE integration in India. We believe our model takes a major step forward from this point.

Overall we conclude, various technology options are there to decarbonise the power system and those could be adopted/applied for Indian power sector as well. The studies, focusing on India, only energy balance with various technologies is discussed. These studies have not dealt with how the power (load) as well as energy demand that will be met with different technologies, each of which have its specific load characteristics (e.g low ramp rate for nuclear power plants) and limitations, especially renewable technologies. None discussed about dealing with flexibilities in presence of high share of intermittent renewables. In this context, the key strength of our study is, it considers least-cost balancing of hourly demand (load (GW) and energy (GWh) both) and supply from the intermittent sources in an average day of 12 seasons (each month represents a season) with the application of various storage (pump storage, battery with 1–6 h storage) options; thereby making important contributions in least cost flexibility planning.

3. Methodology

The study uses International Atomic Energy Agency's MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts)[5] model. To reflect the inherent uncertainties in an analysis related to the future developments, scenario approach has been adopted [25]. Indian power system is modelled with MESSAGE, MESSAGE-India power system model is then used for developing and analysing scenarios. Other similar modelling tools such as TIMES, PLEXOS also could be used, however, those software are expensive, whereas, IRADe has obtained the permission to use MESSAGE from the IAEA with an agreement and IRADe has in-house expertise on the use of MESSAGE. MESSAGE is an inter-temporal, bottom-up, linear optimization model that minimizes the present discounted value of the power system cost including investment in generation and associated transmission capacity, fuel and other operating costs (please see Appendix I for description of the MESSAGE). Key decision variables are new capacity (in MW) by technology to be added, optimal electricity generation (MWh) by technology and time slice balancing the demand, and so on. It allows detail representations of a variety of power system technologies with specific characteristics (pump-storage hydro, Battery storage with different hours of storage options (1 h, 2-h and so on), Fossil fuel power plant with Carbon capture and storage etc) different from the conventional power generation technologies. For example, a grid-connected Battery storage system stores electricity drawing from the grid when there is excess generation from the solar, wind etc and discharges it when there is a need. A 4-h battery storage with 1 MW of power capacity will have a storage duration of 4 h with a maximum possible instantaneous discharge capability of 1 MW. These characteristics have been modelled in MESSAGE with user-specified equations. MESSAGE also allows finer time resolution, which we have taken as an hour, as that is necessary to ensure technical feasibility of the solution when large amount of renewable power capacity is involved. It facilitates analysis of flexible reserves/storage and their utilisation.

The electricity demand, time variant load profile and potential supply options (resource, technology, various costs, etc.) constitute the model inputs, while new investment requirement in generation and transmission capacity, optimal generation (by hour) and technology mix, hourly discharge and recharge of storage technologies, roadmap of the technologies to be deployed, electricity supply cost, emissions etc. are the outputs.

Another methodological issue is development of an optimal emissions trajectory. If a net zero year is imposed to the cost-minimization model, the emissions will increase till the net zero year, then suddenly decrease making all mitigation investment in the last period/year, which makes deriving an optimal path and mitigation strategy unrealistic and difficult to implement. Therefore, to develop a smooth emissions path following approach is adopted

- Emissions path in Business-as-Usual (BAU) scenario (no emissions constraint) is the starting point
- Various peaking year and reduction rate are employed on BAU emissions trajectory to obtain emissions trajectory with different net zero years, here, 2050 and 2060.
- Each of these net zero emissions trajectories has been fed as constraint into the model in the form of scenario for optimization to derive least-cost mitigation strategy.

A second approach would be to define what is India's share in cumulative global emissions between 2020 and the target date and put this as an upper bound with no zero-date stipulated. This would be more equitable but controversial and so we have used the first approach.

4. Approach

Time frame for modelling is 2015–2085, so that different net zero years e.g., 2050, 2060, 2070 and their techno-economic implications could be analysed. All costs are in 2015 constant prices and the assumed discount rate is 4%. The Indian power system is modelled to represent the physical structure (power plants, transmission and distribution infrastructure etc.) to balance both, load (GW) and energy (GWh) demand with supply on hourly basis. Solar plant generation varies from hour to hour and wind generation varies from month to month. As, demand and availability vary from month to month and also from hour to hour in a typical day, model identifies more accurately the storage requirement for 1 h, 2 h, 4 h etc. capturing the variation in the cost of storage options with different storage hour duration. This helps to establish the technical and economic feasibility of large scale renewable integration. Characteristics (vintage, techno-economic performance, rehabilitation schedules, etc.) of the various existing generating plants, under construction and committed projects, future power generation options, transmission and distribution facilities, energy flows, demand, load characteristics, energy resources and import/export links are modelled.

4.1. Electricity demand

Final annual electricity demand of India is projected assuming GDP growth rates and electricity-GDP elasticity and exogenously specified. Although there are some fluctuations, but India's electricity-GDP elasticity has fallen over last 40 years from about average 2.0 to around 0.8 recently (Author's estimates). However, nearly 26 million households were provided electricity connections under SAUBAGYA scheme between September 2017 and March 2019,[6] which has opened a possibility of large penetration of the domestic appliances with the increase in households income and hence growth in domestic electricity demand. India's electricity demand and GDP are predicted to rise in the future.

Table 1 presents the assumptions on GDP growth rates and electricity-GDP elasticity[7] in estimation of final demand of electricity (demand at the consumer's doorstep). Development in Electricity-GDP elasticity reflects the pattern that is observed in the countries while moving from low income to high income status. Assumptions on GDP growth rate align with the India's aspiration to move from low income to high-income economy.

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[5] https://www.iaea.org/topics/energy-planning/energy-modelling-tools.

[6] https://www.livemint.com/politics/policy/26-02-million-households-get-electricity-connections-under-saubhagya-scheme-1554018490695.html.

[7] This is based on generation data, adjustment for transmission and distribution losses is made to reach at the final demand.

Table 1
Assumptions on electricity demand estimation.

Time period	GDP Growth Rate (%)	Electricity-GDP Elasticity	Electricity growth rate (%)
2020–30	8	0.8	6.4
2030–40	8	0.7	5.6
2040–50	7	0.5	3.5
2050–60	7	0.3	2.7

This demand development (Fig. 1) presents modest growth in electricity demand reflecting the past performance and does not include possibility of future electrification of the end uses like industrial process heating, transportation etc. which is increasingly becoming important option of decarbonising the entire energy system and will be carried out in next phase of the analysis. Our projection of electricity demand for the year 2030 is slightly higher (14%) than the CEA baseline projection of 2415 TWh [26]. Our projection includes electricity demand for both utility and captive sources. Electricity demand is projected as 6977 TWh and 9309 TWh in 2050 and 2060 respectively, although, it is 5–7 time higher than current electricity demand, per capita electricity demand in these two milestone years remain modest. Per capita electricity demand at 4256 kWh in 2050 remains 20% lower than the China's present per capita consumption of 5331 kWh.[8]

Electricity demand needs to be met at real time and demand varies by seasons, by day, by hour even by second. Load shape changes over time as electricity use pattern varies due to changes in economic activities, lifestyle pattern, demand response measures etc. However, due to unavailability of data, load shape of 2019 has been replicated throughout the model horizon. On supply side, availability of certain sources like, hydro, wind, solar which will have larger presence in future supply system, vary over season and during various time of the day. Time resolution in the model is quite detail to capture the seasonal, daily, and hourly load pattern as well as the supply variations of hydro, solar and wind. The 8760 hourly load of the year 2019 has been arranged into 288-time slices (12*24, include 12 seasons where each month represents a season and 24-hourly load of an average day represents a month). The load curve approximated from 8760 hourly real data that is modelled, is presented in Appendix B. The model balances the demand and supply for each time slice (hourly load of a typical day) at minimum cost. In the case of a system with high penetration from renewable energy, this fine time resolution enables the analysis of flexibility needs in the form of storage.

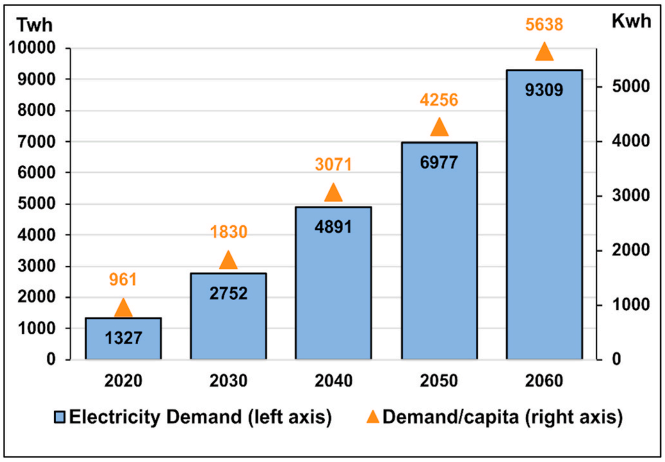

Fig. 1. Development in electricity demand.

4.2. Technologies

A comprehensive list of technology options is considered for future expansion of the power system and replacement of the existing facilities. MESSAGE being technology rich process model, its in-built features (variables and equations) allow to model various types of technology, their operational characteristics, close to reality. Each technology is represented with the technical and economic parameters (capacity factor, construction period, thermal efficiency, capital cost, operating cost (fixed and variable) etc) and emissions factor (CO2). For the coal power plants with CO2 capture, 90% of the CO2 emissions will be captured and stored, 10% still will be released in the atmosphere [27]. Assumptions on these techno-economic parameters are given in Table 2. Capital costs of renewable and storage technologies which are assumed to decline in coming years are reported in Table 3.

To limit unrealistic adoption of the least cost technology options, an upper bound on capacity of some technologies at different milestone years are imposed (reliable assessment of potentials of some of these technologies are still not available) (Table 4).

No sub-critical coal power plant will be built and there is no upper limit on new built super critical and ultra-super critical coal power plants.

Assumptions on T&D losses are 13%, 11%, 10% and 8% for the years 2030, 2040, 2050 and 2060 [26]. The capital cost for new transmission and distribution asset has been assumed as 220 and 235 USD per kW respectively. Respective O&M costs per year are 1% and 3% of the capital expenditure. Additional transmission investment of USD 71/kW (2015 USD) is assumed for integrating renewable capacity like solar and wind to the main grid based on the Government of India's Green Energy Corridor scheme.

In addition, CO_2 transport, and storage are modelled. Work on assessment of CO2 capture, transport and storage is in its preliminary stage in India. A conservative potential of India's cumulative CO_2 storage available for power sector is assumed as 25 Gt [43] and cost of CO2 transport and storage is assumed as US$ 15/tonne [44].

4.3. Fuels and prices

Fossil sources will be part of the energy mix in the medium to long term future of the energy transition and with CO2 capture and storage, can play important role in decarbonisation scenarios as well. Availability of domestic and imported fossil sources like coal, lignite and natural gas for power generation is modelled. Production profile of domestic fossil sources like coal, lignite and natural gas has been developed based on government production target in 2030 and assuming CAGR (Compound Annual Growth Rate) thereafter. Prices of key imported fuels are estimated by the authors based on World Energy Outlook [45] Stated Policy Scenario. Prices of domestic coal and imported coal remain in the range of respectively 23–24 USD/tonne (4000 kCal/kg at pithead) and 58–74 USD/tonne (6000 kCal/kg at portside), whereas same for domestic and imported natural gas are expected to be 3.3–3.9 USD/MMBTU and 9.4–11.4 USD/MMBTU. For both domestic PHWR and imported LWR, nuclear fuel cost is assumed as USD 9.33/MWh (front-end fuel costs of USD 7/MWh and back-end fuel cost of USD 2.33/MWh) [36].

5. Scenarios and results

5.1. Scenarios

MESSAGE-India power system model as described above is used for development and analysis of scenarios. Three scenarios are developed,

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[8] https://www.statista.com/statistics/867590/china-per-capita-electricity-consumption/#:~:text=In%202020%2C%20electricity%20consumption%20in,5%2C331%20kilowatt%20hours%20per%20capita.

Table 2
Assumptions on technical and economic parameters of power generation technologies.

Technology	Parameters	Start year	Thermal efficiency	Fuel type	Annual availability factor	Life time (Years)	Construction time (Years)	Fixed O&M cost(USD/ kW)	Investment cost (USD/kW)
Coal	Super-critical	2015	0.35	Fossil fuel (Coal)	0.8	25	4	25.6	1118
	Sub- critical	2015	0.32		0.8	25	4	23.2	1012
	Ultra-super-critical	2025	0.41		0.8	25	4	38.7	1291
	Integrated Gasification Combined Cycle (IGCC)	2030	0.41		0.8	25	5	67.3	2243
	Power Plant with CO2 Capture	2030	0.3		0.8	30	5	88.2	2504
Gas	Combined cycle	2015	0.41	Gas	0.8	25	2	24.8	620
	Open cycle	2015	0.29		0.8	25	2	10.6	530
Nuclear	Indigeous Pressurised Heavy Water Reactor (PHWR)	2015		Uranium	0.8	30	6	28.5	1667
	Light water Reactor (LWR)*	2015			0.85	60	7	28.5	3771
Hydro	Large hydro	2015		Non fossil (Water)	0.39	60	6	41.7	1667
	Small hydro	2015			0.23	35	5	27.1	1083
	Pumped Storage Hydro	2015			0.25	60	6	21.0	800
Biomass	Biomass power plant	2015	0.26	Bio products (Rice husk)	0.6	20	3	16.2	812
Solar	Solar PV	2015		RE	0.19	25	1	Cost decline in next Table	
	Concentrated Solar Power	2015			0.19	25	3		
Wind	On-shore	2015		RE	0.25	25	2	Cost decline in next Table	
	Off-shore	2015			0.32	25	3		
Battery Storage	1 Hour storage	2022	0.85		0.04	15	1	Cost decline in next Table	
	2 Hour storage	2022	0.85		0.08	15	1		
	3 Hour storage	2022	0.85		0.125	15	1		
	4 Hour storage	2022	0.85		0.17	15	1		
	6 Hour storage	2022	0.85		0.25	15	1		

Data Source: [28–35], *Source of Investment cost of Light Water Reactor: [36].

Table 3
Capital cost development of renewable and battery storage technologies.[a]

Technology	2020	2030	2040	2050	2060
Solar PV	638	298	219	172	164
Solar CSP	1537	877	738	660	646
Wind onshore	848	587	510	460	451
Wind offshore	3707	1845	1543	1400	1373
Storage-1Hr	754	312	233	180	170
Storage-2Hr	932	385	288	222	210
Storage-3Hr	1109	459	343	264	250
Storage-4Hr	1287	532	398	307	290
Storage-6Hr	1632	675	504	389	367

[a] **Solar PV, Solar CSP:** A) NREL Annual Technology Baseline (ATB) 2020 (https://atb-archive.nrel.gov/electricity/2020/data.php); B) [37]; C) [31] Wind on shore and wind offshore: A) [38]; B) [39] Storage Li Ion: A) [40].; B) Chernyakhovskiy I., Joshi M., Palchak D., and Rose A., [41].; C) NREL Annual Technology Baseline Database, https://data.openei.org/submissions/4129.

Table 4
Upper bound on capacity potential (GW) of selected technologies.

Technology	2020	2030	2040	2050	2060
Nuclear	6.8	20	40	60	80
Solar PV	35.0	280	1000	2000	3000
Wind offshore	0.0	20	100	300	600
Wind onshore	37.8	140	300	500	750
Large hydro	43	64	90	120	145
Pump storage	3	16	36	56	76

Source: [29,30,42], also expert judgement

Business-as-Usual (BAU) Scenario and two Net Zero scenarios based on achieving net zero emissions in two different years, 2050 and 2060.

In additions to all assumptions described in the previous sections, BAU Scenario includes all policies those are in place including the new pledges made in COP26 such as 500 GW of capacity from the non-fossil sources (nuclear + large hydro + renewables). Emissions are not constrained, and the emissions trajectory showed for the BAU scenario in Fig. 2 is the optimal emissions, outcome of the model simulation of the BAU scenario. Reduction in costs of renewable and storage technologies leads to large penetration of these technologies in the power system after 2050, bringing down the emissions even in the BAU scenario after peaking in 2045, but continue with more than 3000 Million tonnes (MT).

Net Zero Scenario 2050 (NZ50): A constraint on emissions has been imposed and remaining assumptions remain same as in the BAU scenario. Based on the BAU scenario emissions, emissions trajectory has

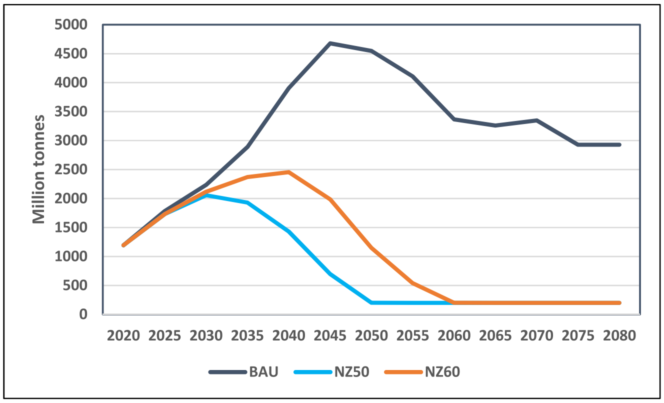

Fig. 2. Emissions trajectories in different scenarios.

been developed with emissions peak in 2030 and then gradually declining to 200 Million tonne (MT)[9] by 2050 and fed into the model as constraint (Fig. 2).

Net Zero Scenario 2060 (NZ60): Similar emissions trajectory has been developed with peak in 2040 and declining to 200 MT by 2060 and fed to the model as constraint.

5.2. Results

5.2.1. Capacity and generation

5.2.1.1. BAU scenario. Fig. 3 presents the capacity (left side) and generation (right side) in the BAU scenario over the period 2020–2060. Both capacity and generation need to grow multiple times to meet the burgeoning electricity demand in coming years. By 2030, capacity from non-fossil sources includes 280 GW of solar PV, 140 GW of wind onshore, 52 GW of large hydro, 18 GW of nuclear, 18 GW of other renewables, totalling to 510 GW, slightly outstripping the policy target of 500 GW. Total capacity in 2030 is projected to be 861 GW, therefore, non-fossil sources to have share more than 50%, higher than the NDC commitment. As current study considers electricity demand from both utility and captive power, projected capacity in 2030 is higher than the capacity reported by Ref. [30] of 817 GW or 792 GW by the IEA (2021).

The total capacity requirement will increase manifold in 2050 due to the demand growth as well as deployment of the intermittent technologies like solar PV, wind, those have low availability factors supported with the storage technologies (battery and pump storage). Generation and storage capacity together would be 2663 GW. Without any emissions constraint, coal capacity keeps rising up to 2050 reaching at 659 GW, there after it starts declining as some capacity retires. With fast declining capital and operating costs of the renewables and storage technologies, intermittent renewables (solar PV and wind onshore) supported by 6-h battery storage replace coal, limiting any new coal capacity addition. The solar PV and onshore wind capacity are projected as 1044 GW and 500 GW, respectively, by 2050. With further increase in solar PV and wind those have low availability factors, the total capacity requirement will increase to 6302 GW by 2060, including a storage capacity of 1975 GW (76 GW of hydro pump storage and 1899 GW of battery storage) which will support the steep increase in intermittent renewables.

Total electricity generation increases to 3404 TWh (Fig. 3, right side) in 2030 from 1592 TWh in 2020. Since this includes captive generation also, therefore higher than the 2518 TWh generation in 2030 reported by Ref. [30]. By 2050, to meet the demand, generation is expected to be 7911 TWh (within the range as reported in various scenarios from studies reviewed by Ref. [15]); increasing five times from the generation level in 2020. Generation further increases to 10583 TWh in 2060, some part of it goes for recharging the storage. In 2030, non-fossil sources (wind onshore, solar PV, large hydro and nuclear) contribute about 33% of the generation, whereas coal's share falls from 73% in 2020 to 65%. Share of coal increases again to 72% in 2040. Thereafter, share of coal starts declining, reaching to 59% in 2050 and then 32% in 2060. In 2050, without any climate action, non-fossil sources contribute about 41% of the total generation in 2050 which goes up further to 67% in 2060, however, not enough to bring down net emissions to zero.

5.2.1.2. Net zero scenarios. Fig. 4 presents the total capacity requirement in two Net Zero scenarios disaggregated between fossil, non-fossil (hydro, renewables and nuclear) and storage capacity. The system needs to be adjusted towards low CO2 technologies and storage technologies before 2030. Over time, coal and gas capacity needs to be replaced by nuclear, large hydro, and renewables. Faster penetrations of non-fossil and storage technologies will be required in the short and medium term to achieve net zero emissions in the NZ50 scenario compared to the NZ60 scenario. The high presence of intermittent technologies with a much lower availability factor makes the total capacity requirement higher than the BAU scenario. Higher intermittent capacity also triggers large storage capacity addition.

Figs. 5 and 6 show further break-up of the fossil and non-fossil sources capacity by technologies in both NZ scenarios. In the NZ50 scenario, conventional coal capacity peaks in 2030 and declines rapidly later (Fig. 5). By 2050, 21 GW of coal plants without CCS will remain in the system as stranded assets without any generation. Coal + CCS, on the other hand, penetrates rapidly, and by 2050, 229 GW of the capacity is needed to reach net zero emissions in that year.

In the NZ60 scenario, conventional coal capacity peaks five years later in 2035 at 339 GW as the net zero emissions target year is postponed to 2060. In 2050, about 151 GW of conventional coal capacity is expected to be operational as 1147 MT of emissions are still allowed. By 2060, 63 GW of conventional coal capacity stays in the system, operating at a plant factor of 8%. The requirement of coal + CCS capacity is much lower than the NZ50 scenario, 60 GW and 169 GW in 2050 and 2060, respectively.

Fig. 6 presents the non-fossil (nuclear, renewable, large hydro) and storage capacity in NZ scenarios (NZ50 (left) and NZ60 (right)). Solar PV dominates, followed by wind (onshore and offshore), which is in alignment with other national or international studies on decarbonisation [6,13,15,17] on India and other countries/region. In the NZ50 scenario, India needs to deploy 1041 GW of solar PV capacity in 2040 compared to the current capacity of 57.7 GW. Between 2030 and 2040, it needs to add 75 GW per year, compared to 10 GW in2021[10]. By 2050, to freeze emissions at 200 MT, it needs to deploy 2000 GW of solar PV, so between 2040 and 2050, there is a need for annual addition of 100 GW (similar patterns are reported in other studies also, for example, in Ref. [4] for Europe). India needs to start building its supply chain to meet this challenge. The same deployment rate needs to continue to reach 3000 GW in 2060. Solar PV alone contributes 61% of the total generation capacity in both years 2050 and 2060, respectively. In 2050 and 2060, the absolute upper limit imposed on solar PV capacity is exploited, indicating an appetite for more solar capacity. The next important technology for decarbonisation is wind, based on onshore and offshore technologies. By 2040, 300 GW of wind onshore and 100 GW of wind offshore are projected to be required. In 2050, 500 GW of wind onshore and 300 GW of wind offshore capacity need to be deployed. These capacities are the maximum upper limits imposed on the model. The respective figures are 750 GW and 600 GW in 2060. Solar and wind together contribute 85% and 90% of the total generation capacity in 2050 and 2060, respectively. Studies on net-zero strategies on China, Europe, world project the similar findings [1,12,11]. As the same annual upper limits on capacity potential are imposed, the NZ60 scenario deploys the same amount of solar PV and wind capacity in 2060 as in the NZ50 scenario. However, the deployment of other renewable sources, including small hydro, biomass power, etc., is slightly lower than in the NZ50 scenario.

The other critical emissions-free sources include large hydro and nuclear. In both NZ scenarios, about 120 GW and 145 GW (maximum potential in the country) of large hydro need to be deployed in 2050 and 2060 respectively. These are the upper limits imposed on the model based on the potential exists in the country and fully exploited. For nuclear also, full upper limits on capacity imposed in the model are exploited. In both NZ scenarios, respectively 60 GW and 80 GW of nuclear capacity need to be deployed in 2050 and 2060.

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[9] India has large carbon sequestration potential, meaning negative emissions, so some amount of positive emissions would be possible from sectors where mitigation is expensive or difficult. We allocated 200 million tonnes of emissions for the power sector.

[10] https://economictimes.indiatimes.com/industry/renewables/india-adds-10-gw-solar-capacity-in-2022-mercom-report/articleshow/91346764.cms.

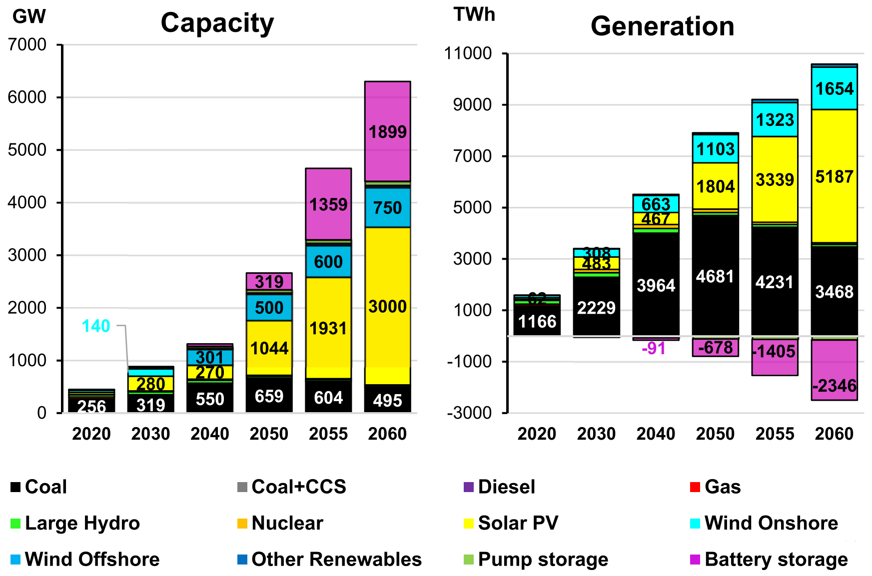

Fig. 3. Capacity and generation pathways in BAU scenario.

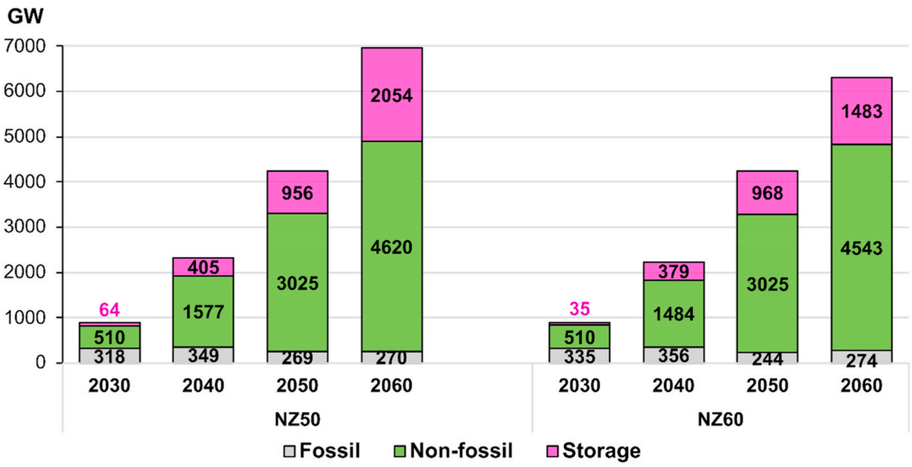

Fig. 4. Total capacity requirement in NZ scenarios.

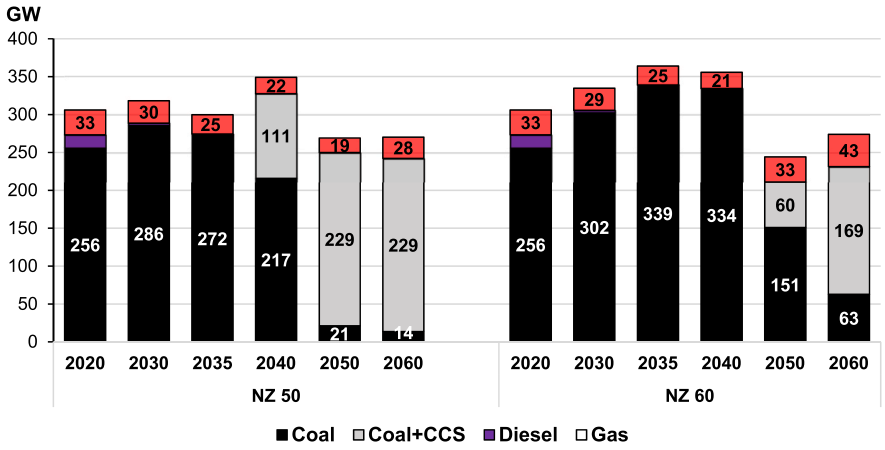

Fig. 5. Pathways for fossil capacity in NZ scenarios.

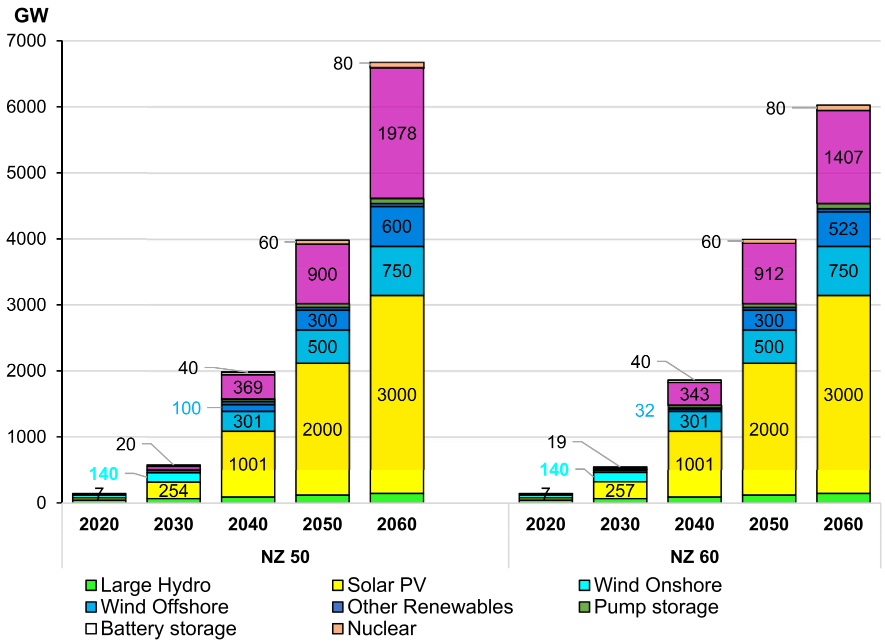

Fig. 6. Pathways for non-fossil (nuclear + Large hydro + renewables) capacity in NZ scenarios.

Fig. 6 also presents storage capacity requirement in Net Zero scenarios. To ensure a robust power system, the model balances the supply and demand of both energy and load hourly over 12 months of the year. A heavy presence of intermittent renewables needs a large storage capacity to balance the load and energy when there is no sunshine or wind. The storage capacity requirement in NZ50 scenario is 369 GW, 900 GW and 1978 GW in 2040, 2050 and 2060 respectively. This would be slightly lower in the NZ60 scenario. As both CAPEX and OPEX of battery storage are assumed to fall substantially over time, pump hydro storage loses its cost-competitiveness to battery storage after 2030. However, as India lacks minerals for battery storage manufacturing, to prevent overdependence on battery storage, pump storage is forced to the system. Among several battery storage options, given the large presence of solar, which provides energy for an average of 6–7 h a day, 6-h battery storage becomes the optimal solution for flexibility.

Fig. 7 presents the generation pathways in NZ scenarios. In NZ50 scenario, generation from conventional coal capacity peaks in 2030 at 1995 TWh, declines to 1313 TWh in 2040 and then reaches zero in 2050. In the NZ60 scenario, conventional coal-based generation peaks at 2451 TWh in 2040, ten years later than NZ50 scenario and declines thereafter. This compares well with the findings of Chaturvedi and Malyan [14]. In 2040, generation remains highly diversified based on coal, coal + CCS, solar PV, wind onshore, wind offshore etc. In 2050 and thereafter, solar PV and wind dominate in achieving net zero emissions, contributing about 68% and 81% in 2050 and 2060, respectively, in both Net Zero scenarios. Other low/no carbon sources making significant contributions include coal plants with CCS, large hydro and nuclear. Discharging electricity when intermittent sources are not generating, battery storage plays an important role by providing flexibility.

Power system operations in Net zero scenarios would be very different from the current system with conventional technologies. Fig. 8a and b presents the power system operation in a typical day of summer (April with higher sunshine and lesser wind availability) and monsoon (August, less sunshine due to the monsoon and high wind availability) seasons in 2050 in NZ50 scenario. During sunshine hours, solar generation outstrips the demand by manifold, therefore charging the storage technologies. Storage technologies discharge after sunset and before sunrise.

5.2.2. *Fuel requirement*

Fig. 9 presents the power sector's coal and natural gas requirements in different scenarios. In the BAU scenario, as expected, coal demand continues to increase, reaching 3069 MT by 2050 and starts declining thereafter. Gas demand in BAU scenario increases till 2035 and starts declining as domestic availability of natural gas starts falling, and imported gas for power generation is not competitive compared to coal.

Coal requirement is low in net zero scenarios but not insignificant due to the deployment of the coal power plant with CCS technology. Coal demand would peak at about 1484 MT in 2040 (almost double of today's consumption) and declines later. In both Net zero scenarios, about 1000–1200 MT of coal will be required in 2050 if coal power plants with CCS are deployed. This is good news for India's large coal industry, which does not need to be completely closed down even in the NZ scenarios if CCS technology is deployed. By 2060, coal requirement is 577 and 687 MT in NZ50 and NZ60 scenarios, respectively.

Overall, gas consumption in the power sector is not expected to increase significantly from the current level since domestic gas availability declines and imported gas is expensive. Gas demand in the NZ50 scenario rises marginally till 2040 from the current consumption level and declines in 2050. However, as generation from the coal + CCS power plants is restricted with the upper limit on cumulative CO2 storage capacity of 25 GT, generation from low carbon fuel gas increases again from 2055 and so is the gas demand (200 MT of emissions are allowed to continue). One should note that generation from coal + CCS plant is not completely emissions free as technology allows 90% of emissions capture. In the NZ60 scenario, gas use increases to reach 25 billion cubic meter in 2050 as higher emissions are allowed and stabilises thereafter.

5.2.3. *Investment and costs*

Fig. 10 presents the investment needed for new generation and storage capacity and transmission and distribution network over 2031–60 in three scenarios. India must massively invest in power generation and storage infrastructure to meet its electricity demand. In the BAU scenario, the total investment needed over 2031–60 is 3195 billion USD when no aggressive climate action is implemented. The average annual investment requirement is 106 billion USD (Table 5).

The investment requirements are much higher if India wants to

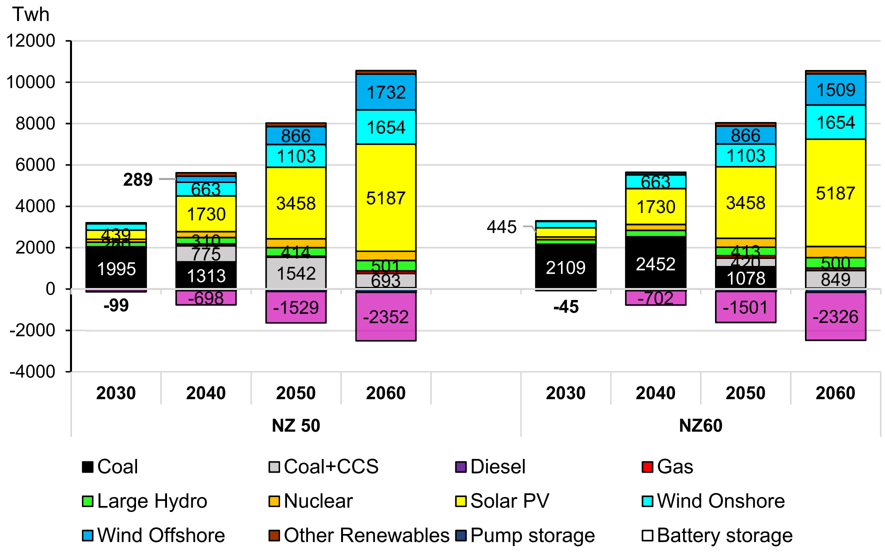

Fig. 7. Generation pathways (NZ50 (left) and NZ60 (right)).

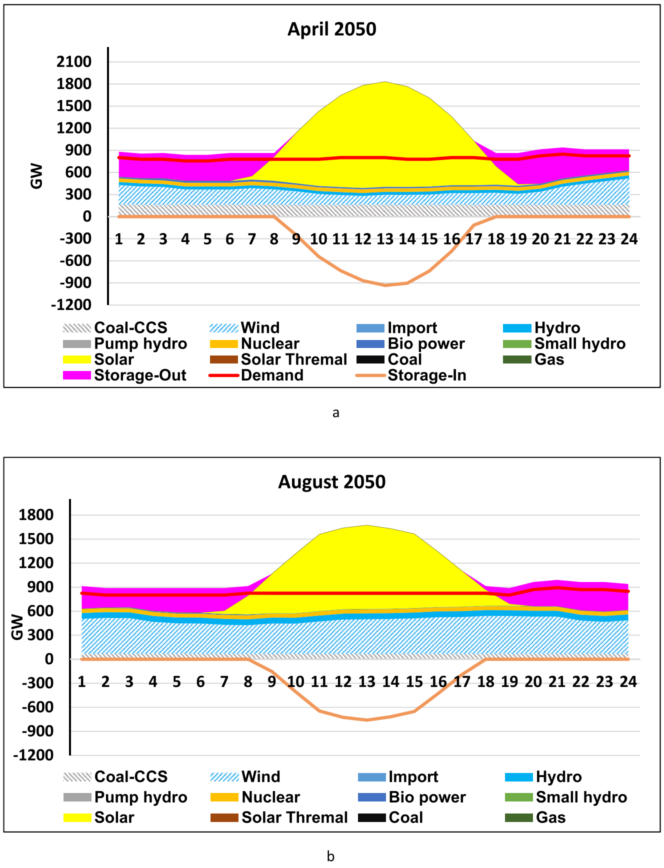

Fig. 8. a: Power system operation in a typical day of summer (April) of 2050 in NZ50 Scenario. b: Power system operation in a typical day of monsoon (August) of 2050 in NZ50 Scenario.

decarbonise its power system. To decarbonise its power system by 2050, the additional total investment requirement over the BAU scenario over 2031–60 is 1.6 trillion USD and slightly less at 1.4 trillion USD if it is postponed to 2060. Early decarbonisation for example, in 2050, is slightly more investment intensive than postponing it to 2060 (Table 5).

In the NZ50 scenario, the average annual investment requirement is 160 billion USD between 2031–60, 50% higher than the annual investment needed in the BAU scenario. If India postpones its decarbonisation target to 2060, the average annual investment needs compared to the BAU scenario is still high; however slightly lower at 153 billion USD (Table 5). The large additional investment requirements in the power sector decarbonisation underline the need for low-cost, long-term international climate finance, in the absence of which these investments would have to come at the cost of other sectors and public services, therefore, obstructing much-needed development.

Fig. 11 presents undiscounted electricity system costs (generation, storage, and T&D) over the modelling horizon 2021–60 in three scenarios, broken into major components like investment, O&M costs, and fuel costs. Decarbonising the power sector is substantially expensive. Electricity supply costs increase by 24% if India intends to decarbonise the power system by 2050, indicating the implication on electricity supply price. In the BAU scenario, fuel costs account for 26% of the total energy system costs. In the NZ50 scenario, the dominance of renewables, supported with nuclear and coal power plants with CCS and storage, along with their grid integration investment, makes investment as the leading cost of supply. Some amount of fuel costs are contributed by the use of fossil fuels during the initial period and then the use of coal power plants with CCS. O&M cost is also higher in the decarbonised power system. In the NZ60 scenario, the energy supply cost is 14% higher than in the BAU scenario.

6. Sensitivity analysis

Sensitivity analysis is carried out with the model for NZ 50 scenario on 1) coal + CCS technology, 2) nuclear, and 3) future development in costs of renewable and storage technologies. Findings are highlighted in the following sections:

6.1. Coal + CCS

India's large coal industry which provides about 13 million jobs [46] may benefit from the CCS technology. However, India's CCS future is

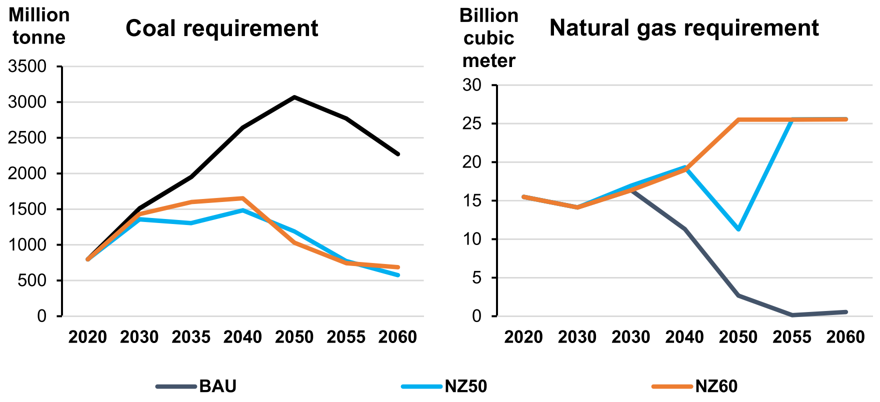

Fig. 9. Coal (left) and Natural gas (right) requirement in Indian power sector in various scenarios.

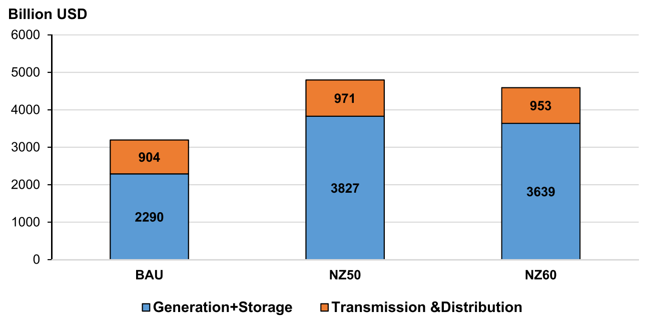

Fig. 10. Investment (undiscounted) in scenarios (2031–60).

Table 5
Investment implications (in billion USD) in net zero scenarios (2031–60).

	BAU	NZ50	NZ60
Total investment	3195	4798	4592
Additional investment for decarbonisation (over BAU)		1603	1398
Average annual investment	106	160	153

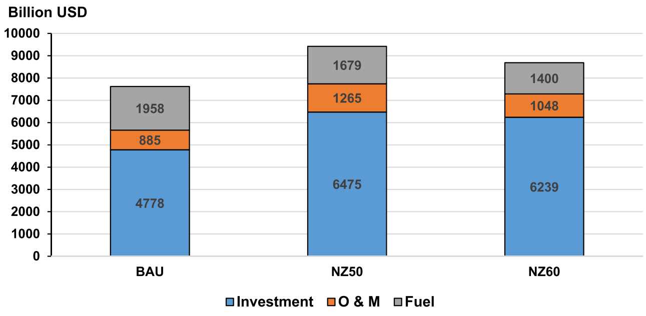

Fig. 11. Total undiscounted electricity system costs (2021–60) in scenarios Fuel costs include CO2 storage costs for NZ50 and NZ60 scenarios.

uncertain. The Department of Science and Technology is funding some basic research projects,[11][12]. Recently, the Government of India has announced to set up two national centres of excellence (CoEs) on carbon capture and utilisation,[13] however, at policy level, there is little momentum. We did a sensitivity case of achieving net zero emissions by 2050 without Coal + CCS option.

Model makes investment in gas capacity to replace Coal + CCS in 2040, however, this gas capacity remains almost un-utilised in 2050. In 2050, additional 700 GW of solar PV, and 400 GW of 6-h battery storage capacity replace about 229 GW of coal + CCS capacity. Achieving NZ50 scenario without CCS is 7% more expensive. As expensive coal + CCS capacity is replaced by less investment intensive gas (CC) and solar + storage capacity, investment remains more or less same. However, it needs to import low carbon but more expensive natural gas to replace generation from Coal + CCS partly in 2040, contributing to the higher fuel costs.

6.2. *Nuclear*

Nuclear is a baseload low carbon technology. As India's future electricity demand is expected to be in bulk, the presence of dispatchable nuclear in the net-zero emissions power system, which intermittent renewable technologies would otherwise dominate, is hugely important. India's nuclear power programme has started way back in 1970's, however, the progress has been slow. The total installed capacity stands at 6780 MW in 2021 and in last 10 years, about 3000 MW has been added. In our scenarios we have assumed 20 GW of nuclear by 2030 [30] and thereafter, increase of 2 GW per annum, reaching for example 40 GW by 2040, 60 GW by 2050 and so on. Based on the past performance of the Indian nuclear energy sector, the possibility of achieving this target remains uncertain. We did a sensitivity case of achieving net zero emissions by 2050 with nuclear capacity limited to 30 GW. Model simulation shows with the low nuclear capacity, it is possible to achieve net zero emissions by 2050. Higher amount of gas based capacity is employed in 2040 as this year still allows 1369 MT of emissions and coal + CCS capacity is reduced by 14 GW just to have more CCS in 2050 when only 200 MT of emissions are allowed. In 2050, 30 GW of non-intermittent nuclear is replaced by 11 GW of additional CCS capacity, 100 GW of solar PV and battery storage. Electricity system cost is marginally higher (3%).

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[11] https://dst.gov.in/carbon-capture-utilisation-and-storage-ccus.

[12] https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf.

[13] https://timesofindia.indiatimes.com/india/climate-action-india-to-set-up-two-carbon-capture-and-utilisation-centres/articleshow/89556753.cms.

6.3. *Costs development of renewable and storage technologies*

Investment and other costs of emerging technologies like Solar PV, etc and storage technologies have declined substantially over the last ten years. Average installation cost/kW of utility scale solar PV projects in 2020 was 19% of the costs in 2010 [47]. Cost development up to 2050 of important technologies is projected by some organisations like IRENA, NREL[14] etc. IRADe has compiled those projections and classified the cost development into two categories - fast and slow decline. Table 6 presents the investment cost of various technologies in 2050 as percentage of the costs in 2020 in fast and slow decline case.[15] For example, in fast decline case, investment cost of solar PV in 2050 will be only 27% of what it costs today (2020), whereas, in slow decline case, it would be at 47% of today's cost. The results we have reported so far are based on faster reduction in cost of renewable and storage technologies. O&M cost as linked with investment cost, has also declined fast.

Since the trajectory of the future costs of these technologies is uncertain, a sensitivity analysis on NZ50 scenario has been carried out based on the slow decline in costs (Table 6). Impacts on capacity are insignificant, capacity requirement and technology mix remain more or less same. Fig. 12 compare the impacts on power system costs. In this slow cost decline case, achieving net zero by 2050 needs 45% more investment over 2021–50 compared to the fast cost decline case. The total energy system cost is about 30% more expensive, indicating a higher electricity price.

Table 6
Assumptions on decline in CAPEX of various technologies in 2050 over 2020.

Technology	Fast	Slow
Solar PV	27%	47%
Solar CSP	43%	92%
Wind onshore	54%	66%
Wind offshore	38%	69%
Storage-6Hr	24%	72%

Source: Compilation of Integrated Research and Action for Development (IRADe) from various sources

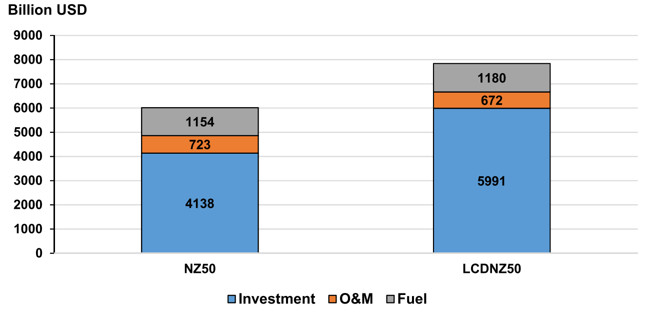

Fig. 12. Impacts of low-cost decline on electricity system costs(undiscounted).

7. Summary and policy recommendations

By developing optimal net zero pathways for the Indian power sector, this paper attempted to identify 1) least cost energy technologies that would be key to achieve the net zero emissions goal in two different years, 2050 and 2060, 2) the amount of capacity of those technologies need to be deployed at different milestone years, 3) and their economic implications (investment requirement and energy supply costs). These outputs (e.g optimal capacity with technology mix and time scheduling along with investment implications) could be used by the policy/decision makers/planners/power industries to guide the future development of the Indian power sector leading to zero emissions. Key findings include:

- With the timely and adequate deployment of low carbon technologies such as solar PV, wind offshore and onshore, coal + CCS, nuclear and storage options like pump hydro storage and battery storage, India can decarbonise its power system by 2050 and at slightly lesser costs by 2060.
- To achieve its target of 500 GW from non-fossil fuel capacity by 2030, India needs to add around 260 GW of solar capacity, 140 GW of wind capacity, 64 GW of large hydro capacity, 20 GW of nuclear. Given India's solar PV and wind capacity as 58 GW and 41 GW as on June 2022, India needs to add 25 GW of solar PV and 12 GW of wind every year till 2030.
- To achieve net zero emissions by 2050 or 2060, India needs to deploy Solar PV capacity in the order of 1000 GW, 2000 GW and 3000 GW by 2040, 2050 and 2060 respectively. The respective numbers for wind are 400 GW, 800 GW (500 GW wind onshore + 300 GW of wind offshore) and 1350 GW (onshore 750 GW + offshore 600 GW). Between 2030 and 2040, therefore, about 75 GW of solar PV and 25 GW of wind capacity need to be added annually. This will be further up to 100 GW and 40 GW respectively in the following decade.
- Solar and wind combined would contribute respectively 85% and 90% of the total generation capacity in 2050 and 2060 respectively, in line with similar studies carried out in other countries/region.
- Intermittent solar and wind power need to be supported by battery and pump storage technologies. About 400 GW, 956 GW and 2054 GW of storage (battery and pump storage) capacity need to be deployed in 2040, 2050 and 2060, respectively. Given that solar plays a dominant role and the sun shines on average 5–6 h daily, longer hour (6-h) battery storage is an optimal flexibility solution. Other carbon-free/low carbon technologies such as, large hydro, coal + CCS and nuclear also have role to play in decarbonisation given India's huge electricity demand needs to be met at the same time.
- For net zero emissions in 2050, conventional coal capacity peaks in 2030 and rapidly declines thereafter; It peaks five years later in 2035 if net zero emissions are achieved in 2060. By 2050, generation from conventional plants reaches to zero, so is the coal demand. However, deployment of coal + CCS could slow down the closure of the domestic coal industry which employs 13 million people. Coal + CCS plants will demand about 1.1 billion tonnes of coal in 2050 even if emissions reach net zero in that year. This would help to retain the livelihood of millions of people associated with the coal industry directly or indirectly.
- Decarbonisation of the power system comes with a large increase in investment and electricity supply costs. Additional investment requirement (on generation, storage and T&D) over the period 2031–60 would be 1.6 trillion USD (over BAU) if India targets to achieve complete power system decarbonisation by 2050 and slightly lower at 1.4 trillion if decarbonisation target is postponed to 2060.

Power sector decarbonisation needs vast amount of solar and wind capacity. Currently available estimates on solar PV and wind-onshore potentials are old and wind offshore potential has not even been assessed. Both, the technology as well as method of potential assessments have improved. For example, design improvement like taller tower can tap stronger wind resources that exist at higher levels, while larger rotor allows wind turbines to sweep more area, capture more wind, and produce more electricity than it was a decade ago. Similarly,

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[14] NREL Annual Technology Baseline Database, https://data.openei.org/submissions/4129.

[15] Study has assumed CAPEX of a technology will stabilise from 2050 and thereafter.

the average conversion efficiency of crystalline solar PV modules increased from 14.7% in 2010 to 20.9% in 2021 [48], which has increased the electricity availability; there is a large potential of further efficiency improvement. The land intensity of solar PV has also fallen, meaning more electricity from the same amount of land, which is important for land-scarce countries. To ensure whether required quantity of potentials exists or not, India needs reliable and advanced assessment of it's solar PV and wind (onshore and offshore) potentials taking into account potential future progress in technologies. Otherwise, different pathways need to be developed. Also feasibility of deploying so large capacity every year in terms of land, materials, manpower requirement, manufacturing capacity development needs to be investigated and appropriate policies and measures need to be designed and deployed.

India added 10 GW of solar PV capacity and 1.5 GW of wind (onshore) capacity in 2021, it needs to expand the supply chain, manufacturing capacity by manifold to keep up with the need for expansion of the capacity using these technologies if decarbonisation targets need to be met.

Deployment of battery storage is at preliminary stage in India. A massive amount of work on technology, production, standards, market development, is needed. Also issues on availability of raw materials for battery manufacturing need to be examined. India is rightfully making efforts to be part of the new US-led partnership initiative of 11 nations called the Minerals Security Partnership (MSP), that aims to bolster critical mineral supply chains.[16] India has large pump-storage potential which the model finds less economical in competition with battery storage based on the assumption of rapid decline in battery cost. Work needs to be done to explore how to bring down costs of the pump-storage plant to avoid the dependence on one technology as storage option. This will also reduce the over dependence of the minerals needed to manufacture batteries.

Optimal pathways pick up 229 GW and 60 GW of CCS technology by 2050 for NZ50 and NZ60 scenarios, respectively. Sensitivity analysis shows that without CCS technology, the costs of decarbonisation will go up. Preliminary conversations on CCS have only commenced in India, and it is an untested technology. However, its technical and economic viability need to be understood, and CO2 storage potentials need to be assessed. If viable, policies and regulations need to be developed and implemented.

Decarbonisation of power system needs conventional coal based capacity to decline after 2030, and the coal demand from the conventional coal power plant to reach zero by 2050 if decarbonisation is achieved in the same year. That needs closing down of an industry that currently employs 13 million people. This can be avoided by deploying coal power plants with CCS technology which also improve system stability by providing dispatchable power in highly intermittent technology dominated future power system. Optimal pathways pick up 229 GW and 60 GW of CCS technology by 2050 for NZ50 and NZ60 scenarios, respectively. Sensitivity analysis shows that without CCS technology, the costs of decarbonisation will go up. Preliminary conversations on CCS have only commenced in India, and it is an untested technology. However, its technical and economic viability need to be understood, and CO2 storage potentials need to be assessed. If viable, policies and regulations need to be developed and implemented.

India's nuclear power programme is 50 years old, but progress on nuclear power capacity development has been slow. Nuclear being non-intermittent and carbon free, has favourable technical and economic impact on decarbonisation process. After signing 123 agreement in 2008, India is allowed to import nuclear fuel as well as the reactors. Faster development of nuclear capacity would ease the operation of the decarbonised power system and bring down the additional costs.

India needs technology support from the international community on solar PV (further improvement), wind (especially offshore), CCS, nuclear, and storage technologies and on better assessment of resources (especially solar and wind) and storage potentials. Government of India also needs to build local capacity on R&D, products manufacturing, certification and standards etc which need regulations, policies, and incentives. Various policies and incentives are available for solar and wind which need to be strengthened and extended to other technologies.

A huge additional investment (over BAU) needed to build net zero power system. This is a clear case for international low-cost long term climate finance support. Further work is needed in this area.

In the past decades, costs of low emissions power generation and storage technologies have declined rapidly due to the efforts made by several countries, including India and more aggressive efforts need to continue. Our exercise shows that with realisation of certain future low carbon technologies and cheaper finance, Indian power sector can achieve Net zero emissions by 2050.

Limitations and future work: Load shape of a country changes over time and that has implications on technology, capacity and investment planning, however, due to the unavailability of data, this aspect has not been included in the study. Electricity demand used in the study does not include possible future electrification of the end uses like industrial process heating, transportation etc. which is increasingly becoming important option of decarbonising the entire energy system and will be carried out in next phase of the analysis. Net zero emissions trajectories are estimated outside and fed into the optimization model, therefore, not the optimal trajectories, MESSAGE at its current structure cannot develop optimal trajectory.

New policies, market mechanisms, Regulations, cheap financing and financial models, and other actions required to drive the power sector in decarbonisation path need to be topics of future research.

Credit author statement

Anjana Das: Methodology, modelling, database, scenario analysis, writing, **Vinay Saini**: Model database development, **Kirit Parikh**: Conceptualisation, Supervision, Methodology, demand estimation, writing, reviewing, **Jyoti Parikh**: Reviewing and writing, **Probal Ghosh**: Electricity demand estimation, **Mario Tot**: Support on modelling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix I

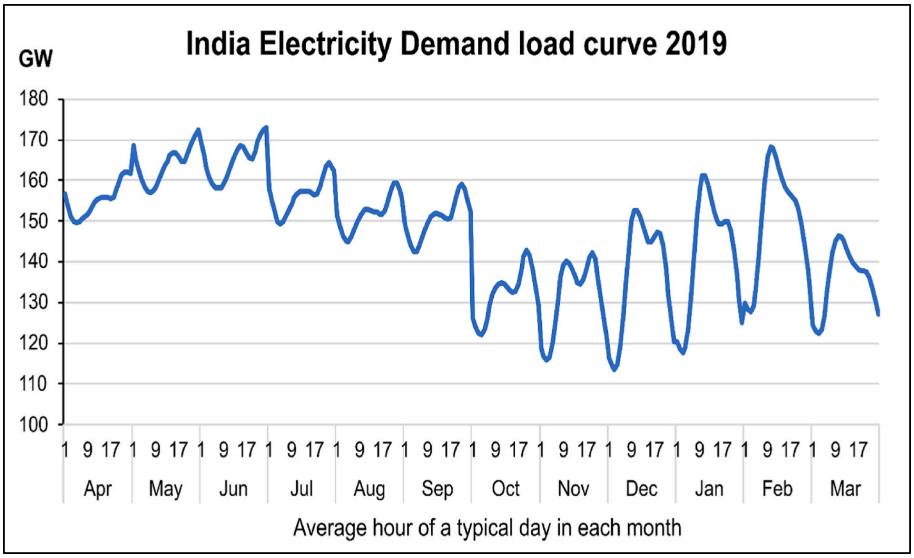
MESSAGE model

The International Atomic Energy Agency's (IAEA) MESSAGE model is a highly flexible and versatile tool for assessment, planning and analysis of the energy system and is used by 100 countries for sustainable energy planning.[17] MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) was originally developed by the International Institute for Applied Systems Analysis (IIASA) in Austria. A special agreement between IIASA and the International Atomic Energy Agency permits its use within the IAEA and its member states. The model has been further enhanced/updated by the IAEA, for example, addition of a user-friendly interface.

MESSAGE is a dynamic, bottom-up, multi-year, linear and mixed-integer optimization model. Since one of the key user of the model is the national utility company applying the software for the planning of the power system, representation of the power system is as much as possible close to the reality, for example, load variation over 8760 h in a year can be modelled. Similarly, it is possible to model hourly, daily and seasonal variations in supply from the intermittent sources like solar, wind. Detail representations of variety of energy technologies (production, conversion, end-use etc) some of with specific characteristics (pump-storage hydro, Fossil power plant with Carbon capture and storage etc) can be modelled. Its flexibility permits the analysis of an energy system in its entirety, or a more focused assessment of partial aspects of the system, e.g., electricity generation, hydrogen fuel chain etc. MESSAGE is built on Reference Energy System network (existing and its future evolution over the time frame of the analysis), that links resource supplies, energy conversion, and processing technologies, and end-use demands and the devices that meet them, tracking the flows of energy and associated emissions. Demand for energy services are exogenous to the model and MESSAGE solves for optimal supply strategy while meeting those demand and several other constraints for example emissions constraints.

The model finds the least-cost path through the RES network to meet user-specified electricity demand, subject to constraints that enforce network integrity as well as any user-imposed (policy) constraints (e.g. emissions constraint) by performing a perfect foresight, perfect information minimization of the net present value of total power system costs, including the capital and operating costs of all devices, fuel costs built up from stepped resource supply curves, and any taxes and subsidies the user imposes.

Appendix II



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