Final Report

ASSESSING POTENTIAL CARBON NEUTRALITY TARGET YEARS FOR INDIA'S POWER SECTOR

IRADe-PR-96(2022)

20 YEARS IRADe Integrated Research and Action for Development

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Disclaimer

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Preface

India has pledged to achieve net zero emissions by 2070 at COp26 Glasgow. Developing a smooth net zero pathway for decarbonising the Indian economy has become critical so that India could decarbonise its economy without compromising its development and growth priorities, especially achieving several development goals. India's energy need is expected to grow several fold due to the increasing population, low per capita energy consumption currently, and to fuel its aspired high economic growth for many years to come. The power sector is the single largest contributor of greenhouse gas (GHG) emissions and is being taken up on priority for decarbonisation. In this study, the technology options and economic implications of achieving net zero emissions for the Indian power sector in target years 2050 and 2060 are examined by tracing a least cost pathway. A comprehensive list of technology options needed to decarbonised the power system, is examined, which includes power plants with CO2 capture and storage (CCS), nuclear, solar PV and thermal, battery storage, pumped storage hydro and so on, in addition to conventional technologies like large hydro, biomass power plants, coal power plants with sub-critical, super-critical and ultra-super critical technologies etc. Also system reliability aspects of the power system in the dominating presence of intermittent renewables (solar PV, wind) supported with various storage options are examined with detailed (hourly) representation of demand and supply of both energy and load. His most unique feature is that 24 hour-load balance is ensured for 12 months to get realistic capacity mix needed considering seasonal and hourly load variations. Additional investment needed and implications on energy supply cost in the net zero electricity sector are reported. Findings presented in this report will be useful information for policy and decision makers.

I am grateful to the Shakti Sustainable Energy Foundation , New Venture fund for supporting this useful and much needed exercise. I am also grateful to IRADe team led by Dr. Anjana Das for undertaking execution of this work.

Dr. Jyoti K. Parikh

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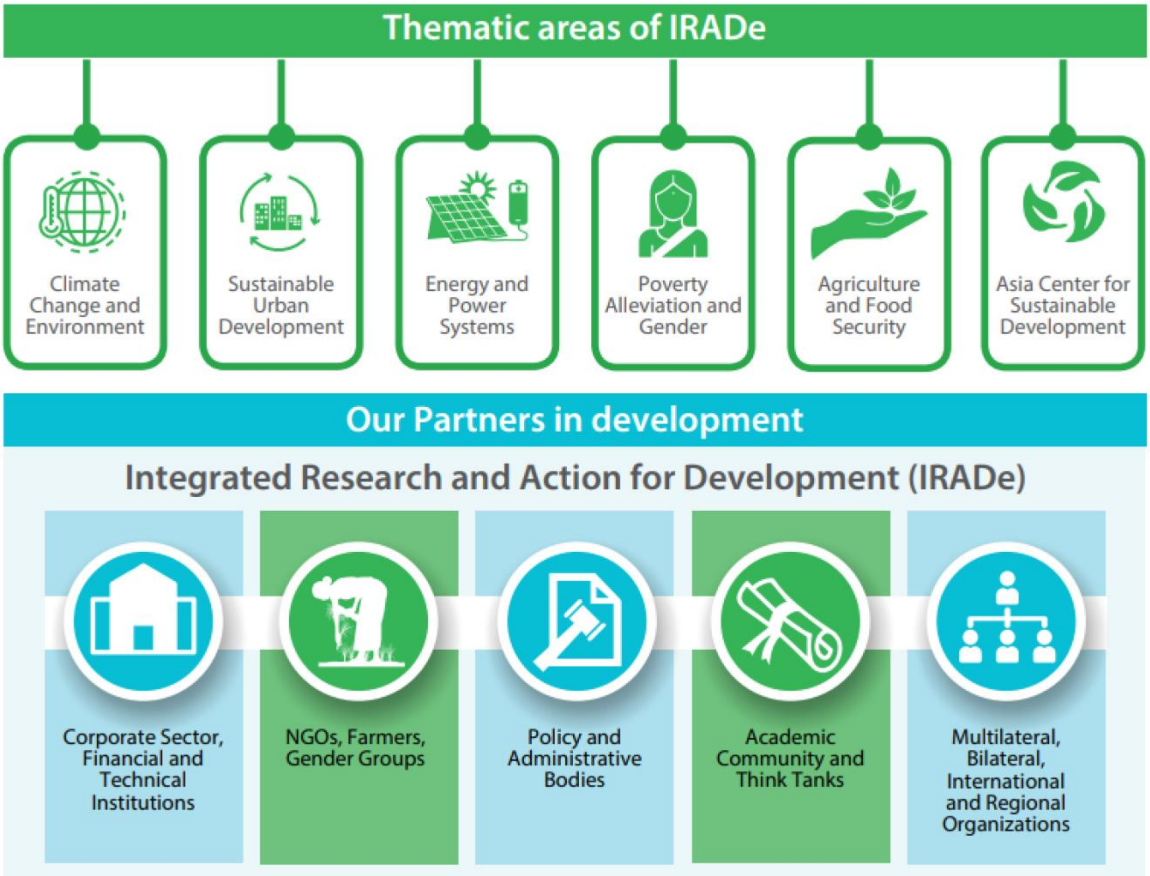
About IRADe

IRADe is an independent non-profit, advanced research institute that aims to conduct research and policy analysis to engage stakeholders such as government, non-governmental organizations, and corporations, academic and financial institutions. Energy, climate change, urban development, poverty, gender equity, agriculture, and food security are some of the challenges faced in the 21st century. IRADe's research covers these issues and the policies that affect them. IRADe focuses on effective action through multi- disciplinary and multi-stakeholder research to arrive at implementable solutions for sustainable development policy research and effective governance that accounts for techno-economic and socio-cultural issues. It also provides expertise to several ministries, national and international institutions, and partners with reputed organizations.

IRADe was established under the Society's Act in 2002 at New Delhi. It is certified as a Research & Development Organisation by the Department of Scientific and Industrial Research (DSIR), Ministry of Science and Technology (MoST), Government of India. It has also been selected as a Centre of Excellence by the Ministry of Housing and Urban Affairs (MoHUA), Government of India, for urban development and climate change.



Executive Summary

Developing a smooth net zero pathway for decarbonising the Indian economy has become critical after India pledged to achieve net zero emissions by 2070. India's energy needs predicted to grow in every sector due to increasing population, urbanisation and low per capita energy consumption. The power sector is the single largest contributor of greenhouse gas (GHG) emissions and is being taken up on priority for decarbonisation. Additionally, the government also intends to increase electrification in household, transport, and industrial sector. Thus, the demand for green electricity will be huge. The technologies for decarbonising the power sector (primarily wind and solar) are widely available and commercial. Green electricity will not only decarbonise the power sector, but it could be used to decarbonise the household, transport and industrial segment (with low heat requirements). Green electricity could also be used to produce green hydrogen which has emerged as a critical alternative fuel to decarbonise the hard to abate sector with high heat requirements.

In this study, the technology options and economic implications of achieving net zero in target years 2050 and 2060 are examined by tracing a least cost pathway. A dynamic least cost optimisation software Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is used to model the decarbonisation scenarios of the Indian power system. This Model allows to balance demand and supply of load and energy on hourly basis at minimum cost, which is ideal for treating the increasing role of intermittent renewables and power storage in the power system. The electricity demand is exogenous and projected assuming GDP growth and GDP-electricity elasticity as shown in the figure A.

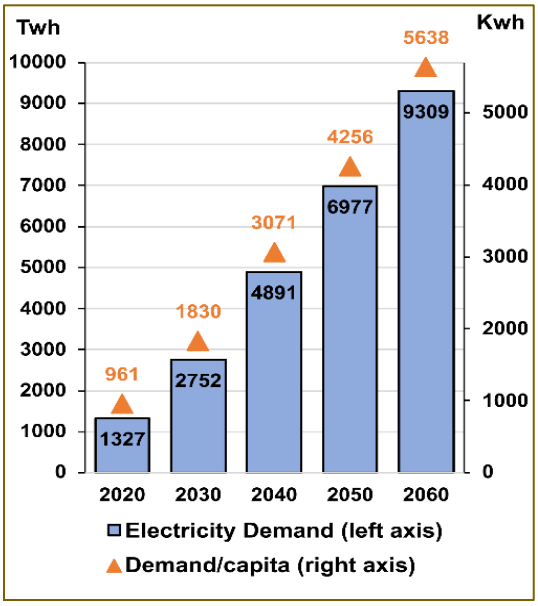


Figure A: Electricity Demand

A comprehensive list of technology options is modelled, which includes power plants with CO2 capture and storage (CCS), nuclear, solar PV and thermal, battery storage, pumped storage hydro and so on, in addition to conventional technologies like large hydro, biomass power plants, coal power plants with sub-critical, super-critical and ultra-super critical technologies etc.

These technologies are represented based on its technical and economic parameters (capacity factor, unit size, construction period, thermal efficiency, capital cost, operating cost (fixed and variable) etc.) and emissions factor. The data and assumptions on parameters for these technologies are obtained from government reports and international organisation. In case of emerging technologies (solar PV, wind, battery storage etc), fast decline in their CAPEX and OPEX is assumed.

Three scenarios are developed using the model.

BAU Scenario includes all policies which are in place including the new pledges up to 2030 made in COP26. The emissions are not constrained, and allowed to increase in the modelling period

Net Zero Scenario 2050 (NZ50): In the NZ50 scenario, the BAU scenario emissions trajectory is followed till the year 2030 when power sector emissions peak and then the emissions are gradually allowed to decline to 200 million tonnes[1] by 2050 and fed into the model as constraint.

Net Zero Scenario 2060 (NZ60): Like NZ50 scenario, emissions gradually decline to 200 mt by 2060 instead of 2050. Similar emissions trajectory as has been developed with emissions peaking in 2035 and declining to 200 mt by 2060 and fed to the model as constraint.

The optimal pathways and technology mix for achieving Net Zero in the Indian power sector by 2050 and 2060 are depicted in the figure B below.

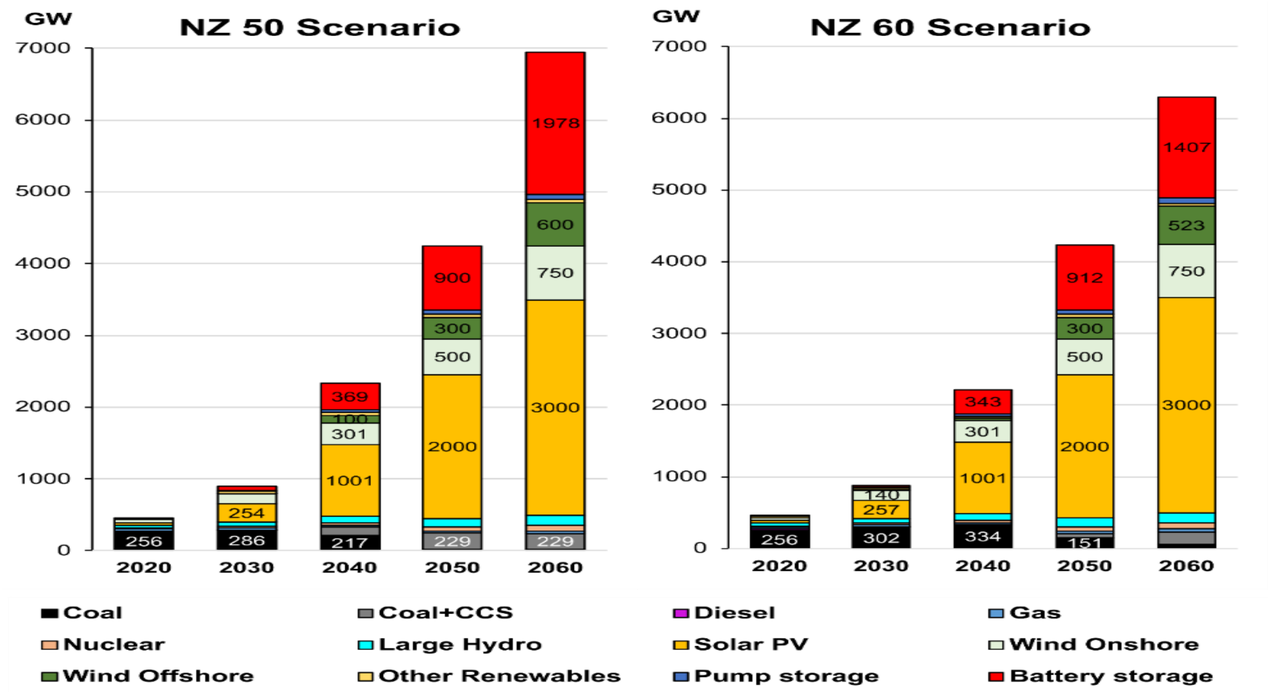


Figure B: Optimal pathways, Net Zero 2050 (NZ 50) and Net Zero 2060 (NZ 60)

Some of the key results from the study are highlighted below:

Conventional coal capacity needs to peak in 2030 and 2035 for power sector decarbonisation in 2050 and 2060 respectively. Consequently, phasedown of the coal industry must begin from 2030 and by 2050 coal demand from the conventional coal power plant in the power sector reaches zero in NZ50 scenario. Deployment of CCS in coal-based power plants can delay the phasedown of the coal industry and usage of coal can continue even after 2050 in net zero system. Coal demand is about 1 billion tonne in 2050 when CCS is deployed. This would help to retain the livelihood of millions of people associated with the coal industry directly or indirectly.

To achieve its target of 500 GW from non-fossil fuel capacity by 2030 (or 50% of total capacity from the non-fossil sources), 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 compare with, India added 10 GW of solar PV and 1.5 GW of wind onshore in 2021.

[1] 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.

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 in the following decade.

Solar and wind technologies together contribute 85% and 90% of the India's 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 369 GW, 900 GW and 1978 GW of storage (battery and pump storage) capacity need to be deployed in 2040, 2050 and 2060, respectively in NZ50 scenario. Given that solar plays a dominant role and the sun shines on average 5-6 hours daily, longer hour (6-hour) battery storage is a 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 in the future.

Decarbonisation of the power system comes with a large increase in investment and electricity supply costs. Additional cumulative investment (undiscounted) requirement (on generation, storage, and T&D) during 2031-60 would be 1.6 trillion USD (over BAU) and slightly lower at 1.4 trillion USD if decarbonisation target is postponed to 2060 as shown in table below.

Investment implications (2031-60) in USD billion

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

The decarbonisation of Indian power system is challenging and achieving the target would require that the assumed trajectory of technical and economic performance of technologies in IRADe model follows during implementation. Achieving the cost declines and capacity additions in renewable technologies are dependent on the long term availability of low-cost financing, policies and regulations to promote and incentivize renewables, and coordinated engagement of all stakeholders, government, industries, and public.

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. Robust assessment of future technology and its potential is still lacking. For example, design improvement like taller tower can tap stronger wind resources that exist at higher levels and produce more electricity. Similarly, the average electrical conversion efficiency of solar PV modules is also increasing. There is a large potential for further technology improvement. India needs to commission reliable and advanced assessment of its solar PV and wind (onshore and offshore) potentials to ensure required potentials exist. Otherwise, alternative pathways will be needed to decarbonise the power sector. Also, feasibility of deploying such large capacities every year in terms of land, materials, manpower requirement 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. Massive amount of work on technology, production, standards, market development, is needed. The availability of raw materials for battery manufacturing needs 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[2]. India has large pump-storage potential, however, IRADe model finds it less economic compared to battery storage technology 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 single technology as storage option.

IRADe analysis shows that deploying dispatchable coal power plants with CCS technology could improve system stability in highly intermittent technology based future power system and at the same time preventing rapid closure of the coal industry that is employing 13 million people. Optimal pathways pick up 229 GW and 169 GW of Coal+ CCS technology for the year 2050 (NZ50 scenario) and 2060 (NZ60 scenario) respectively leading to significant amount of coal demand in the power sector which would otherwise be almost zero. Sensitivity analysis shows that without this technology, costs of decarbonisation will go up. Preliminary conversations on CCS have only commenced in India, and it is an untested technology. As a starting point, its technical and economic viability need to be understood, CO2 storage potentials need to be assessed. If found viable, then policies, safety standards and regulations need to be developed and deployed.

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 and the reactors. Faster development of nuclear capacity would ease the operation of the decarbonised power system and bring down the additional investment and costs. Sensitivity analysis shows that electrification of end use-sectors will increase the electricity demand and the costs of decarbonisation.

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 needs regulations, policies, and incentives. Various policies and incentives are available for solar and wind which need to be strengthened and extended to other technologies.

High investments (over BAU scenario) will be needed to achieve net zero power system. There is a clear case for availability of international low-cost long term climate financial 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. IRADe exercise shows that pathways exist and with realisation of certain future low carbon technologies, support on cheaper finance and domestic policies, Indian power sector can achieve Net zero emissions by 2050.

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[2] https://indianexpress.com/article/explained/explained-sci-tech/explained-rare-earth-elements-india-global-alliance-supply-8070563/

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Chapter 1. Introduction

1.1. Background

India is one of the fastest-growing major economies in the world. The economy (in real terms) is estimated to grow by 9.2% in 2021-22 after contracting by 7.3% in 2020-21 due to COVID (Government of India, 2022). GDP (real) is projected to grow by 8- 8.5 percent in 2022-23. India is the third largest producer and consumer of electricity in the world. Its power generation capacity has grown 100-fold since independence in 1947, and electricity demand is growing faster due to high economic growth (IBEF, 2020a). As of 30 June 2022, India's total installed capacity (utility) is 403 GW with 58.5% thermal, 1.7% nuclear, 11.6% hydro and 28.1% renewables[3]. India's electricity sector continues to be dominated by fossil fuels, particularly coal. On the renewable front, India has ambitious renewable installed capacity target of 175 GW by 2022 and 450 GW by 2030 (MNRE, 2020). In COP26, India announced an even more ambitious renewable energy target for 2030[4]. India's solar PV capacity was 57.7 GW on June 30, 2022, adding a record 10 GW in 2021. According to the Power Minister, 70 billion USD has been invested in renewable energy in the last seven years[5].

India plays an important role in the global energy scenario as the world's third-largest energy consumer (IEA, 2021b). Energy consumption has doubled since 2000 due to rapid economic growth, urbanisation, industrialisation, and a burgeoning population. 82% of energy demand continues to be met by coal, oil, and solid biomass[6]. Large inequalities across states and between rural and urban areas result in India's per capita emissions and electricity consumption being less than half of the world average. Affordability, reliability, and sustainability of energy are key issues faced by consumers.

On a per capita basis, India's energy use and emissions are less than half the world average. However, India is the third largest GHG emitter (IEA, 2021b). According to the third Biennial Update report (MOEFCC, 2021), due to heavy dependence on coal-based power generation, electricity production accounted for approximately 40 per cent of the total national GHG emissions without LULUCF in 2016, which is the highest emitting category. In 2016, power generation contributed 1135 million tonnes of GHG emissions.

At COP 26 meeting, India pledged to achieve net zero by 2070. As the power sector is the single largest emitter, it is essential to start developing a net zero pathway for the power sector. Also, decarbonising the end-use sectors such as transport and many industrial sub-sectors will require substituting fossil fuels with green electricity. Therefore, to achieve economy-wide decarbonisation, net zero power generation is critical. Reaching net-zero for the power sector requires addressing different technologies and measures. Policies are to be framed and strengthened to overcome the obstacles, adopt new technologies, retire old ones, and change behaviour. These will involve costs and impact the economy and society in various ways. For India to consider potential dates for reaching net-zero, these implications need to be understood, and policies must be widely discussed and accepted. Different net zero years may have different technology and economic implications as the availability of technologies, their implementations and cost performance are a function of time.

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[3] https://powermin.gov.in/en/content/power-sector-glance-all-india

[4] https://www.mea.gov.in/Speeches-Statements.htm?dtl/34466/National+Statement+by+Prime+Minister+Shri+Narendra+Modi+at+COP26+Summit+in+Glasgow

[5] https://economictimes.indiatimes.com/industry/renewables/renewable-energy-sector-in-india-gets-usd-70-billion-investment-in-7-years-r-k-singh/articleshow/83838622.cms

[6] https://energy.economictimes.indiatimes.com/news/renewable/opinion-indias-transition-to-a-clean-energy-system/88247507

Therefore, India needs to assess the alternative possibilities of power generation, the technologies required, and the costs of reaching net-zero in the power sector by the year 2050 or 2060. Achieving early net zero may be more expensive. An integrated assessment is necessary to consider multiple alternative technologies such as pumped storage, battery storage, nuclear, carbon capture use and storage (CCUS) etc., for the ecosystem of the Power sector and their economic implications in achieving net zero.

1.2. Objectives

This project has assessed various technology options and pathways to achieve NetZero emissions in the Power Sector in the years 2050 and 2060 and its economic implications. The project's primary outcomes are to provide feasible technology options to India's Power Sector, consistent with its geographical, technological, political, and socio-economic situations, and to provide a road map for reaching the Net-Zero pathway for development and implementation.

Short-term outcomes achieved during the project's execution provide a basis for discussion on NetZero targets founded on analysis-based options. The mid-term outcomes will lead to the policy debate on alternative pathways. In the long-term, it will initiate policies to achieve the goals of technology development, providing incentives for behavioural changes and resource allocation.

In summary, the objective of this project is to assess the alternative possibilities, the policies required, the technologies needed, and the costs of reaching net zero in the power sector in different target years, for example by 2050 or later. Consequently, the following questions are investigated.

1.3. Research Questions

The questions to be explored include:

- What technologies need to be deployed, and which technology/technologies will play dominant roles in decarbonizing the power system?
- What potentials of different renewable sources will be required to achieve decarbonized power system?
- What would be the economic implications of the power sector for achieving Net Zero emissions by different years, let say 2050, or 2060 in terms of
    - investment
    - cost of electricity supply;
- What would be the role of
    - storage technologies with different storage duration to ensure peak and uninterrupted operation of the power supply system in the presence of a large amount of intermittent technologies as demand (energy and load) varies hourly in a day and from month to month;
    - dispatchable low carbon technologies like carbon capture and storage (CCS) and nuclear?

1.4. Project Activities

The following activities were carried out to achieve the project objectives,:

- A review of the existing Indian power sector
- Techno-economic assessment of existing, emerging, and new technologies for future expansion of the Indian power sector to achieve carbon-free electricity generation has been carried out. The focus was on the technical and economic performance of these technologies like availability factor, thermal efficiency, various costs, technology readiness level, etc. Technologies are selected based on expert

consultations and published literature, including clean coal technologies, hydro power, nuclear, coal power plant with carbon capture and storage, pump storage, Battery Electricity Storage System (BESS), etc. The assessments include developing a database on the current and future performance of the techno-economic characteristics such as costs, efficiency, GHG reduction potential, etc., and upper bounds on realistic penetration of these technologies in the future expansion of the power sector given their physical potential and barriers if any, which would be input to the power system model and validated with expert consultations.

- A literature review on global NetZero research & strategies carried out for other countries, regions or at the global level, what worked and what did not, what is feasible now, and what would be implemented in the future and best practices.
- Modelling of the Indian power system using MESSAGE software, based on dynamic linear optimisation framework, is used for developing and analysing net zero scenarios. Work involved include-

    a. Data collection, Organisation, and Validation,

    b. Input model data and model development

    c. Development of the Business-as-Usual scenario with the model that includes current policies and no hard climate actions. Business as Usual (BAU) scenario considers the energy and climate policies (e.g., NDC measures) already in place up to a certain year (2021 in our case) and examine power system future expansion and emissions implications, not necessarily achieving decarbonisation.

    d. Development of net zero scenarios with different specified net zero dates, e.g., 2050, 2060, has been developed imposing some emissions constraints, simulated, and results are compared with the BAU scenario for technology choice, investments, costs etc.

    e. In addition, sensitivity analysis is conducted for different scenarios based on the value of certain parameters (e.g., availability of certain technologies like coal plants with carbon capture and storage (CCS)), future development of the capital cost development of emerging technologies, let say battery storage) or availability of technologies (e.g., coal power plant with CCS) etc.

These activities are supplemented by discussions with various stakeholders (Niti Aayog, Ministries) to get their feedback on technology choice, technology roadmap, costs etc.

1.5. Report Structure

This report presents the work carried out in the project, and the structural framework is presented in Figure *1*.

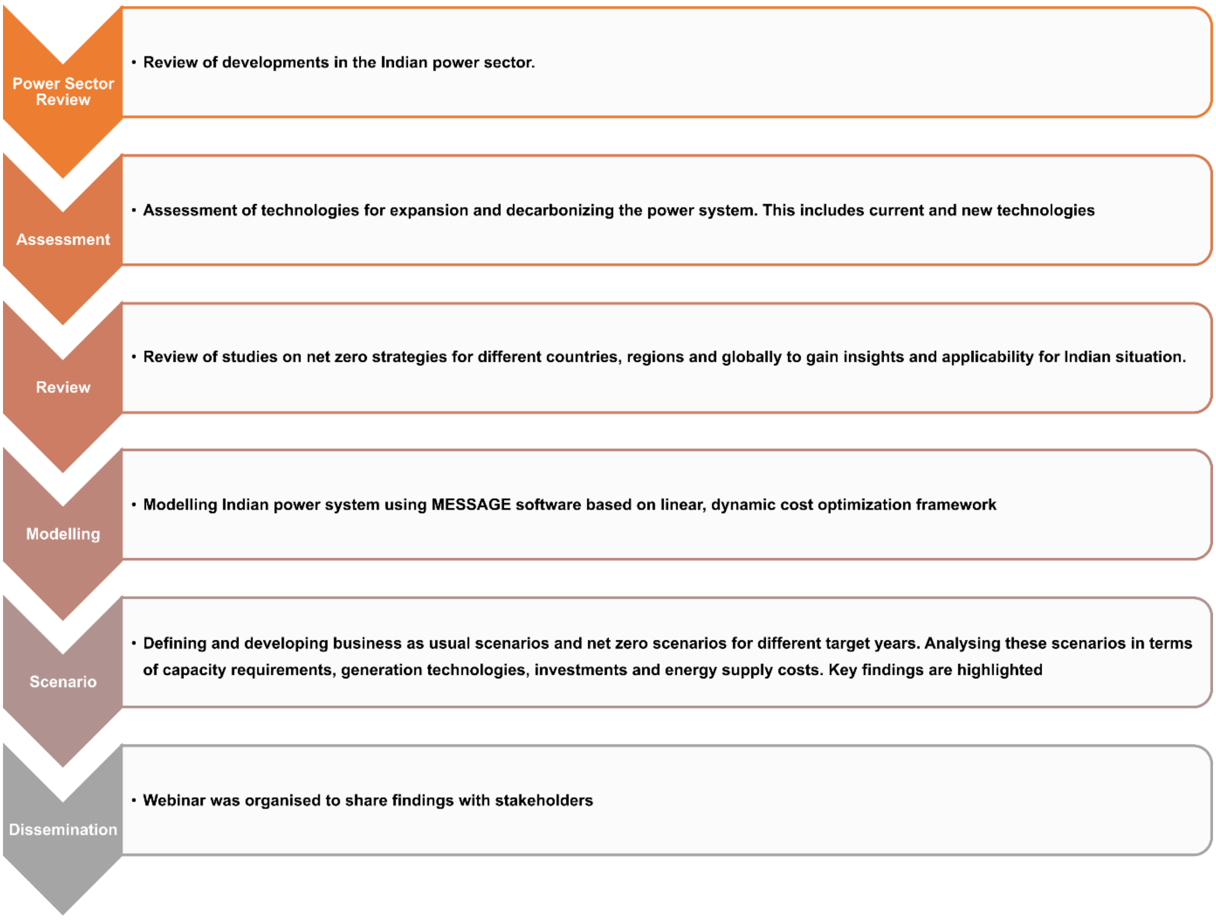


Figure 1: Project Framework

Chapter 2. Review of the Indian Power Sector

India recently has achieved a tremendously high grid electricity access of 96.7% for it's population; however, the per capita electricity consumption is low at 1208 kWh/year (CEA, 2020; CEEW, 2020) and has the potential to grow manifold. India's power generation is dominated by fossil fuels, mainly coal which contributes 74% of overall electricity generation (CEA, 2020). Till recently, coal being the cheapest source of reliable electricity, has hindered India's diversification of electricity generation by accounting for the largest source of fuel in the electricity generation. India is aiming to mass deploy renewable energy in the future. Solar energy has expanded in recent years due to the government's efforts, declining costs, and better infrastructure.

India is the third largest electricity producer and consumer and the third largest emitter of CO_2 emissions (CEA, 2020). India has the fifth-largest electricity generation capacity in the world, with the third-largest solar capacity and fifth-largest wind and hydropower capacity. India has a wide range of policies aimed at clean and sustainable energy, such as renewable purchase obligation, renewable energy certificates market, etc. With growing electricity demand, India needs reliable, affordable, secure, and sustainable electricity, which requires diversification of the generation mix.

In 2021-22, India had a peak demand of 2,03,014 MW, and the peak demand met was 2,00,539 MW (Ministry of Power[7]). Figure 2 shows the load shape at an all India level on a typical day in March 2020.

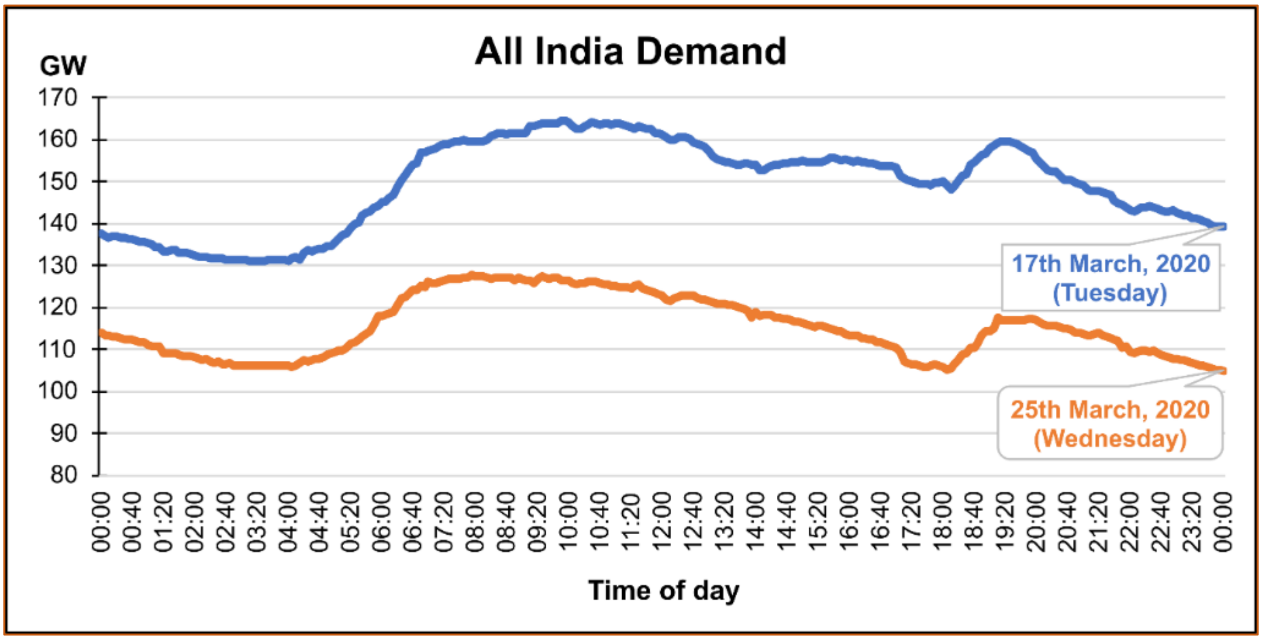


Figure 2: March 2020 Load curve for India

(Data Source: Power System Operation Corporation Limited)

Table 1 shows that by the end of 2020, India's total installed capacity was 375 GW (utility), constituting 104 GW state, 177 GW private sector and 94 GW central sector. The trends in installed capacity from 2010 to 2020 are

[7] https://powermin.gov.in/en/content/power-sector-glance-all-india

shown in Figure 3 and are classified by technology type. In addition, India has 78 GW of captive power capacity, including 50 GW of coal, 15.8 GW of diesel, 8.9 GW of gas, and 0.108 GW of hydro and rest renewables.

Table 1: India's Installed Power Generation Capacity (utility) for December 2020

Technology	Capacity in MW (% Share)
Coal	2,06,124 (55%)
Natural Gas	24,956 (6%)
Diesel	509 (<1%)
Nuclear	6,780 (2%)
Large Hydro	45,798 (12%)
Renewable	91,152 (24%)
– Small Hydro	4,750 (1%)
– Wind power	38,624 (10%)
– Bio-power	10,314 (3%)
– Solar PV	37,464 (11%)
Total Installed Capacity	3,75,322 MW

(Data source: Central Electricity Authority)

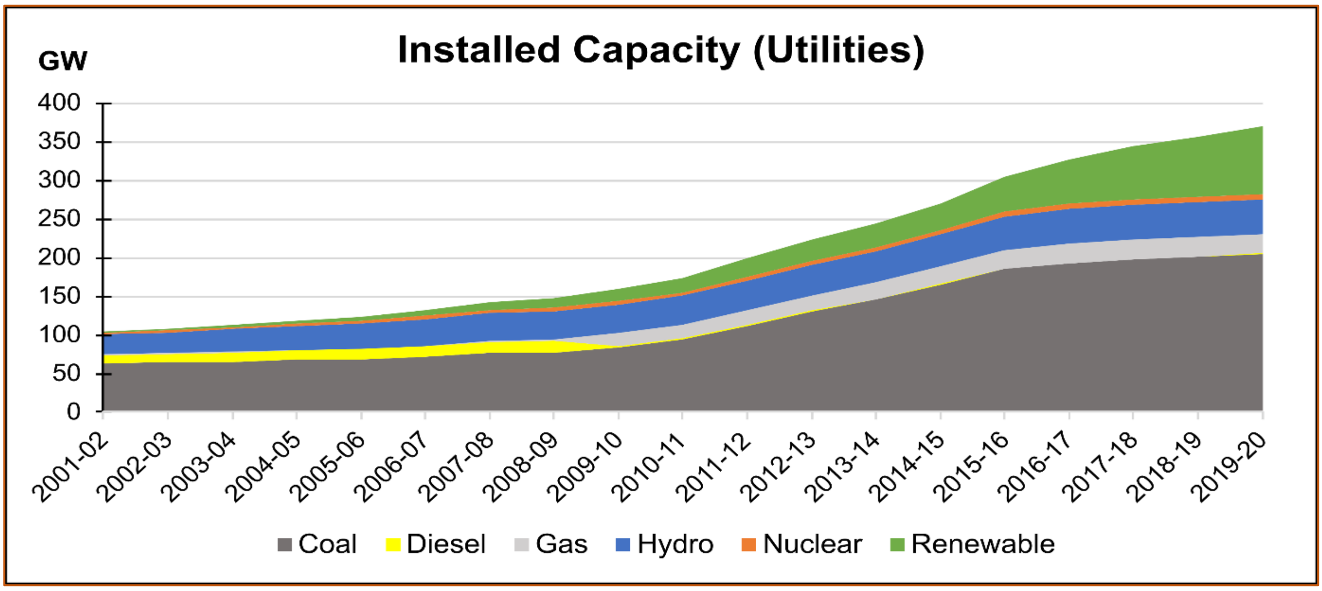


Figure 3: India's Installed Capacity (utility) trend from 2002 to 2020

Power Trading by India: Presently, India exports electricity to Nepal, Bangladesh, and Myanmar, while India imports power from Bhutan. However, sometimes India also exports power to Bhutan during the lean hydro season. In the year 2019-20, India imported 6165 GWh from Bhutan while it exported 1839 GWh to Nepal, 6168 GWh to Bangladesh and 7 GWh to Myanmar (MOP, 2021). India has signed memorandum of Understanding (MoU) with Bhutan, Bangladesh, Nepal, and Myanmar to improve power connectivity.

Import of fossil fuels: The import of coal has been rising along with crude oil and natural gas imports. The average quality of coal found in India is low. The power sector in India is the major consumer of low-quality non-coking coal. Due to logistic and fuel availability constraints, imported non-coking coal is also utilized for power generation and other industries. India consumes 965 mt of coal, of which 235 mt was imported. Of the imports, 80 mt was thermal coal for the power plants. As domestic gas production dwindled, India increasingly has become more dependent on LNG imports. India imports 60% of its gas consumption. India's LNG terminal capacity is 42.5 million tonnes and is expected to increase by 5-mtpa when the floating storage and regasification unit (FSRU), located at Jafrabad in western Gujarat, is commissioned in April 2022. The power sector is not the priority sector as far as domestic gas allocation is concerned; hence, it has to depend on expensive imported gas. India, the world's fourth largest LNG importer, wants to raise the share of natural gas in its energy mix to 15% by 2030, from the current 6.2%, to cut emissions.

Energy Security: India aims to become a global leader in energy to fuel its energy needs for infrastructure, skill development and employment generation. However, India's energy future continues to be vulnerable to sharp fluctuations in crude oil prices. India has prioritised energy security by creating a single national power system and investing in installing power generation capacities. India's power system is being transformed with a higher share of renewables, which also improves energy security, and the power system is becoming flexible. India has facilitated greater interconnection within the country and is promoting affordable battery storage. The government is also striving for electricity market reforms. With limited oil reserves compared to domestic demand, India's oil import dependency will increase significantly in the coming year.

Chapter 3. Assessment of technologies relevant to the Indian power sector

Although coal-based power generation has been the backbone of the Indian Power sector, India has deployed and explored a range of technologies for power generation such as gas combined cycle, gas open cycle, large hydro run-of-the-river and storage type, pump-storage, nuclear and recent technologies like solar PV, concentrated solar thermal, wind onshore, biomass power, small hydro etc. Due to immediate climate change concerns, India is also exploring wind offshore, carbon capture and storage, battery storage technologies, green hydrogen technologies, etc. India has adopted clean coal technologies in the case of coal, moving from sub-critical to super-critical and ultra-supercritical technology. In the following sections, we give brief descriptions and assessments of the technologies expected in the future power system to supply electricity in the short, medium, and long-term as India explores its decarbonisation path. As future power system is expected to be dominated by intermittent technologies like solar, wind etc., flexibility would become important, so we focus on both power generation technologies and storage technologies.

3.1. Generation - Existing technologies

3.1.1. Coal based technologies

Coal will stay in the short and medium term to generate electricity in India as some power plants are under construction or at an advanced planning stage. India relied on sub-critical technology for a long time. According to the CEA report, as of May 2021, 16130 MW of coal power plants using sub-critical technology are under construction[8]. These plants are less efficient in fuel consumption, resulting in high emissions. Due to environmental concerns, clean coal technologies such as supercritical technology have been adopted. The efficiency of these supercritical units would be about 2-3% higher than the efficiency of present 500 MW sub-critical units. This would lead to corresponding savings in coal consumption and a reduction in GHG emissions. The thermal units in the country have the largest size unit capacity of 800 MW. Sixty supercritical units of 660/800 MW with a total capacity of 41,310 MW have been commissioned, and 40520 MW is under construction. The national average thermal efficiency of coal/lignite-based power plants was about 34% in 2013-14 (CEA, 2018b). It is expected that the efficiency of coal-based generation will further improve in 2017-22 due to the commissioning of large super-critical units. Auxiliary consumption is in the range of 5.75%-9%, depending upon the unit size and technology.

In 2019, National Thermal Power Corporation (NTPC), the country's leading power generator, commissioned the country's first ultra-supercritical unit of 660 MW capacity at Khargone in Madhya Pradesh[9]. This plant operates at an efficiency of 41.5%, which is 3.3% higher than the conventional super-critical ones. The high efficiency will result in less coal consumption for generating the same amount of electricity vis-à-vis super critical plants and will reduce carbon dioxide emissions by 3.3%.

3.1.2. Gas-based technologies

India has been using natural gas-based technologies such as combined cycle and open cycle since the late nineties. Adding gas-based capacity is considered necessary to reduce CO2 emissions and utilise their capability

[8] https://cea.nic.in/wp-content/uploads/thermal_broad/2021/04/Broad_Status_April_2021.pdf

[9] https://www.ntpc.co.in/en/media/press-releases/details/ntpc-commissions-india%E2%80%99s-first-ultra-super-critical-plant-0#:~:text=NTPC%20commissions%20India's%20first%20Ultra%20Super%20Critical%20plant,-30th%20Aug%2C%202019&text=This%20plant%20operates%20at%20efficiency,270%20kg%2Fcm2%20pressure.

to ramp up and down quickly. The advantage of fast ramping capability becomes critical due to the large-scale integration of intermittent renewable energy. As of April 2021, according to the CEA report, 24 924 MW of gas-based capacity is under operation. In addition, the country has 8937 MW of captive power generation capacity[10]. Modern combined cycle gas turbines (CCGTs) have high efficiency of around 55% as compared to coal-based plants (Gross efficiency of supercritical units is about 40%) (CEA, 2018b). According to CEA, the auxiliary consumption norm is 2.5% for CCGT plants and 1% for OCGT plants. However, the domestic production of gas has not been keeping pace with the growing demand for natural gas in the country, including the power sector. The gas supply for gas-based power stations in the country is inadequate, and the country faces huge generation losses. Presently, existing gas-based power plants operate at a very low PLF of about 23%. Few gas-based power plants are lying idle due to the non-availability of domestic natural gas, which also contributes to low thermal efficiency. A significant capacity is presently stranded due to a lack of domestic gas and the high cost of imported LNG. The Central Electricity Authority, in its optimal mix study (till 2029/30), did not consider any additional gas-based capacity apart from the existing capacity of 25,343 MW because of the shortage of domestic natural gas (CEA, 2020).

3.1.3. Nuclear

Presently, Nuclear Power Corporation of India Limited (NPCIL) is operating twenty-one reactors with an installed capacity of 6,680 MW based on indigenous Pressurised Heavy Water Reactor (PHWR) technology, except two reactors of 1000 MW each based on imported Russian VVER 1000 Light Water Reactor (LWR) technology. Presently thirteen reactors with an installed capacity of 4,280 MW are under International Atomic Energy Agency (IAEA) Safeguards and use imported fuel. The remaining eight reactors with an installed capacity of 2,400 MW use indigenous fuel. Two more reactors with Russian VVER 1000 Light Water Reactor technology are under construction, and two more are planned. In future, India is likely to acquire more light water reactors from other industrialised countries. These reactors are larger in size (1000 MW or more). The construction period of nuclear power plants is 6-7 years. CEA (2020) reports capital costs of domestic PHWR technology as 11.7 crore Rs. /MW (1579 USD/kW) and for LWR as Rs 19 crore/MW (2564 US/kW), which we think is on the lower side based on internationally available information[11]. NEA/IEA study (2020)[12] reports overnight[13] capital costs of French EPR (this is also LWR) as 4013 USD/kW whereas US LWR as 4250 USD/kW and Russian VVER as 2271 USD/kW (in terms of 2018 USD). The same report presents fuel cost per kWh of nuclear power plants as about 1 US cent/kWh (front-end fuel costs of USD 7/MWh and back-end fuel costs of USD 2.33/MWh).

3.1.4. Large hydro

Hydropower is essential for India to increase the share of renewable generation in electricity. As per the MOP report (MOP, 2021), India plans to install 70,000 MW of hydropower generation capacity by 2030. As on 31st March 2017, Hydro Electric Schemes (above 25 MW capacity) have a total installed capacity of 39693 MW (excluding Pump storage). Currently, it has 13,000 MW of hydropower plants under construction and 8000 MW in the pipeline. The estimated hydropower potential is 145,000 MW at 60% plant load factor (MNRE,2020). Only 26% of hydropower potential has been exploited till recently (MNRE, 2020). Storage possibilities combined with the instant start and stop of hydropower make it a flexible option.

[10] NSO, 2021, Energy statistics India 2021, National Statistical Office, Ministry of Statistics and Programme Implementation, Government of India, New Delhi, India

[11] https://www.exchangerates.org.uk/USD-INR-spot-exchange-rates-history-2020.html

[12] NEA/IEA, 2020, Projected Costs of Generating Electricity, 2020 Edition, International Energy Agency, Nuclear Energy Agency, Organisation of Economic Cooperation and Development, Paris.

[13] Does not include any financing cost such as interests.

The hydro energy availability varies significantly across the years as it depends on the monsoon rains in a particular year. In the current study, the monthly capacity factor of hydro capacities is modelled based on the average monthly hydro capacity factor from 2011 to 2016, as provided in Figure 4.

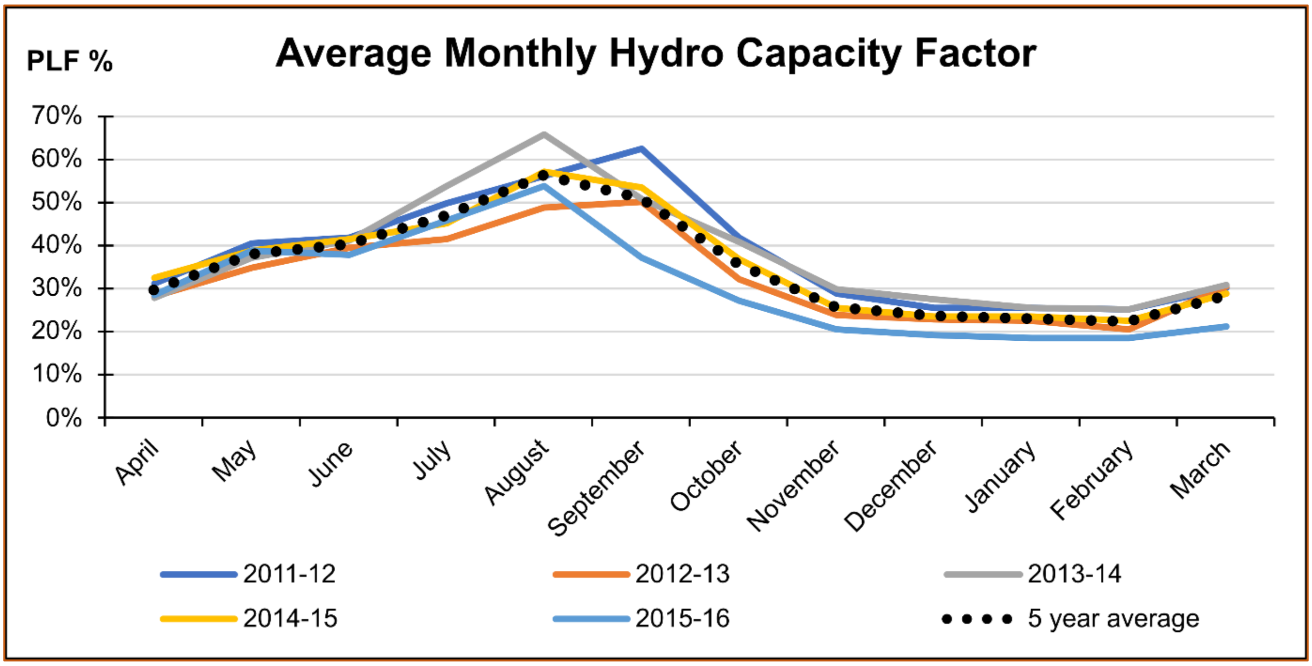


Figure 4: Monthly Hydro power plant capacity factor

(Data Source: Hydro Performance Review, CEA, India)

3.1.5. Renewable Energy Technologies (excl. large hydro)

India's renewable energy expansion plan is the largest and most ambitious in the world (IRENA, 2017). Due to rapidly declining costs and strong policies and measures, there has been a mass uptake of renewable energy like wind, solar PV and small hydropower, which are predicted to be more cost-effective than coal-fired generation. Recently, India has achieved 100 GW capacity milestone in the non-large hydro renewable energy segments. Besides falling costs, renewable energy helps reduce fossil fuel import dependence and risk from price volatility. It also helps to increase energy access and reduce carbon emissions. India has the world's third-largest solar capacity and fourth-largest wind capacity (IRENA, 2021a). The country has ambitious renewable targets of 175 GW by 2022 and has pledged to have 500 GW of capacity from non-fossil sources by 2030[14]. In 2019, India was ranked the fourth most attractive renewable energy market in the world and is expected to be the largest contributor to the renewable upswing in 2021 (IBEF, 2020b). India's annual renewable addition will double from 2020 since many auctioned wind and solar PV projects will become operational. During the past seven years, over USD 70 billion investment has been made in renewable energy in India[15]. According to the newspaper report[16], 60.66 GW of renewable projects is under various stages of development, while 23.14 GW capacity is under the bidding stage.

[14] https://www.mea.gov.in/Speeches-Statements.htm?dtl/34466/National+Statement+by+Prime+Minister+Shri+Narendra+Modi+at+COP26+Summit+in+Glasgow

[15] https://www.business-standard.com/article/economy-policy/renewable-energy-sector-in-india-gets-70-bn-investment-in-7-years-121062500953_1.html

[16] https://www.thehindu.com/business/indias-renewable-energy-capacity-at-114-gw-till-june-end/article65659015.ece

3.1.6. Solar Energy (SE) Technologies

Solar energy generation involves using the sun's energy to provide hot water via a solar thermal system or electricity via solar photovoltaic (PV) and concentrated solar power (CSP) systems. India has vast solar energy potential. Around 5000 TWh of energy per year is incident on India's land area, with most parts receiving 4-7 kWh/km^2/day (MNRE,2020). From an energy security perspective, solar is the most secure energy source due to its abundance and low cost.

Solar Photovoltaic

Solar photovoltaic (PV) systems directly convert solar energy into electricity. The basic building block of a PV system is the PV cell, a semiconductor device that converts solar energy into direct-current (DC) electricity. PV module is formed by interconnecting a large number of PV cells. The PV modules are combined with application-dependent system components to form a PV system. Modular PV systems are linked to provide power ranging from a few watts to tens of megawatts. The most established solar PV technologies are silicon-based systems. More recently, thin film modules consisting of non-silicon semiconductor materials have become important. Thin films have a lower efficiency than silicon modules. However, the price per unit of capacity is lower in thin films.

The National Institute of Solar Energy has assessed India's solar potential to be 748 GW assuming 3% of wasteland is covered with solar PV[17]. Ministry of New and Renewable Energy also mentions that about 5,000 trillion kWh18 per year of energy is incident over India's land area, with most parts receiving 4-7 kWh/mt^2/day. Solar energy is key to India's National Action Plan on Climate Change with programmes like National Solar Mission. The Mission targets 100 GW solar by 2022, and recently, India has achieved the fifth position in solar deployment, surpassing Italy (MNRE, 2020). India's installed solar energy capacity has increased by more than 20 times, from 2.63 GW in March 2014 to 57.7 GW in June 2022.

As sunshine varies over an hour, day, and season, so does the solar panel's energy availability. The hourly behaviour of the solar plant as calculated in IRADe using the PV Watt calculator is shown in Figure 5. The annual availability factor remains in the range of 18-20%.

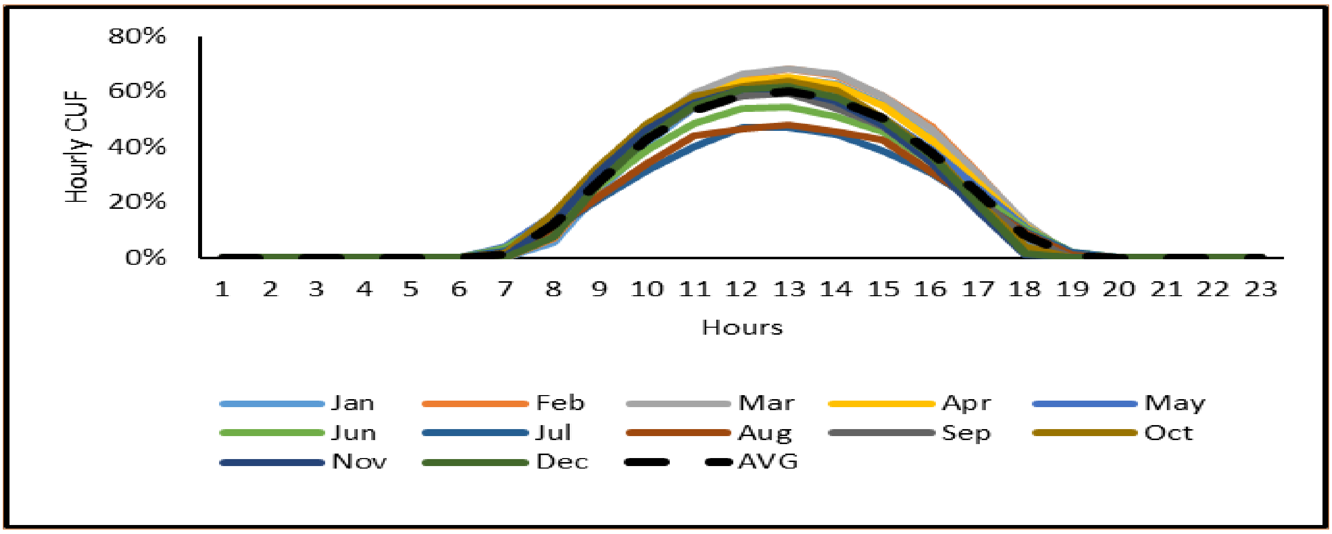


Figure 5: Solar power plants hourly variations

(Data source: PV watt calculator, NREL)

[17] https://mnre.gov.in/solar/current-status/
[18] https://mnre.gov.in/solar/current-status/

Today, India's solar tariff is very competitive and has achieved grid parity. IRENA (2021b) reports that India's utility-scale solar PV installation costs have declined by 84% between 2010 and 2020, and the installation cost is 596 USD lowest among the countries it has analysed. The largest reduction in the utility-scale levelised cost of electricity (LCOE) was also observed in India. Between 2010 and 2020, costs declined by 85% to USD 0.038/kWh – a value 33% lower than the global weighted average in 2020.

India's import dependence for meeting its solar equipment demand was more than 90 per cent in the past three financial years, as reported in the Parliament on July 19, 2018[19]. To promote the upstream and downstream domestic industry associated with the value chain of the manufacturing of solar cells /modules, the Union government imposed a 25% safeguard duty in July 2018 for two years on imports of solar cells/modules into India, and then extended for another year to July 2021, at a rate of 15%[20]. The government has decided to impose 40% basic customs duty (BCD) on solar modules and 25% on solar cells from 1 April 2022, making imports costlier and encouraging local manufacturing[21]. To promote domestic manufacturing of high-efficiency solar cells and modules, India also has launched the Production Link Incentive (PLI) scheme with an allocation of Rs 24000 crore in the Union budget 2022/23[22].

Concentrated Solar Power

In Concentrated Solar Power (CSP) technology, a concentrated direct beam solar irradiance is used to heat a liquid, solid or gas used in a downstream process for electricity generation. Large-scale CSP plants most commonly concentrate sunlight by reflection instead of refraction with lenses. Concentration is done on a line (linear focus) as in a central receiver or on a dish system. CSP technology can be used to produce electricity from small distributed systems of tens of kW to a large, centralized power station of hundreds of MW. With the dominant presence of intermittent solar PV and wind in the decarbonised grid, an important advantage of CSP is that it can offer storage options along with the battery and pump hydro storage. The capacity factor of CSP is higher than solar PV, wind etc. The capacity factor of CSP plants increased from 30% in 2010 to 42% in 2020. As the technology improved, costs for thermal energy storage declined, and the average number of hours of storage for commissioned projects increased.

CSP technology remains expensive. According to the IRENA (2021b), although the weighted average LCOE of CSP plants fell by 68% between 2010 and 2020, the costs remain high at USD 0.108/kWh. In 2020, 150 MW of new CSP was installed, and the global weighted average total installed costs of these CSP plants was USD 4581/kW, 50% lower than in 2010. Between 2018 and 2020, three projects in China were commissioned with more than 10 hours of storage, with a total installed cost range of USD 4126 to USD 5154/kW.

According to the IRENA capacity statistics, the installed capacity of CSP in India was a mere 229 MW in 2020 (IRENA, 2021b). There was plenty of enthusiasm in India about this technology about 10-12 years ago. However, that has slowly faded, perhaps due to the high cost of the technology and the rapid cost decline of solar PV. However, in IRADe study, this technology, with and without storage, has been considered a future low carbon option for expanding the Indian power system.

[19] https://economictimes.indiatimes.com/industry/energy/power/indias-import-dependence-for-solar-equipment-over-90-per-cent-in-last-3-fiscal-government/articleshow/65055838.cms?from=mdr

[20] https://www.financialexpress.com/economy/how-safeguard-duty-on-solar-imports-from-china-benefited-domestic-suppliers-and-india/2040200/

[21] https://mnre.gov.in/img/documents/uploads/file_f-1615355045648.PDF

[22] https://economictimes.indiatimes.com/industry/renewables/govt-to-enhance-funding-under-pli-for-solar-manufacturing-to-rs-24000-cr-says-r-k-singh/articleshow/87695133.cms?from=mdr

3.1.7. Wind Power

Wind power is produced through the conversion of kinetic energy associated with the wind to mechanical energy first and then to electrical energy. The amount of kinetic energy in the wind theoretically available for extraction increases with the cube of the wind speed. However, a turbine only captures a fraction of that available energy (40- 50%). To maximize energy capture, turbine designs, including materials used for the turbine, blade sizes etc., have been changing. The objective has been to minimize the total cost of power produced from wind turbines by capturing maximum wind energy and efficient conversion thereof into reliable electrical energy.

Onshore wind power refers to turbines located on land rather than over water. They are typically located in sparsely populated areas with low conservation value. The infrastructure required for onshore wind power is significantly less expensive than that required for offshore wind. Sometimes, it is half the cost and can provide investment payback as quickly as two years.

As there is hourly, daily, and seasonal variability in the wind, so is the energy available from the wind power plant. The availability factor or capacity factor remains low at around 20%. Wind variability has been modelled in the current study. Figure 6 presents the Wind Power Plants Hourly variations for India.

Driven by technological advances and global climate change policies, wind power is becoming more financially sustainable. Global onshore wind capacity in 2020 was 699 GW, with China leading at 273 GW. (Data source:

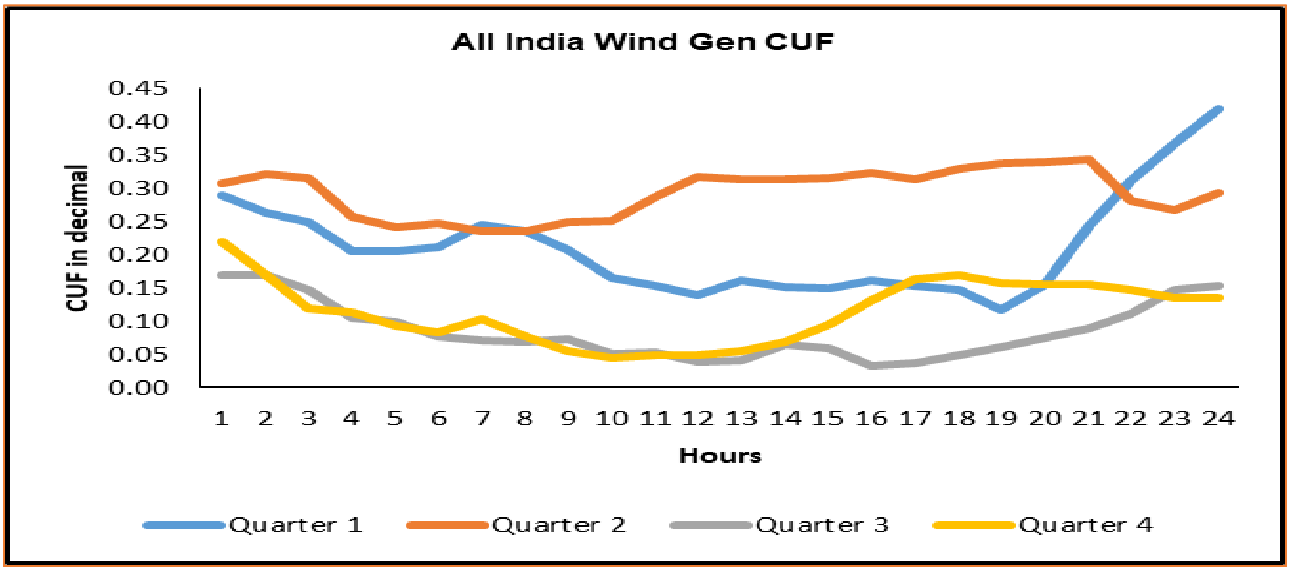


Figure 6: Wind Power Plants Hourly variations for India

Draft National Electricity Plan- Vol 2-Transmission, CEA)

India has an onshore wind capacity of 40.7 GW in June 2022. The recent assessment indicates a gross wind power potential (includes both onshore and offshore) of 302 GW in the country at 100 meters and 695.50 GW at 120 meters above ground level.

Technology has progressed significantly over time, resulting in higher energy generation from the wind. In 1985, typical turbines had a rated capacity of 0.05 megawatts (MW) and a rotor diameter of 15 metres. The average rotor diameter in 2020 was about 125 meters (410 feet)—longer than a football field. Larger rotor diameters allow wind turbines to sweep more area, capture more wind, and produce more electricity. The unit size of machines has gone up to 3.0 MW. Technology improvements have resulted in an almost one-third improvement in the global weighted-average capacity factor, from 27% in 2010 to 36% in 2020 (IRENA, 2022).

The Wind Turbine Generator technology has evolved, and state-of-the-art technologies are available in India to manufacture wind turbines. The current annual production capacity of domestic wind turbines is about 8000 MW to 10000 MW. Around 70-80% indigenisation has been achieved with strong domestic manufacturing in the wind sector. All the major global players have their presence in India, and around 17 companies manufacture 44 different models of wind turbines through (i) joint ventures under licensed production, (ii) subsidiaries of foreign companies, and (iii) Indian companies with their technology.

The global weighted-average total installed cost has fallen by 31%, from USD 1 971/kW in 2010 to USD 1 355/kW in 2020 (IRENA, 2021b). The global weighted-average LCOE of onshore wind fell 56% between 2010 and 2020, from USD 0.089/kWh in 2010 to USD 0.039/kWh in 2020. There was a 13% year-on-year reduction in 2020. China and India have more mature markets with the most competitive weighted-average total installed costs in 2020 as USD 1 038/kW and USD 1 264/kW, respectively – with installed costs falling by 27% in India and 16% in China since 2010.

3.1.8. Biomass Power

Biomass has always been an important energy source for the country. It is renewable and non-intermittent, widely available, carbon-neutral and potentially provides significant employment in rural areas. Biomass is also capable of providing firm energy. The biomass materials used for power generation include bagasse, rice husk, straw, cotton stalk, coconut shells, soya husk, de-oiled cakes, coffee waste, jute wastes, groundnut shells, sawdust, etc. Ministry of New and Renewable Energy has realised the potential and role of biomass energy in the Indian context. It has initiated several programmes for promoting efficient technologies for use in various sectors of the economy to ensure derivation of maximum benefits. The biomass power & cogeneration programme[23] is implemented to promote technologies for optimum use of the country's biomass resources for grid power generation.

As per a recent study sponsored by MNRE, surplus biomass availability is at about 230 million metric tonnes per annum, covering agricultural residues corresponding to a potential of about 28 GW. About 14 GW of additional power could be generated through bagasse-based cogeneration in the country's 550 sugar mills if these sugar mills were to adopt technically and economically optimal levels of cogeneration for extracting power from the bagasse produced by them. According to CEA (2018a), the biomass potential is 17536 MW, and waste to energy is 7554 MW. After accounting for feedstock handling, the assumed net electrical efficiency of the prime mover (the generator) averages around 30%. However, this varies from a low of 25% to a high of around 36%. CHP plants that produce heat and electricity achieve higher efficiencies, with an overall level of 80% to 85% not uncommon.

3.1.9. Small Hydro Power

Small hydro power plants utilize the flow of water to rotate the turbine blades, which drives the generator to produce electrical energy. The amount of energy generated depends on the amount of water flowing through the turbine and the size of the turbine. Small hydro power plants are used as standalone power systems in remote areas. As reported in MNRE, in India, hydro power plants of 25 MW or below capacity are classified as small hydro, which have further been classified into micro (100kW or below), mini (101kW-2MW) and small hydro (2-25MW) segments. CEA National Electricity Plan (2018a) provides an estimated potential of 19750 GW (however, the MNRE website mentions 21135 MW from 7135 sites for power generation in the country from small/mini hydel projects).

[23] https://mnre.gov.in/bio-energy/current-status

3.2. Emerging power generation technologies

3.2.1. Offshore wind

Offshore wind power refers to wind farms located over shallow open water, usually in the ocean, with higher wind speeds. The term 'offshore wind' can also refer to inshore water areas like lakes and fjords. Most offshore wind farms use fixed-foundation wind turbines in shallow water. However, wind farms can be built over deeper water as technology advances.

Offshore wind speeds are typically faster than on land, and even small increases in speed can produce large increases in energy generation[24]. As such, fewer turbines are needed to produce the same amount of energy as an onshore turbine. Wind speeds offshore don't vary as much, and the wind direction doesn't change as often, so offshore turbines are more consistent (meaning more reliable power generation). Offshore turbines don't have as much visual impact as those on land. They don't interfere with land usage, and there are no physical obstacles that can interrupt the wind flow. For this reason, offshore wind farms can be made larger and generate more energy than those onshore, with less physical impact. Offshore turbines can also be built taller than those onshore, which means they can harness more wind energy and produce more electricity.

India is blessed with a coastline of about 7600 km surrounded by water on three sides and has good prospects of harnessing offshore wind energy. Considering this, the Government had notified the "National offshore wind energy policy"[25]as per the Gazette Notification dated 6th October 2015. As per the policy, the Ministry of New and Renewable Energy will act as the nodal Ministry for the development of Offshore Wind Energy in India and work in close coordination with other government entities for the development and use of Maritime Space within the Exclusive Economic Zone (EEZ) of the country and shall be responsible for overall monitoring of offshore wind energy development in the country. The National Institute of Wind Energy (NIWE), Chennai, will be the nodal agency to carry out resource assessment, surveys, and studies in EEZ, demarcate blocks and facilitate developers for setting up offshore wind energy farms. The Ministry set a target of 5.0 GW of offshore wind installations by 2022 and 30 GW by 2030, which has been issued to give confidence to the project developers in the Indian market. India's Ministry of New and Renewable Energy (MNRE) will open the first offshore wind tender in the next three to four months to lease blocks off the state of Tamil Nadu, which can accommodate around 4 GW of offshore wind capacity [26].

A project was implemented from December 2013 to March 2018 by a consortium led by the Global Wind Energy Council (GWEC) and supported by the European Union (EU) to assist India in its offshore wind power development and contribute to India's transition towards the use of clean technologies in the power sector. The project focused on the States of Gujarat and Tamil Nadu to identify potential zones for development through techno-commercial analysis and preliminary resource assessment. Initial assessment by NIWE within the identified zones suggests 36 GW of offshore wind energy potential exists off the coast of Gujarat only. Further, nearly 35 GW of offshore wind energy potential exists off the Tamil Nadu coast.

The offshore wind energy potential estimation carried out through satellite data needs to be validated through actual ground measurements to make the data bankable. Ministry has decided to launch a measurement

[24] https://www.americangeosciences.org/critical-issues/faq/what-are-advantages-and-disadvantages-offshore-wind-farms#:~:text=Offshore%20wind%20speeds%20tend%20to%20be%20faster%20than%20on%20land.&text=Small%20increases%20in%20wind%20speed,more%20energy%20can%20be%20generated.

[25] https://mnre.gov.in/img/documents/uploads/3debfe9158b643d8a3e06a7a007f2ef9.pdf

[26] https://ieefa.org/articles/india-open-first-offshore-wind-tender-4-gigawatts-capacity

campaign deploying Light Detection and Ranging (LiDARs) at the identified zones off the coast of Gujarat and Tamil Nadu.

According to the IRENA capacity statistics report (IRENA, 2021), global offshore wind capacity was 34.3 GW in 2020, with the UK leading with 10.3 GW, followed by China with 9 GW in 2020. The capacity factor remains an important parameter for the project's viability. Between 2010 and 2020, the global weighted-average capacity factor of newly commissioned offshore wind farms grew from 38% to 40%. Capacity factors have been rising due to the installation of larger wind turbines with higher hub heights and larger swept areas that harvest more electricity from the same resource than older machines. There has also been a contribution from reduced downtime as manufacturers have integrated experience operating wind farm models into new, more reliable designs. GE's Haliade-X 14 MW prototype operating in the Port of Rotterdam, the Netherlands, is one of the largest offshore wind turbines operating in the world.

The global weighted-average LCOE of offshore wind declined by 48% between 2010 and 2020, from USD 0.162 to USD 0.084/kWh, with a 9% reduction year-on-year in 2020 (IRENA, 2021b). Between 2010 and 2020, global weighted-average total installed costs fell 32%, from USD 4 706/kW to USD 3 185/kW. So, unlike wind onshore, wind offshore remains expensive.

3.2.2. Carbon capture and storage (CCS)

CCS is the most promising method to reduce CO2 in the atmosphere, involving capturing and storing CO2 in deep geological formations preventing it from being released into the atmosphere. The current state of technology can capture up to 90% of CO2 emissions released by burning fossil fuels during electricity generation and industrial processes such as steel or cement production[27]. CO2 could also be used to produce commercially marketable products. This is commonly known as carbon capture, utilization and storage (CCUS). When CCS technology is combined with bioenergy technologies for power generation (so-called BECCS – bioenergy with carbon capture and storage), CCS creates then 'negative emissions', removing CO2 from the atmosphere as biomass is CO2 neutral. IEA has claimed that this technology can reduce 17% of global CO2 emissions by 2050. The CCS must be part of the policy in every country worldwide to mitigate the severe effect of global warming (IEA, 2021d).

In India, stakeholders have largely remained sceptical of the CCS technology because of the negligible progress on the deployment of this technology in the last two decades, the perverse incentive it presents to postpone mitigation actions, and the potential increase in the cost of power generation if this technology is deployed (Chaturvedi & Malyan, 2021). The debate on CCUS in India has not been given critical attention, but it is not new to the energy and climate policy space. Department of Science and Technology (DST) aims to nurture the area of Carbon Capture, Utilization, and Storage through an emphasis on research and development and capacity building of both human resources and infrastructure to evolve technologies and methodologies that address issues related to high capital costs, safety, logistics and high auxiliary power consumption[28]. DST is supporting 19 ongoing research projects[29] on various aspects of CCS to the research organisations in the country under the Mission Innovation initiative for joint collaborative Research & Development with member MI countries to identify and prioritize breakthrough technologies in the field of CO_2 capture, separation, storage and CO_2 value addition. In 2021, DST invited further research proposals under the Accelerating CCS Technologies (ACT)

[27] https://www.twi-global.com/technical-knowledge/faqs/what-is-carbon-capture-and-storage
[28] https://dst.gov.in/carbon-capture-utilisation-and-storage-ccus
[29] https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf

initiative to facilitate R&D and innovation to develop safe and cost-effective CO_2 capture, utilisation and storage (CCUS) technologies. The intention is to facilitate the emergence of CCUS by accelerating and maturing CCUS technologies through targeted financing of innovative and research activities. The scope also envisages addressing the challenges related to CCUS in the country's technological, environmental, social and economic context. However, detailed findings of these projects are awaited. In this study, coal power plants with CO2 capture and then transportation of CO2 to the storage are considered, which will be available from 2030 onwards.

Tramošljika et al. (2021) carried out a performance analysis of a 700 MW future planned advanced ultra-supercritical (A-USC) coal-fired power plant fitted with post-combustion carbon capture and storage (CCS) technology. The reference A-USC unit without CCS achieves a net efficiency of 47.6% with CO2 emissions of 700 kgCO2/MWh. For a CO2 removal rate of 90%, the net efficiency of the CCS integrated A-USC unit is 36.8%, the resulting net efficiency loss is 10.8% points, and the electricity output penalty is 362.3 kWh/tCO2 for the present state of CCS technology. EIA (2021) reports overnight capital costs of an Ultra Super Critical (USC) coal power plant with 90% CCS as 5861 US$(2020)/kW, variable O&M costs as 11.03 US$(2020)/MWh, and fixed O&M costs as 59.85 US$(2020)/kW/Yr and Heat rate as 12507 BTU/kWh (27% efficiency, whereas USC without CCS as 39.5% efficiency). IRADe current study includes coal power plants fitted with carbon capture technology of 90% of carbon capture and then CO2 to be transported and stored in a safe location. CO2 storage potential in India is unknown. According to some published sources, theoretical potential ranges from 45 to 143 Gt (Gupta & Paul, 2019; Smith et al., 2021). We have assumed 25 GT as cumulative storage potential for the study period.

3.3. Electricity storage technologies

Power systems worldwide are experiencing higher levels of variable renewable energy (VRE) as wind and solar power plants connect to the grid. Higher penetrations of VRE can drive the additional need for power system flexibility in both short-term essential grid services and longer-term energy shifting and peaking capacity services. Energy storage is one of several sources of power system flexibility that has gained the attention of power utilities, regulators, policymakers, and the media (Chernyakhovskiy et al., 2021). Falling costs of storage technologies, particularly lithium-ion battery energy storage, and improved performance and safety characteristics have made energy storage a compelling and increasingly cost-effective alternative to conventional flexibility options such as retrofitting thermal power plants or transmission network upgrades. This study considers two types of grid-connected storage technologies: pump storage and battery storage.

3.3.1. Pumped Hydro Storage System

Pumped storage power plants store energy by pumping water from a lower to a higher reservoir and converting the potential energy back into electricity. These reservoirs can be natural or artificial. Both types of pumped storage plants enable the power system to receive and store energy in periods of low demand or excessive generation and generate electricity in times of higher demand. The role of pumped storage hydropower plants is twofold: they balance the grid for demand-driven fluctuations and balance generation-driven fluctuations (Morales Pedraza, 2015). Pumped storage technology is the long-term, technically proven, cost-effective, highly efficient and flexible way of energy storage on a large scale to store intermittent and variable energy generated by solar and wind (IRADe, 2020). PSPs improve the overall economy of power system operation and reduce operational problems of thermal stations during low load periods. It could also provide ancillary benefits such as flexible capacity, voltage support, Black start facility, etc. The concept of off-river PSP is becoming popular in recent years due to huge benefits arising from its lower capital cost/operations.

Out of 96,524 MW of pumped storage potential identified in India by CEA at 63 sites, at present, 9 pumped storage schemes with an aggregate installed capacity of 4,786 MW are in operation, out of which only five plants with an aggregate installed capacity of 2,600 MW are being operated in pumping mode (CEA, 2018a). The remaining four plants with an installed capacity of about 2,200 MW are not operating in pumping mode mainly because the 2nd reservoir is under construction or has not been constructed. Efforts must be made to complete and operationalize the pump storage projects not running in PSP mode. Since the energy gained from Pumped Storage Plants (PSP) is less than the energy input, off-peak power must be available at a reasonable tariff to make the pumped storage plants commercially viable. If a PSP pumps for 7 hours daily, it can generate for 5.25 hours, assuming 75% overall efficiency.

The concept of off-river PSP[30] is becoming popular in recent years due to huge benefits arising from its lower capital cost/operations. The Australian National University (ANU) found 16,000 off-river sites in India with a combined energy storage capacity of 56,000 Gigawatt-hours (IRADe, 2020). If each site has storage for 18 hours, then this corresponds to a storage power of 3100 GW. The same study also quotes that the approximate capital cost of a typical off-river PHES system would be 700$/kW.

3.3.2. Battery Energy Storage System (BESS)

Electrochemical storage systems use a series of reversible chemical reactions to store electricity in the form of chemical energy. Batteries are the most common form of electrochemical storage. They have been deployed in power systems in both front-of-the-meter and behind-the-meter applications and electronics and transportation applications. Batteries have durations lasting up to several hours and can change output in the sub-second to several minutes range. Table 2 provides the technical and economic characteristics of various batteries. Lithium-Ion battery storage is widely commercialised and installed at the grid level, with established global manufacturing capacity driven partly by its use in electric vehicle applications. The overlap between the transportation and power system sectors enabled steep price declines in technology costs for lithium-ion batteries, driving higher deployments. Lithium-ion has been used predominantly in utility-scale power sector applications for short-duration, high-cycling services such as frequency regulation. However, it is increasingly used to provide peaking capacity and energy arbitrage services in certain jurisdictions. Lithium-ion has a typical duration in the 2- to 4-hour range, with price competitiveness decreasing at longer durations.

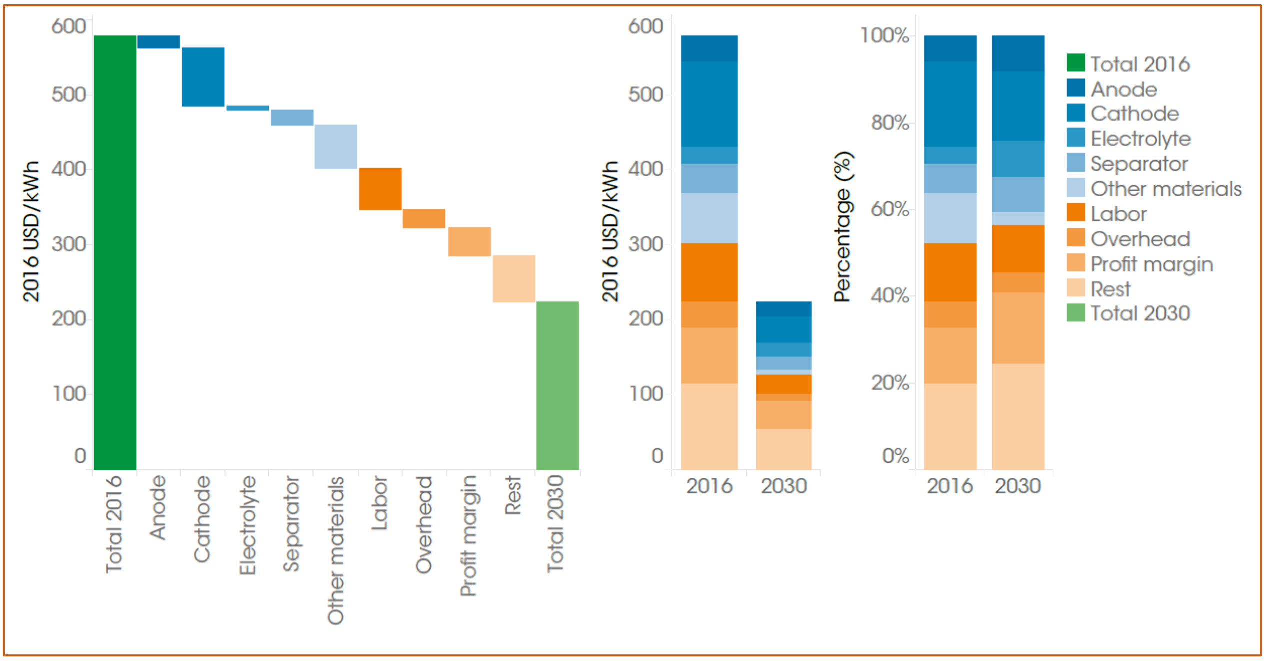
Table 2: Technical and economic characteristics of various electrochemical batteries

Technology	Development Stage for Utility-Scale Grid Applications	Cost range ($/kw) & ($/kWh)	Typical duration of discharge at max power capacity	Reaction Time	Round Trip Efficiency (%)	Lifetime (years)
Lithium-ion	Widely commercial	1408-1947 & 352-487	Minutes to few hours	Subsecond to seconds	86-88	10
Flow	Initially commercial	1995-2438 & 499-609	Several hours	Subsecond to seconds	65-70	15
Lead-acid	Widely commercial	1520-1792 & 380-448	Minutes to few hours	Seconds	79-85	12
Sodium-sulfur	Initial commercial	2394-5170 & 599-1293	Several Hours	Several hours	77-83	15

(Source: NREL, 2021)

[30] An off-river PHES system typically comprises a pair of small reservoirs (a few hundred hectares each) located in hilly country a few kilometres apart, with an altitude difference ("head") of 200–1200 m and connected by a tunnel or pipe containing a pump/turbine. Water is circulated indefinitely between upper and lower reservoirs ("closed loop") (Silalahi et al., 2022).

Lithium-ion battery storage currently dominates the landscape for new, utility-scale installations for electrochemical stationary storage applications and is only surpassed by pumped hydro storage for cumulative capacity. Total electricity storage capacity appears set to triple in energy terms by 2030 if countries proceed to double the share of renewables in the world's energy system (IRENA, 2017). Li-ion batteries in stationary applications have a higher installed cost than those used in EVs due to the more challenging charge/discharge cycles that require more expensive battery management systems and hardware. Benefitting from the growth in scale of Li-ion battery manufacturing for EVs, the cost could decrease in stationary applications by another 54-61% by 2030. This would reflect a drop in the total installed cost for Li-ion batteries for stationary applications to between USD 145 per kilowatt-hour (kWh) and USD 480/kWh, depending on battery chemistry. Lithium-ion battery pack prices, which were above $1,200 per kilowatt-hour in 2010, have fallen 89% in real terms to $132/kWh in 2021[31]



(Source: IRENA, 2017)

Figure 7: Cost reduction potential by source of lithium iron phosphate battery energy storage systems, 2016 and 2030

[31] https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/#:~:text=Bali-,Battery%20Pack%20Prices%20Fall%20to%20an%20Average%20of%20%24132%2FkWh,Commodity%20Prices%20Start%20to%20Bite&text=Hong%20Kong%20and%20London%2C%20November,from%20%24140%2FkWh%20in%202020.

Chapter 4. Review of studies on decarbonisation strategies in other countries/regions/world

Various studies have investigated decarbonisation strategies for the energy sector, including the electricity sector at the country, regional (e.g., EU 27 or Nordic region) and global level. Some studies were carried out for India as well. These studies are reviewed, and key points are highlighted.

4.1. Countries/ Regions other than India

4.1.1. China

IEA (2021b) developed long-term strategies for reaching carbon neutrality in China's energy sector. The Announced Pledges Scenario (APS) reflects the enhanced targets China announced in 2020 of achieving net zero by 2060. The rapid decarbonisation of power supply alongside the electrification of a wide range of end-use sectors will form an important pillar of China's strategy for carbon neutrality. The electricity demand is projected as 14677 TWh and 16515 TWh in 2050 and 2060, respectively, compared to 7230 TWh in 2020. Consequently, electricity generation increases by 130% during 2020-2060 as electrification of end-use sectors becomes a key strategy to achieve decarbonisation. The report recommends a massive expansion of renewable electricity generating capacity and flexible low-carbon resources to maintain electricity system security. Coal's share in electricity generation drops from 60% to 5% in 2060, which is generated in plants with carbon capture facilities. Renewable energy sources – mainly solar PV and wind power – grow rapidly to meet most of the increase in demand and displace existing fossil-based generation. Their output increases nearly sevenfold by 2060, and their share in total generation increases from around 25% in 2020 to 80% in 2060. The two other main low-carbon-generating technologies, nuclear and large hydro, also play important roles.

4.1.2. Nordic region

Nordic[32] Energy Research developed Nordic Clean Energy Scenarios aiming to prioritise actions up to 2030 and map potential long-term pathways to carbon neutrality for the Nordic region. The scenario analysis seeks to balance multiple factors that influence outcomes and are reflected in three scenarios. Direct electrification of end-use sectors is central to all scenarios, with clean electricity directly substituting fuel combustion in transportation, heating, or industrial processes. With strong electricity grids and large hydropower reservoirs, the Nordic region is well-positioned to leverage the falling costs of renewable electricity generation to accelerate the deployment of electric end-use technologies. Wind power is central to the power system transition, enabled by large Nordic wind resources and supported by flexibility in hydropower reservoirs and successful efforts to enhance additional flexibility of the Nordic energy system. The nordic region has good potential for CO2 storage. Achieving net zero emissions will be difficult without CCS technologies and technologies that would enable negative emissions (such as Bio energy with CCS (BECCS)).

4.1.3. European Union (27 countries) region

European Commission (2018) has reported a range of GHG reduction scenarios in the EU region, starting at -80% and going up to -100% by 2050 compared to 1990 level. The power sector in the region has already taken important steps toward decarbonization with the closure of the most inefficient thermal generation, the growth

[32] Nordic region comprises of Norway, Sweden, Finland, Denmark, Iceland

of renewables and the contribution of nuclear capacity. The main driver of decarbonization is electrification in all sectors. Power is nearly decarbonized by 2050 with strong penetration of renewable energy sources (RES) facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a supportive role in the power sector, and CCS deployment faces limitations.

D'Aprile et al.(2020) present a cost-effective, feasible pathway to a net-zero Europe (27 EU countries) by 2050. With wind and solar power generation technologies already available at scale, power would be the quickest sector to decarbonize, reaching net-zero emissions by the mid- 2040s. Since the power demand 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% by 2050 and expand its storage capacity. Remaining electricity will come from nuclear and gas-based power plants with carbon capture. Solar and wind capacity additions need to increase from 15 gigawatts (GW) and 10 GW respectively per year today to 45 GW and 24 GW per year during 2030-50. The EU would also need to increase interconnections among its power grids threefold by 2030 and its battery storage capacity to 25 GW and 150 GW by 2030 and 2050. Decarbonizing the power sector would require an investment of €6 trillion from now through 2050, an average of 1 to 1.5 percent of EU GDP.

4.1.4. World

IEA (2021b) shows that there are still pathways for the global energy system to reach net zero by 2050. The report focuses on the one that is most technically feasible, cost-effective, and socially acceptable. Ever-cheaper renewable energy technologies give electricity the edge in the race to zero. IEA pathway calls for scaling up solar and wind rapidly, reaching annual additions of 630 gigawatts (GW) of solar photovoltaics (PV) and 390 GW of wind by 2030, four times the record levels set in 2020. Hydropower and nuclear provide an essential foundation for transitions. As the electricity becomes cleaner, electrification emerges as a crucial economy-wide tool for decarbonisation. Electricity accounts for almost 50% of total energy consumption in 2050 and is essential to produce supporting energy carriers like green hydrogen. Consequently, total electricity generation will increase over two and a half times between today and 2050. There should be no investments in new unabated coal plants. By 2050, almost 90% of electricity generation will come from renewable sources, with wind and solar PV accounting for nearly 70%, and the remaining (10%) comes from nuclear.

Key points from these studies: As electricity generation becomes cleaner, electrification emerges as a key tool in decarbonising end-use sectors and a source of green hydrogen, increasing electricity demand further. Solar PV and wind are dominant technologies in the decarbonisation of power sector across all countries/regions with flexibility support from battery technology or fossil power with CO2 capture and storage technology. Hydro and nuclear also play critical roles.

4.2. India

TERI/ Shell (2021) study has evaluated the technology and policy options that can lead India towards net-zero emissions by 2050. However, the study presents a scenario sketch, and in-depth insights are missing. According to this study, the electricity system shifts to zero-carbon generation through solar and wind power. The study does not disclose the methodology used while costs implications, capacity and flexibility aspects of the transition pathway are not addressed.

Applying the Global Change Analysis Model (GCAM, CEEW version), Chaturvedi et al. (2021) analysed the implications of energy transition in energy-intensive sectors, including power, in the form of scenarios combining various peaking years and net zero years. 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 5630 GW by 2070. The study also mentions economic losses due to the shift in investment for mitigation but does not specifically indicate the investment and cost implications for the power sector. The representation of power generation technologies in the scenario analysis is detailed. However, the study does not discuss how the power system will deal with the intermittency of a large amount of solar and wind in the grid. It is unclear if the temporal representation of electrical load and supply from intermittent sources are modelled. These are important factors for making technology choices and capacity planning.

(IEA, 2021b) explores the Indian energy outlook through scenario analysis, with time frame of analysis till 2040 and net zero scenarios are not explored. The Sustainable Development Scenario explores how India could mobilise clean energy investment to produce an early peak and rapid decline in future emissions. Electricity demand growth remains low, which makes decarbonisation less challenging. By 2040, coal is almost eliminated from power generation, and CO2 emission from the power sector is 214 million tonnes, less than 20% of the current emissions. Solar power is set for explosive growth in India, powered by battery storage.

Thus, the two studies that developed the net-zero scenario sketch or net zero scenarios lack many important aspects that policymakers in India could use for charting net zero pathway for the Indian power sector .

Chapter 5. Methodology

An energy system model is preferred as technologies play a key role in decarbonising power system. The higher presence of variable renewable energy (VRE) needs a model representing higher time resolution to analyse the flexible reserves requirement and its utilisation. Hence study uses International Atomic Energy Agency's MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts)[33] model, based on a dynamic, bottom-up, linear optimization framework. It allows detailed representations of various energy technologies with specific characteristics (pump-storage hydro, Fossil power plant with Carbon capture and storage etc.). MESSAGE is built on Reference Energy System (RES) (existing and its future evolution) network that links resource supplies, energy conversion, processing technologies, and end-use demands and the devices that meet them, tracking the flows of energy and associated emissions. RES can include the whole energy system or a subsystem. In this study, the Indian power system is modelled. Demand for energy services is exogenous to the model. The model finds the least-cost path through the RES network to meet user-specified electricity demand, subject to the constraints that enforce network integrity and any user-imposed (policy) constraints (e.g., emissions constraint).

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

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

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

A second approach would be to define 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, so we have used the first approach.

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

Chapter 6. Modelling the Indian power system in MESSAGE

The time frame for modelling is 2015-2085 so that different net zero years e.g., 2050, 2060, 2070, etc. and their techno-economic implications could be analysed. All costs are in 2015 constant prices, and the assumed discount rate is 4%. The physical power system of India representing the physical structure (power plants, transmission and distribution infrastructure etc.) and the flows in the power system have been modelled in MESSAGE. This includes characteristics of the various existing generating stations (vintage, techno-economic performance, rehabilitation schedules, etc.), under construction and committed projects, future power generation options, transmission and distribution, energy flows, demand, load characteristics, energy resources and import/ export links. Figure 8 presents the simplified energy flow network for the Indian power system, including the existing and expected future alternatives that have been modelled.

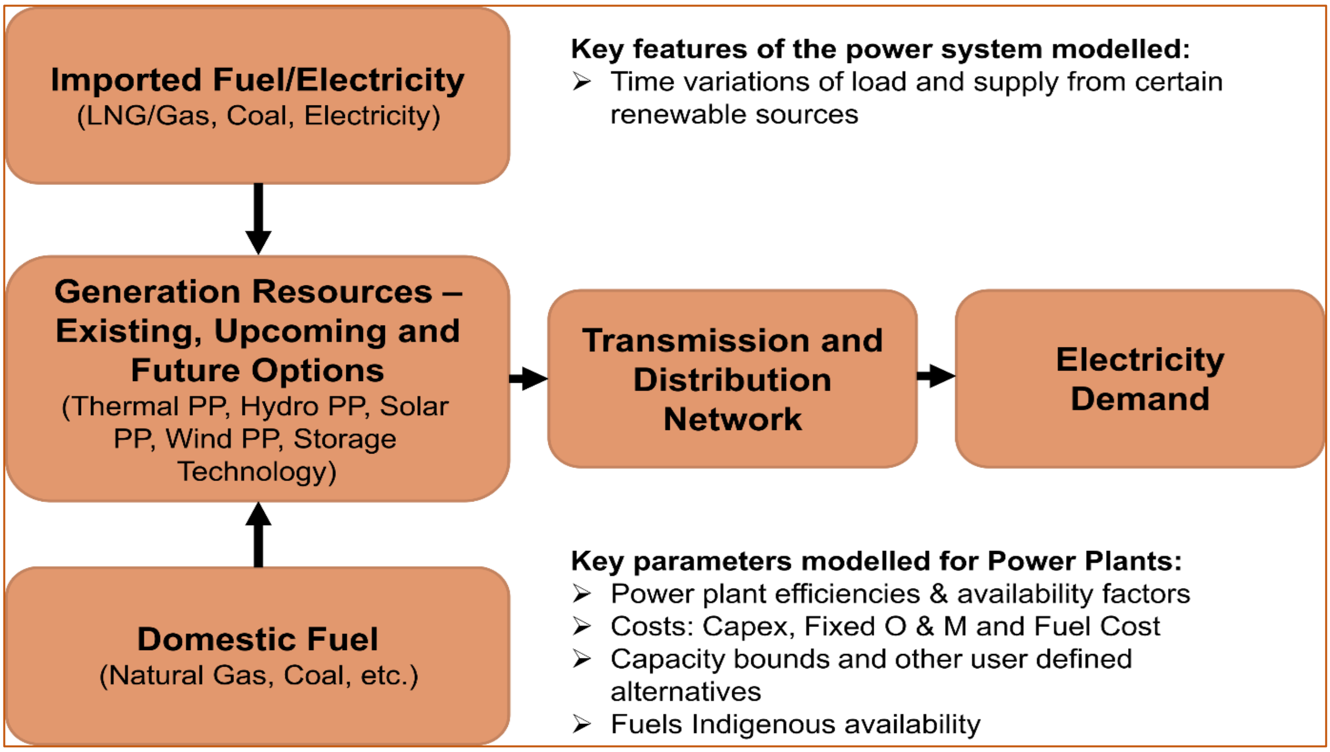


Figure 8: Modelled Reference Energy System

6.1. Electricity demand

The final annual electricity demand of India is exogenously specified to the MESSAGE model and projected, assuming GDP growth rates and electricity-GDP elasticity. Although there are some fluctuations, but India's electricity-GDP elasticity has fallen over the last 40 years from about average 2 to around 0.8 recently (IRADe's estimates). Nearly 26 million households were provided electricity connections under SAUBAGYA scheme between September 2017 and March 2019[34]. As income of household grows, the electricity demand will

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

increase. India's electricity demand and GDP are predicted to rise in the future. Table 3 presents the assumptions on GDP and electricity-GDP elasticity over 2020-2060 used for electricity demand projections.

Table 3: Assumptions on GDP growth rates and electricity-GDP elasticity

Time period	GDP growth (%)	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

Figure 9 presents the electricity demand assumed in the model. This demand development presents modest growth in electricity demand, reflecting the past performance. It does not include the possibility of future electrification of the end uses like industrial process heating, transportation etc. which is increasingly becoming an important lever to decarbonize the entire economy. A separate demand scenario reflecting higher energy efficiency improvement and electrification of end-use sectors has been developed, analysed, and presented after the sensitivity analysis.

IRADe projected electricity demand for 2030 is slightly higher (14%) than the CEA baseline projection of 2415 TWh (CEA, 2019). Electricity demand is projected as 6977 TWh and 9309 TWh in 2050 and 2060, respectively, although it is 5-7 times higher than the current electricity demand. However, compared with a country with a similar population like China, it remains modest. IEA (2021a), in its net zero study for China, has projected the electricity demand as 14677 TWh and 16515 TWh in 2050 and 2060, respectively, much higher than IRADe projections for India in these two years. However, for China, electricity demand numbers include end-use electrification. Per capita electricity demand at 4256 kWh in 2050 remains 20% lower than the China's per capita consumption of 5331 kWh[35] in 2020.

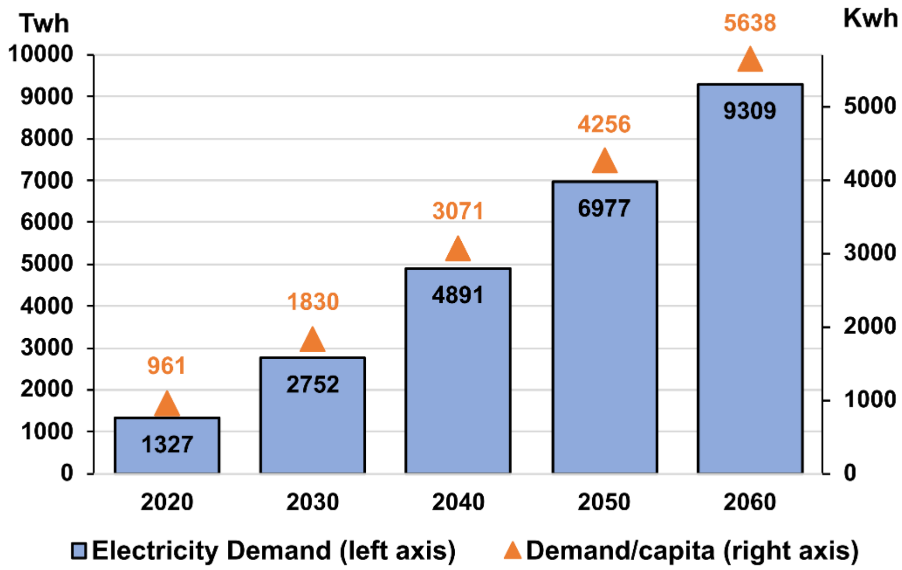


Figure 9: Development in electricity demand

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

Electricity demand needs to be met in real time, and demand varies by season, day, hour, and second. Load shape changes over the years as electricity use pattern changes due to changes in economic activities, lifestyle patterns, demand response measures etc. However, due to the unavailability of data, the load shape of 2019 has been replicated throughout the model horizon. On the supply side, the availability of certain sources like hydro, wind, and solar will have a larger presence in future supply systems, varying over season and during various times of the day. The time resolution in the model is quite detailed to capture the seasonal, daily, and hourly load patterns and the supply variations of hydro, solar and wind. The 8760 hourly load has been arranged into 288-time slices (12*24, including 12 seasons where each month represents a season and 24-hourly load of an average day in each month). Figure 10 presents the organised form of 288-time slices load shape representation of the load curve for the year 2019 in the model. 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 granular time resolution enables the analysis of flexibility needs in the form of storage as some of the technologies remain inflexible.

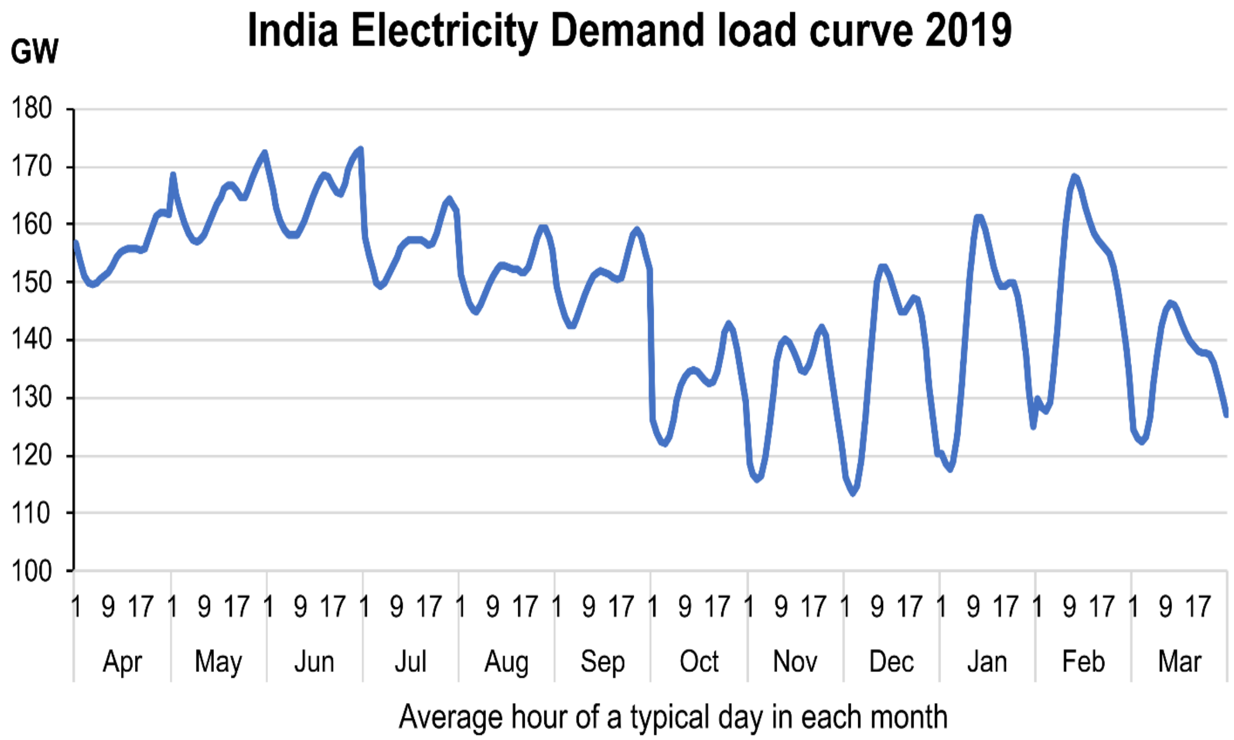


Figure 10: Load curve representation in the model for India

(Data Source: Average System Load Profile India December 2019, Energy Analytics Lab, IIT Kanpur, EAL (2020))

6.2. Technology

A comprehensive list of generation and storage technology options is considered for future expansion of the power system or replacement of the existing facilities as technology represents a key decarbonisation solution and is presented in Table 4.

Table 4: List of technology options for future expansion of the power systems

Energy source	Technology
Coal	- Integrated Gasification Combined Cycle (IGCC) - Coal sub-critical - Coal super-critical - Coal Ultra super-critical - Coal power plant with CO2 capture
Gas	- Combined cycle, - Open Cycle
Nuclear	- Indigenous Pressurised Heavy Water Reactor (PHWR) - Light Water Reactor (LWR)
Hydro	- Large hydro - Small hydro - Pump hydro storage
Biomass	- Biomass power plant
Solar	- Solar PV - Concentrated Solar Power
Wind	- Onshore - Offshore
Battery Storage	- 1 Hour storage, - 2 Hour storage - 3 Hour storage - 4 Hour storage - 6 Hour storage

Technology in MESSAGE is represented based on its technical and economic parameters (capacity factor, unit size, construction period, thermal efficiency, capital cost, operating cost (fixed and variable) etc.) and emissions factor. Assumptions on these techno-economic parameters are shown in Table 5 and Table 6.

Table 5: Assumptions on technical and economic parameters of power generation technologies

Technology	Parameters	Start year	Thermal efficiency	Fuel type	Annual avaibility 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
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		
	Off-shore	2015			0.32	25	3		

Data Source: Central Electricity Authority, Central Electricity Regulatory Commission & NITI Aayog

**Capital cost of Nuclear LWR is sourced from NEA/IEA (2020)*

Table 6: Future development in capital cost of renewable technologies

	Capex in USD per KW				
Scenario	Assumed capex reduction by 2050 compared to 2017 (%)	2015	2017	2050	O & M as % of CAPEX
Solar PV					
Low	57	1077	818	353	1
Medium	67	1077	818	273	
High	79	1077	818	172	
Solar CSP					
Low	11	1871	1853	1653	1
Medium	47	1871	1853	976	
High	64	1871	1853	660	
Wind Onshore					
Low	36	965	957	609	1
Medium	42	965	957	552	
High	52	965	957	460	
Wind Offshore					
Low	36	5260	4683	3003	1
Medium	53	5260	4683	2179	
High	70	5260	4683	1400	

* 2015 and 2017 numbers for solar PV and Wind onshore are from CERC Tariff orders. For Solar CSP and Wind-offshore the number for 2015 and 2017 are taken from IRENA studies. 2050 numbers are assumed based on various projections undertaken by international organisations such NREL and IRENA.

The technical efficiency and life of Li-ion battery storage technologies are assumed as 85% and 15 years. Costs assumptions are given in Table 7.

Table 7: Costs assumptions Li-Ion batteries

	Capex in USD per KW			
Scenario	Assumed capex reduction by 2050 compared to 2017 (%)	2017	2050	O & M as % of CAPEX
Storage 1 Hour				
Low	30	890	623	2.5
Medium	58	890	374	
High	79	890	187	
Storage 2 Hour				
Low	30	1100	770	2.5
Medium	58	1100	462	
High	79	1100	231	
Storage 3 Hour				
Low	30	1310	917	2.5
Medium	58	1310	550	
High	79	1310	275	
Storage 4 Hour				
Low	30	1520	1064	2.5
Medium	58	1520	638	
High	79	1520	319	

* Capex includes both Energy/Storage and Power system cost

(Data Source: Cost Projections for Utility-Scale Battery Storage, 2019, NREL)

As MESSAGE is a least cost software, to limit the model to choose an unrealistic amount of least cost technology options, upper bound on the capacity of some technologies in different milestone years are imposed as shown in Table 8. It should be noted that reliable assessments of potential of some of these technologies like solar and wind are still unavailable.

Table 8: Upper bound on capacity potential (GW) of selected technologies

Technology	2050	2060
Nuclear	60	80
Solar PV	2000	3000
Wind offshore	300	600
Wind onshore	500	750
Large hydro	120	145
Pump storage	56	76

The All-India Transmission & Distribution (T & D) loss in 2018 was 21.15%. For future reduction in T&D loss at the national level, the loss reduction trajectory provided in the 19th Electric Power Survey report of CEA is used (CEA, 2019). Respective assumptions on T&D losses are 13%, 11%, 10% and 8% for the years 2030, 2040, 2050 and 2060. On the investment side, the CAPEX cost for new transmission and distribution assets has been assumed as 220 and 235 USD per kW, respectively. The O&M cost per year is assumed to be 1% and 3% of the capital expenditure for transmission and distribution assets.

In addition, the cost of grid integration of the renewables projects is included. The Government of India launched the Green Energy Corridor (GEC) scheme for the evacuation & integration of renewable energy (RE). GEC I approved in 2015/16, the total fund requirement of evacuating 32 GW was initially assessed as Rs. 34141 Crore for developing the transmission system and control infrastructure for the addition of RE capacity in the renewable-rich States of Andhra Pradesh, Gujarat, etc[36]. GEC II was approved in 2022 to establish a transmission grid at the cost of Rs 12031 crore to evacuate 20 GW of renewable power[37]. Based on this information, an additional transmission investment of USD 71/kW (2015 USD) is assumed for integrating renewable capacity like solar and wind into the main grid.

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 the power sector is assumed to be 25 Gt for the entire modelling period. The CO2 transport and storage cost is assumed to be US$ 15/tonne (Gupta & Paul, 2019; Smith et al., 2021).

6.3. Fuels and Prices

Fossil sources will be part of the energy mix in the medium to long-term future of the energy transition and CO2 capture and storage can also play an important role in decarbonisation scenarios. The availability of domestic and imported fossil sources like coal, lignite and natural gas for power generation is modelled. The production profile of domestic fossil sources like coal, lignite and natural gas has been developed based on the government production target in 2030 and assuming CAGR (Compound Annual Growth Rate) for later period. Out of the total coal production forecast for India, around 83% (average offtake of coal between 2012 to 2019) is assumed to be

[36] https://powermin.gov.in/en/content/transmission-works-under-green-energy-corridors-i#:~:text=Green%20Energy%20Corridor%20is%20a,MW%20during%2012th%20Plan%20Period.

[37] https://mnre.gov.in/green-energy-corridor

available for the power sector; while for natural gas, around 32% (average of domestic natural gas consumed by Indian power sector from 2013 to 2019) is assumed to be available for the power sector.

Prices of key domestic and imported fuels are estimated by the IRADe experts based on World Energy Outlook (IEA, 2021d) Stated Policy Scenario and presented in Table 9.

Table 9: Price development of fossil sources

Fuel	Unit	2020	2030	2040	2050	2060
Coal (Domestic)	USD/tonne	23.4	21.5	22.6	23.7	23.1
Coal (Imported)	USD/tonne	64.5	58.5	64.5	71.0	74.5
Natural gas (Domestic)	USD/MBTU	3.4	3.3	3.6	3.9	3.9
Natural gas (Imported)	USD/MBTU	9.4	10.1	10.5	10.9	11.4

Source: World Energy Model Documentation, 2019 Version, International Energy Agency. https://iea.blob.core.windows.net/assets/d496ff6a-d4ca-4f6a-9471-220adddf0efd/WEM_Documentation_WEO2019.pdf

For domestic PWHR and imported LWR, nuclear fuel cost is assumed to be USD 9.33/MWh (front-end fuel costs of USD 7/MWh and back-end fuel costs of USD 2.33/MWh) (NEA/IEA, 2020).

Chapter 7. Scenarios and results

The MESSAGE model of the Indian power system described in the previous chapter has been used for scenario development and analysis. Business-as-Usual (BAU) Scenario and two Decarbonisation scenarios are developed based on two net-zero years, 2050 and 2060.

7.1. BAU Scenario:

BAU Scenario includes all policies, including the new pledges up to 2030 made in COP26. In this scenario, emissions are not constrained, and the trajectory shown in Figure 11 is the optimal emissions outcome of the scenario simulation. 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).

7.2. Net Zero Scenario 2050 (NZ50):

In this scenario, emissions from the power system are constrained exogenously. Based on the BAU scenario emissions, the emissions trajectory has been developed, with emissions peaking in 2030 and then gradually declining to 200 million tonnes[38] by 2050 and fed into the model as a constraint.

7.3. Net Zero Scenario 2060 (NZ60):

This scenario is similar to the NZ50 scenario, with emissions gradually declining to 200 MT by 2060 instead of 2050. A similar emissions trajectory has been developed, with emissions peaking in 2035 and declining to 200 MT by 2060 and fed to the model as a constraint. Figure 10 presents emissions trajectories for different scenarios.

Results of scenario simulations are presented in the following sections:

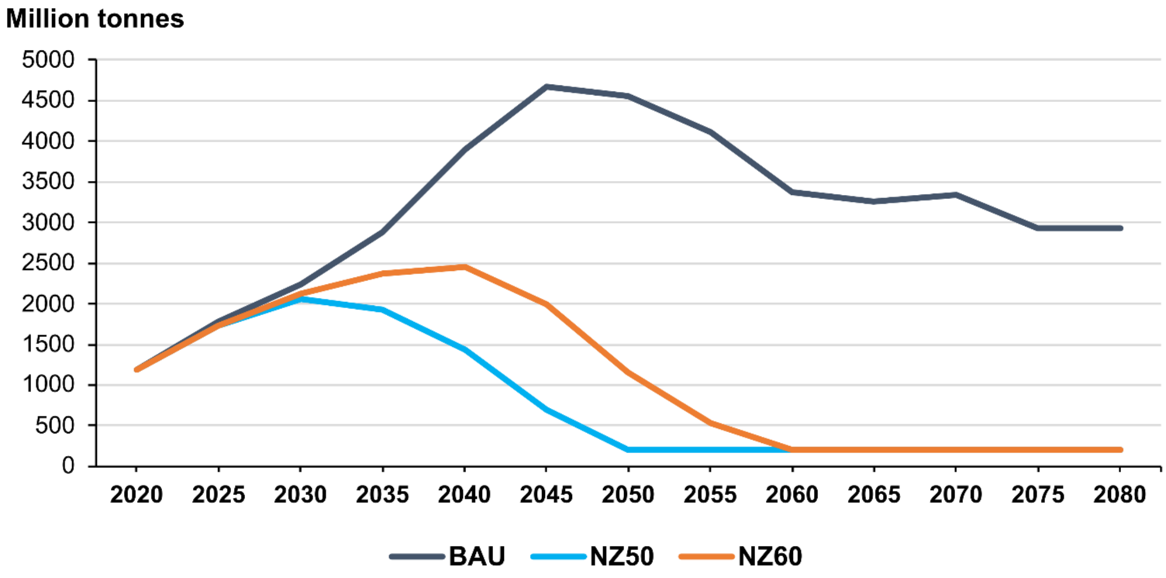


Figure 11 Emission trajectories for different scenarios.

[38] 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.

7.4. Scenario results and analysis

7.4.1. Capacity and generation

BAU scenario

Figure 12 presents the capacity (left side) and generation (right side) in the BAU scenario over 2020-2060. The capacity and generation need to grow to meet the burgeoning electricity demand in the coming years. By 2030, according to the recently announced targets, 500 GW of capacity needs to be from non-fossil sources, which comprises 280 GW of solar PV, 140 GW of wind onshore, 3 GW of wind offshore, 52 GW of large hydro, 18 GW of nuclear, 18 GW of other renewables, slightly outstripping the policy target, totalling to 510 GW. The total capacity in 2030 is projected to be 861 GW. Therefore, non-fossil sources will have more than 50% share, higher than the NDC commitment.

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 upto 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-hour 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.

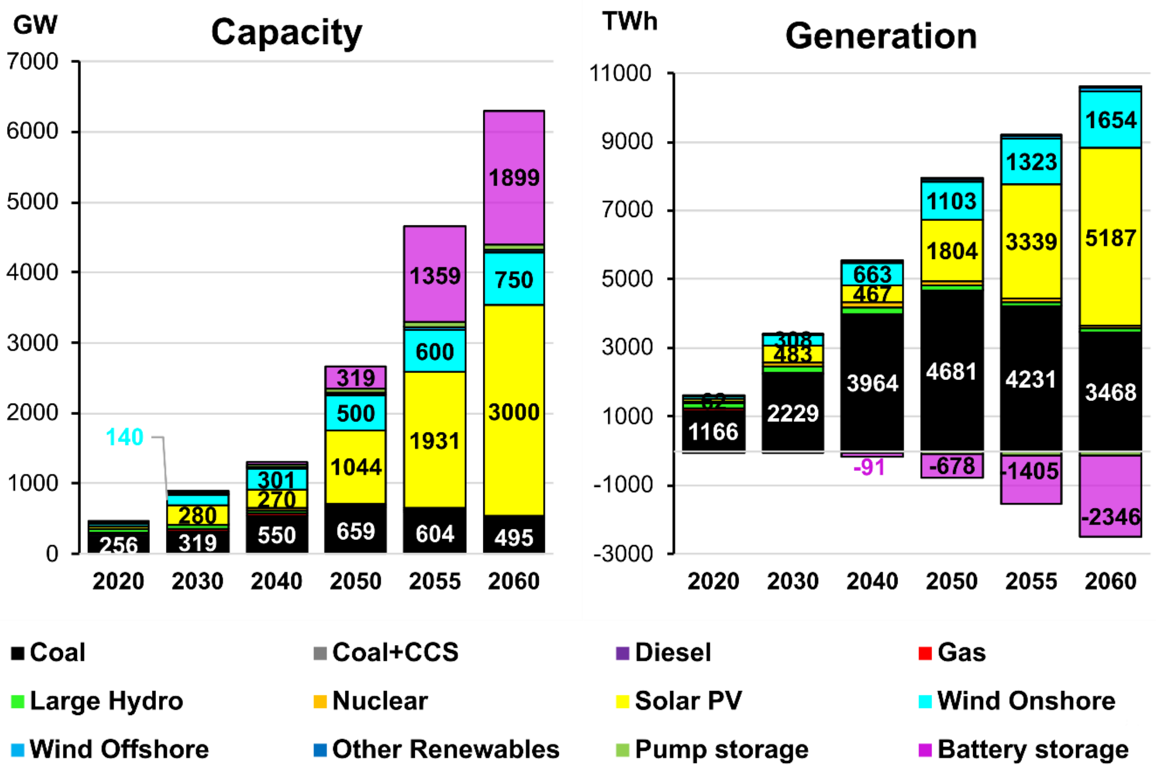


Figure 12: Capacity and Generation pathways in BAU scenario

Total electricity generation increases to 3404 TWh (Figure 12, right side) in 2030 from 1592 TWh in 2020. 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 Durga et al.(2022), 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 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.

Net zero scenarios

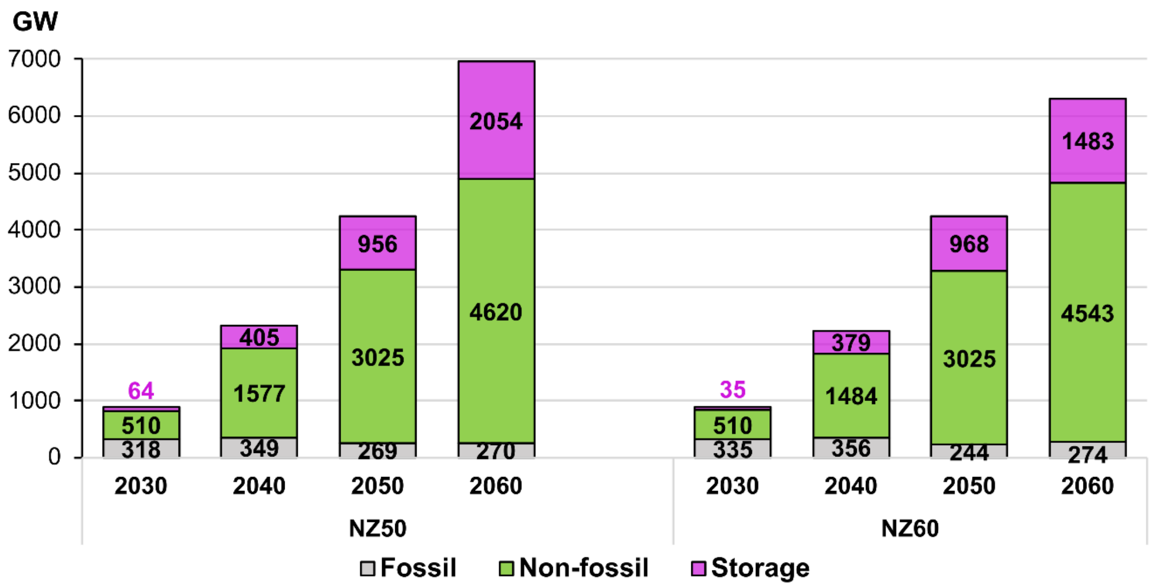


Figure 13: Total capacity requirement in NZ scenarios.

Figure 13 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 other 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.

Figure 14 and Figure 15 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 (Figure 14).** 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.

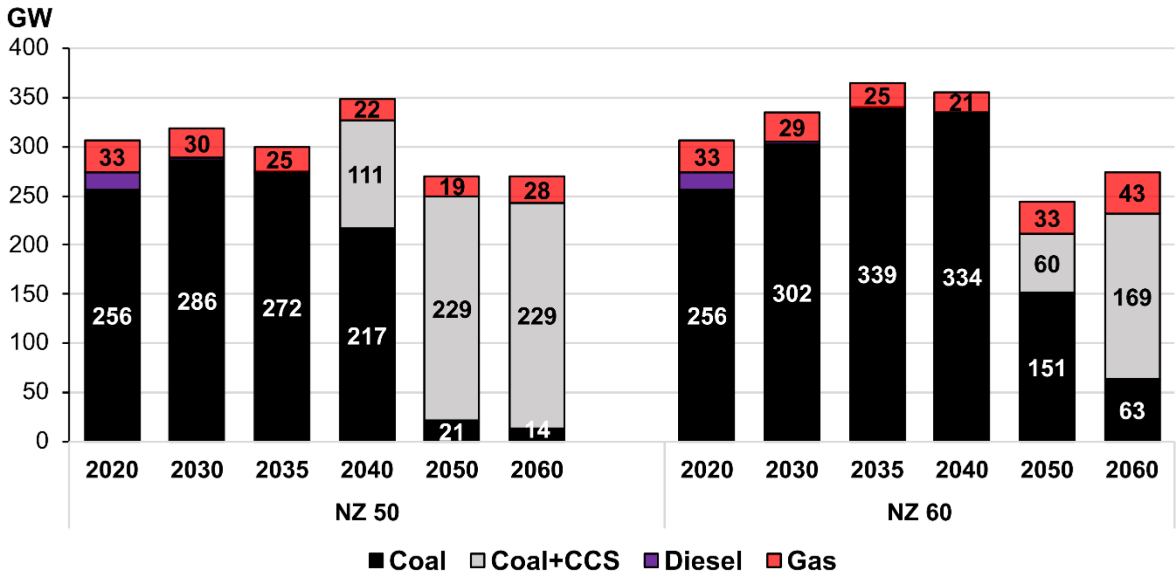


Figure 14: Pathways for fossil capacity in NZ scenarios

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.

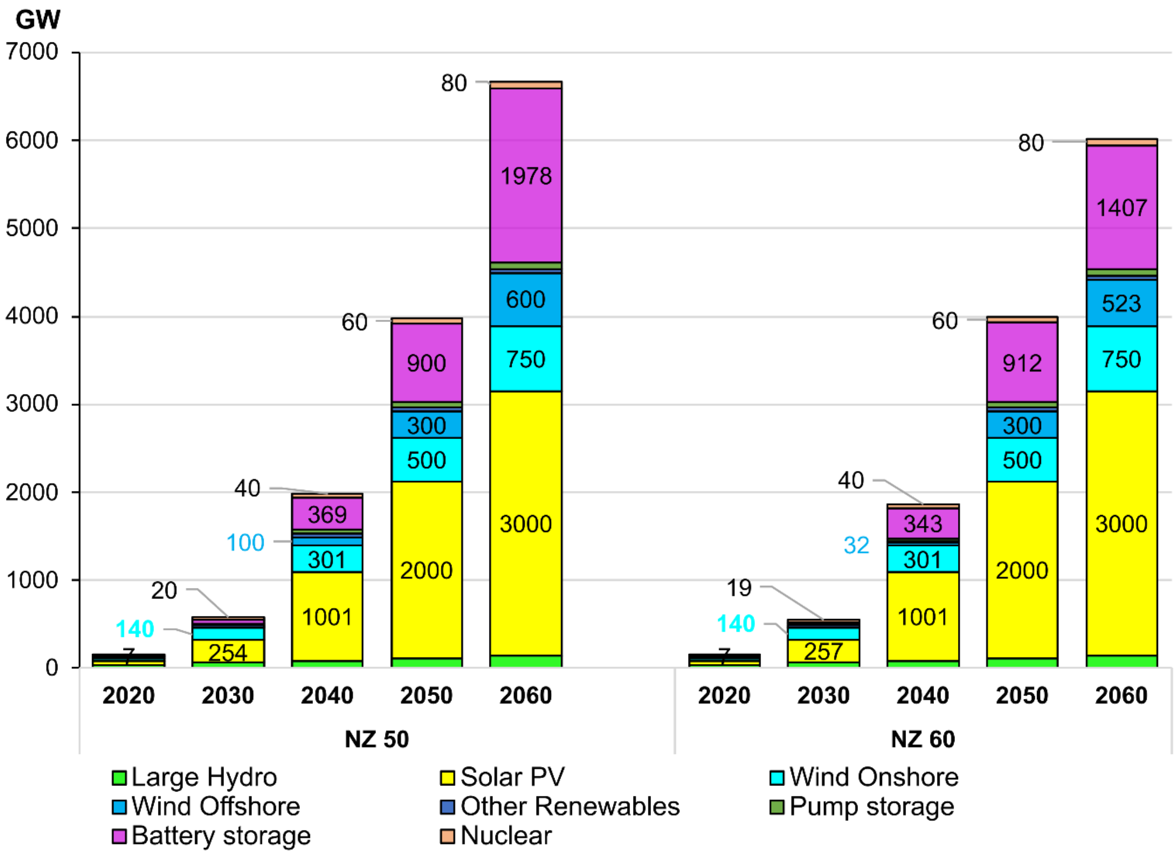


Figure 15: Pathways on Non fossil (Nuclear+Renewable+ large hydro) + storage capacity in NZ scenarios

Figure 15 presents the renewable, nuclear, 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 (Chaturvedi et al., 2021; Durga et al., 2022; IEA, 2021c; TERI/Shell, 2021) 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 in 2021[39]. 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. 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 project the similar findings (IEA, 2021a, European Commission, 2018). The other critical emissions-free sources include large hydro and nuclear. About 120 GW and 145 GW of large hydro need to be deployed in the NZ50 scenario in 2050 and the NZ60 scenario in 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.

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.

Figure 15 also presents storage capacity requirements in both Net Zero scenarios. To ensure a robust power system, the model balances the supply and demand of energy and load hourly over 12 months. 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 fall substantially (assumption) 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 over-dependence 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 hours a day, 6-hour battery storage becomes the primary solution for flexibility.**

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

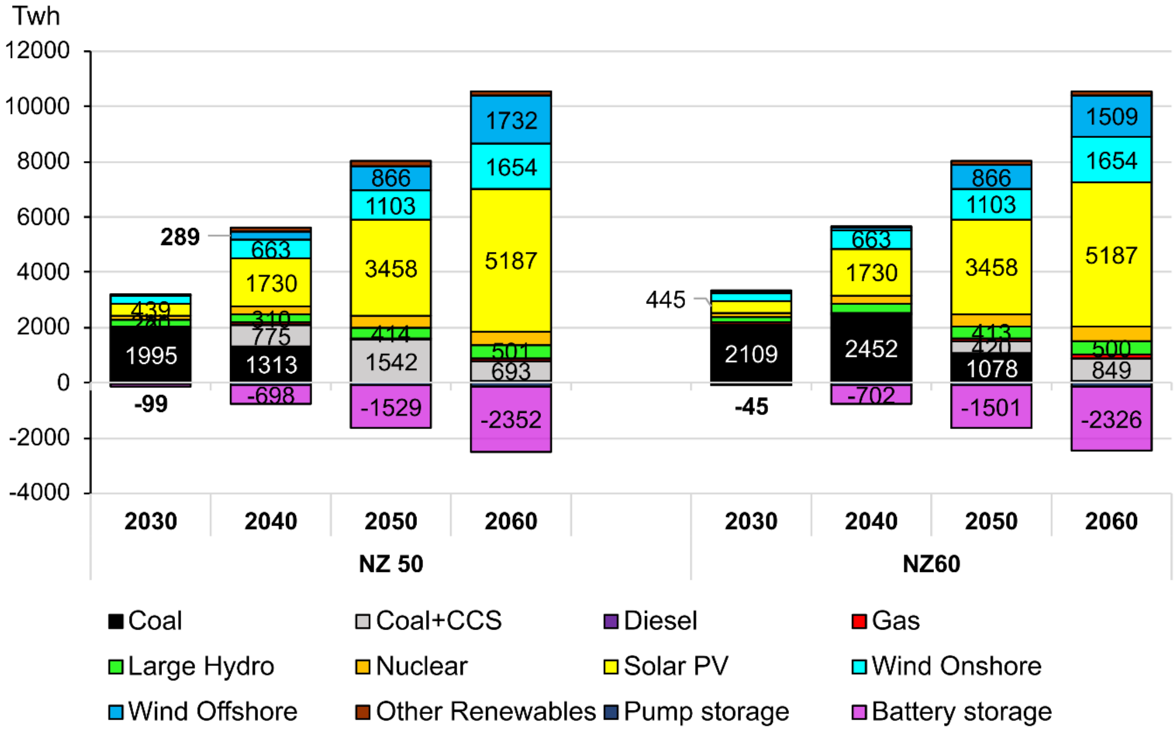


Figure 16: Generation pathways in NZ50 and NZ60 scenarios

Figure 16 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 delayed than NZ50 scenario and declines later. 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. Generation from battery storage plays an important role by providing flexibility.

Power system operations with the heavy presence of intermittent and storage technologies in net zero scenarios would be very different from the current system with conventional technologies. Figure 17 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 the NZ50 scenario. During sunshine hours, solar generation outstrips the demand and charges the storage technologies. Storage technologies generate after sunset and before sunrise.

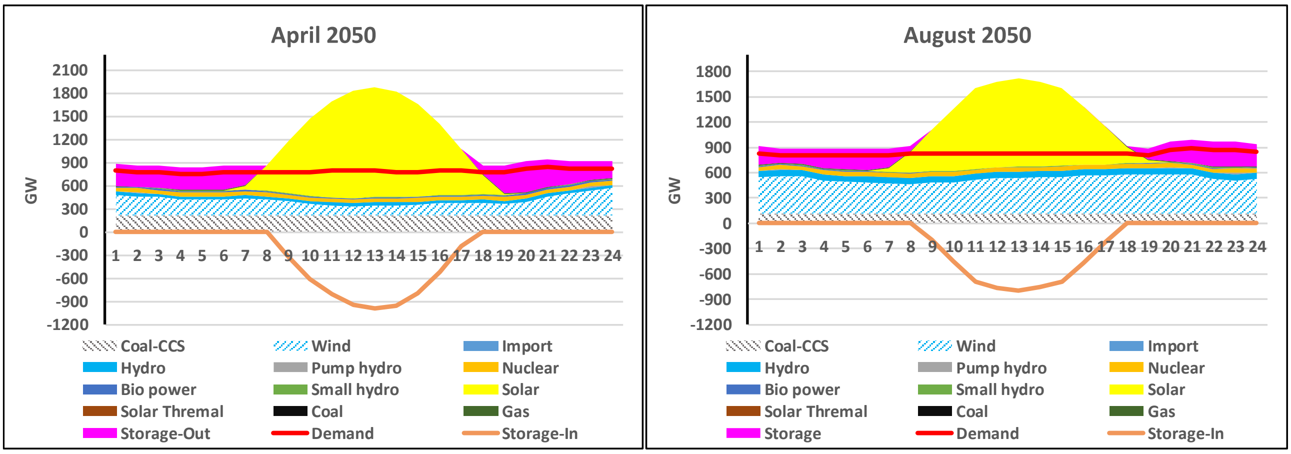


Figure 17: Power system operation in a typical day of summer (April) and monsoon (August)

7.4.2. Fuel requirement

Figure 18 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.

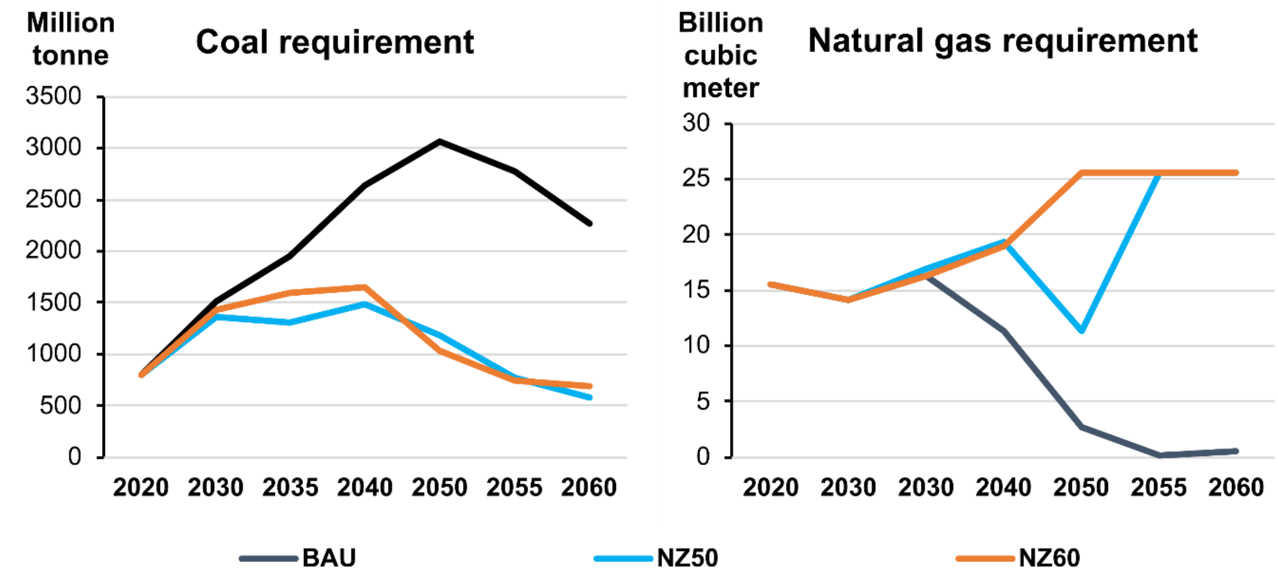


Figure 18: Coal (left) and Natural gas (right) requirement in Indian power sector in various scenarios

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 winded up 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. 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.

7.4.3. Cumulative CO2 emissions

Figure 19 presents the cumulative emissions from the power sector over 2020-60 in different scenarios. In the NZ50 scenario, India's cumulative power sector emissions would be about 47 Giga Tonne (GT), about one-third of the emissions in the BAU scenario.

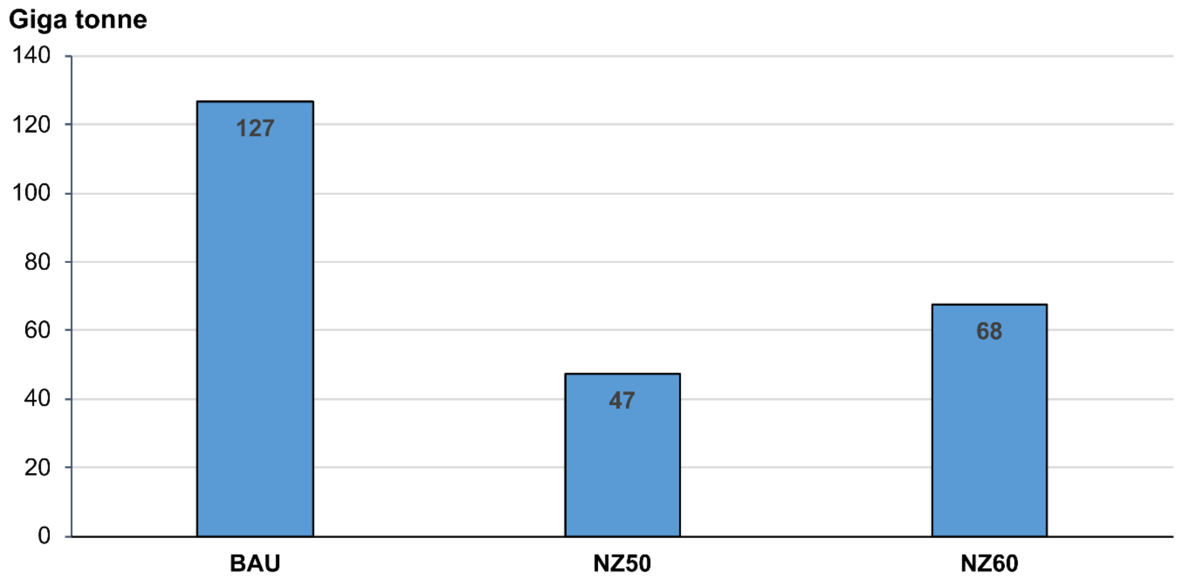


Figure 19: Cumulative CO2 emissions in scenarios

It will be slightly higher at 68 GT in the NZ60 scenario. It is interesting to point out that cumulated emissions by USA and China during 1992- 2017 are 147 GT and 149 GT, respectively which are far higher than future (2020-2050 or 2060) emissions by India even for the BAU scenario (Parikh & Parikh, 2021).

7.4.4. Investment and costs

Figure 20 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 10).

The investment requirements are much higher if India wants to 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 10).

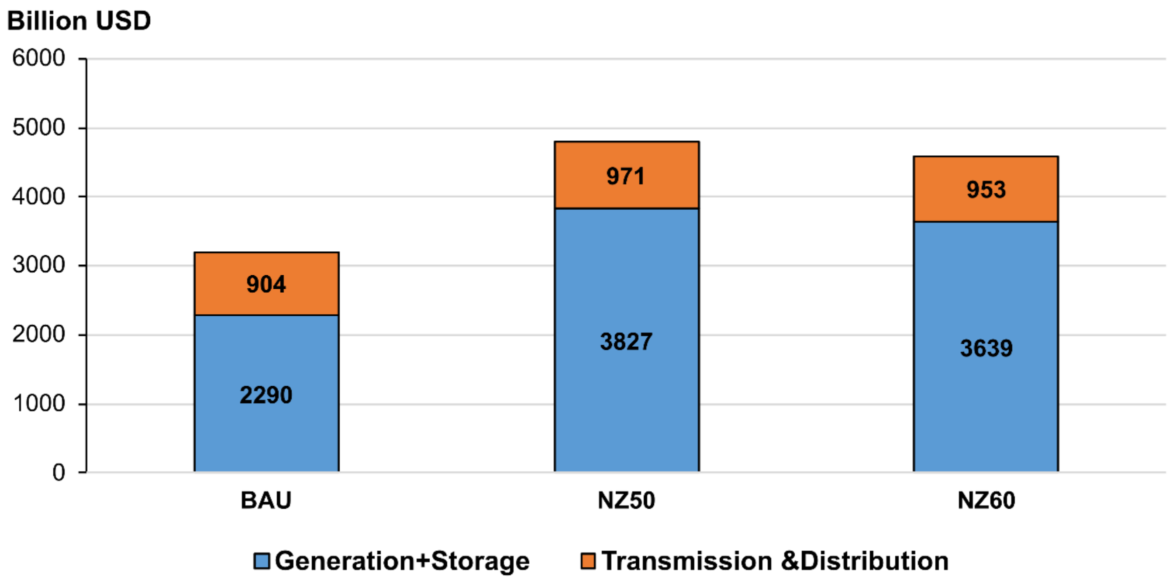


Figure 20: Cumulative investment (undiscounted) in scenarios (2031-60)

Table 10: Investment implications (in billion USD) in net zero scenarios (2031-60)

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

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 10). 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.

Figure 21 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.

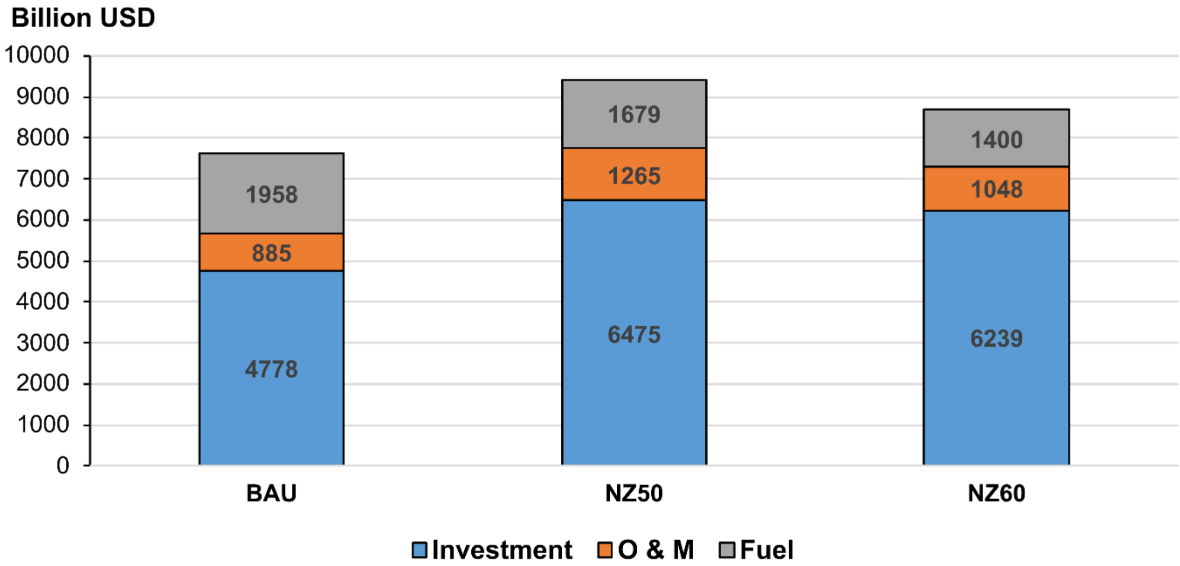


Figure 21: Total undiscounted electricity system costs (2021-60) in scenarios[40]

7.5. 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:

7.5.1. Coal + CCS

India's large coal industry, which provides about 13 million jobs (Dsouza & Singhal, 2021) may benefit from the CCS technology. However, India's CCS future is uncertain. The Department of Science and Technology is funding some basic research projects [41, 42] . Recently, the Government of India has announced to set up two national centres of excellence (CoEs) on carbon capture and utilisation[43]. However, at the policy level, there is little momentum. We did a sensitivity case of achieving net zero emissions by 2050 without Coal+CCS option.

It is possible to decarbonise the power system without CCS. The model makes investments in gas capacity to replace Coal+CCS in 2040 as some emissions are still allowed. However, this gas capacity will remain almost un-utilised in 2050 (Figure 22). In 2050, additional 700 GW of solar PV and 400 GW of 6-hour battery storage capacity will replace about 229 GW of coal+CCS capacity. It 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 (Figure 23).

[40] Fuel costs include CO2 storage costs for NZ50 and NZ60 scenarios
[41] https://dst.gov.in/carbon-capture-utilisation-and-storage-ccus
[42] https://dst.gov.in/sites/default/files/List%20of%20CCUS%20projects%20supported%20under%20Mission%20Innovation%20IC3%20F.Y.%202019-20%20_1.pdf
[43] https://timesofindia.indiatimes.com/india/climate-action-india-to-set-up-two-carbon-capture-and-utilisation-centres/articleshow/89556753.cms

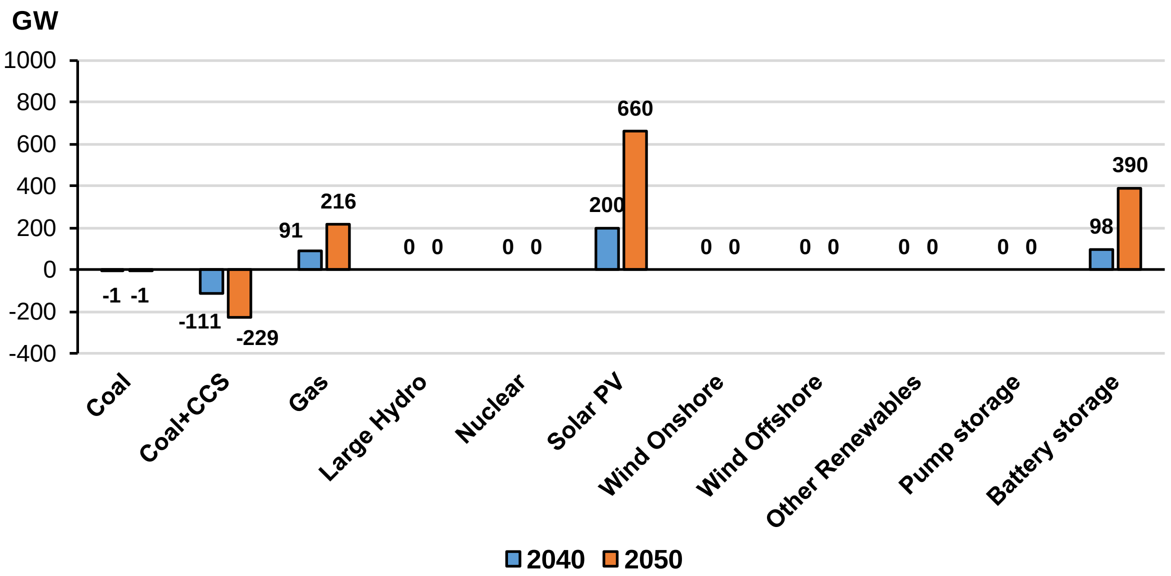


Figure 22: Impact on capacity

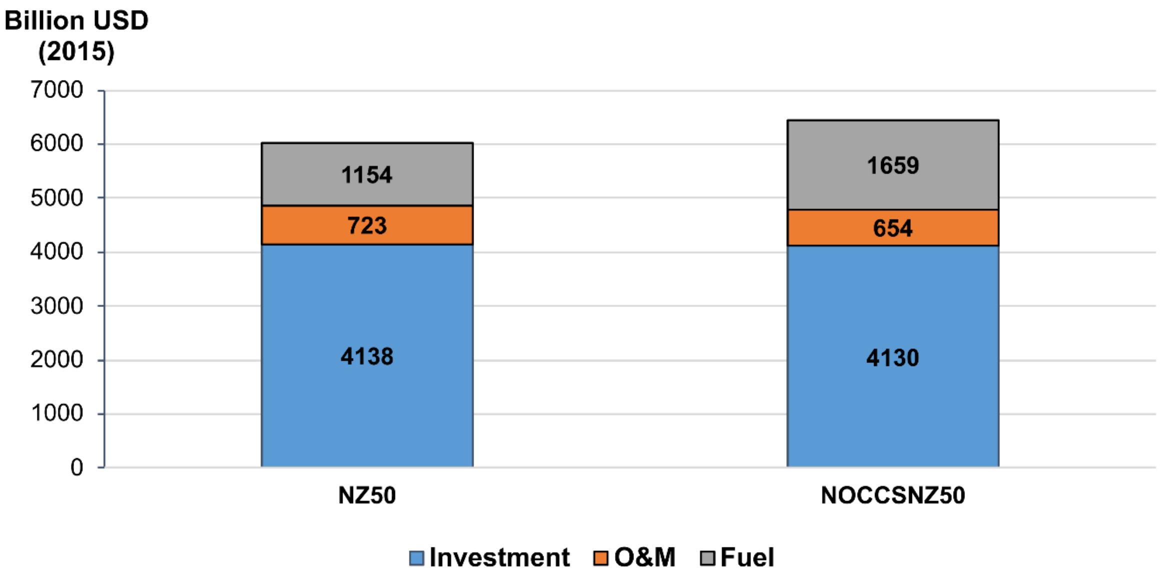


Figure 23: Undiscounted energy system costs (2021-50) with and without CCS

7.5.2. 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 started way back in the 1970s; however, the progress has been slow. The total installed capacity stood at 6780 MW in 2021, and in the last 10 years, only 3000 MW has been added, 300 MW per annum. In current study scenarios, have assumed 20 GW of nuclear by 2030 (CEA, 2020) and thereafter, increase of 2 GW per annum, reaching 40 GW by 2040, and

60 GW by 2050. 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 net zero emissions by 2050 with nuclear capacity limited to 30 GW. Model simulation shows that 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. However, the electricity system cost is marginally higher (3%) (Figure 24).

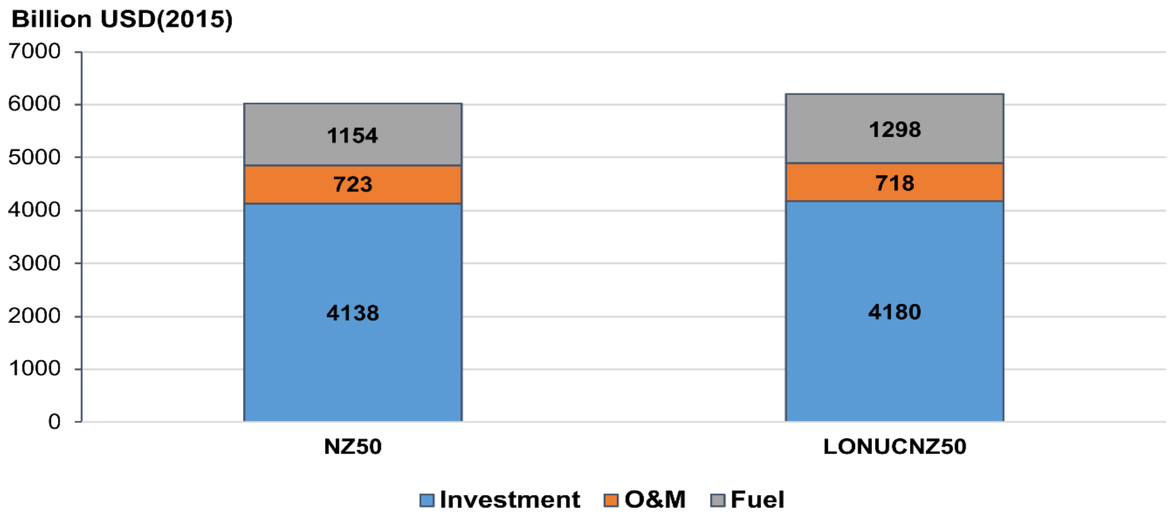


Figure 24: Impacts of low nuclear capacity on investment and total energy system costs.

7.5.3. Cost development of renewable and storage technologies

Investment and other costs of renewable technologies like solar PV, etc. and storage technologies have declined substantially over the last ten years. According to the IRENA (2021b) report, the average installation cost/kW of utility-scale solar PV projects in 2020 was 19% of the costs in 2010. Organisations like IRENA, NREL[44] etc. project the cost development of important technologies up to 2050. IRADe has compiled those projections and classified the cost development into two categories - fast and slow decline. Table 11 presents the investment cost of various technologies in 2050 as a percentage of the costs in 2020 in fast and slow decline cases[45]. For example, in a fast decline case, the 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 47% of today's cost. The results we have reported so far are based on a faster reduction in the cost of renewable and storage technologies. O&M cost, as linked with investment cost, has also declined fast.

Table 11: 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 6-Hr	24%	72%

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

44 NREL Annual Technology Baseline Database, https://data.openei.org/submissions/4129

45 Study has assumed CAPEX of a technology will stabilise from 2050 and thereafter.

Since the trajectory of the future costs of these technologies is uncertain and can have strong implications on the least-cost technology solutions, we have conducted a sensitivity analysis on the NZ50 scenario based on the slow decline in costs (Table 11). Impacts on capacity are insignificant, capacity requirement and technology mix remain more or less same. Figure 25 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.

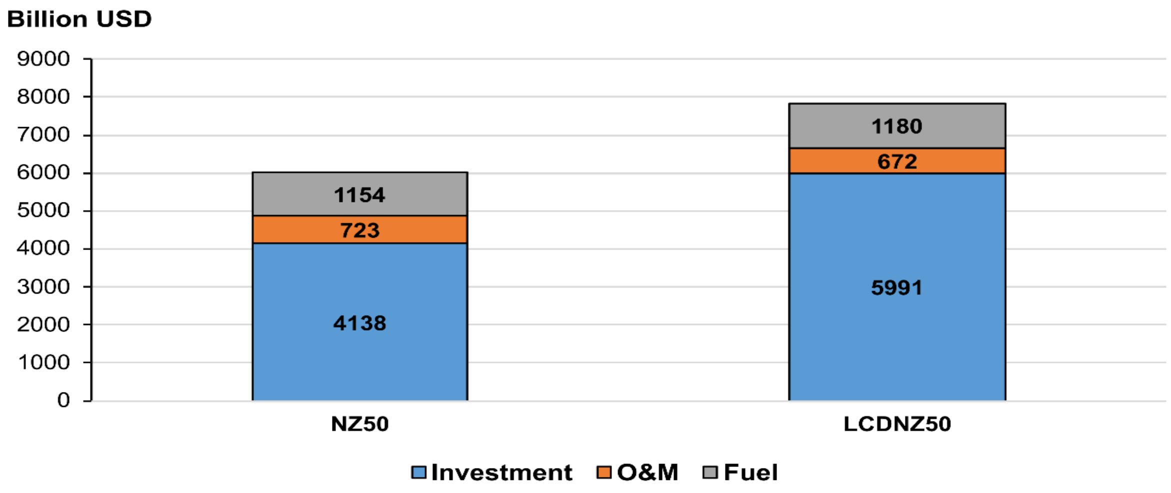


Figure 25: Impacts of low-cost decline on electricity system costs(undiscounted)

7.6. New Electricity Demand Scenario

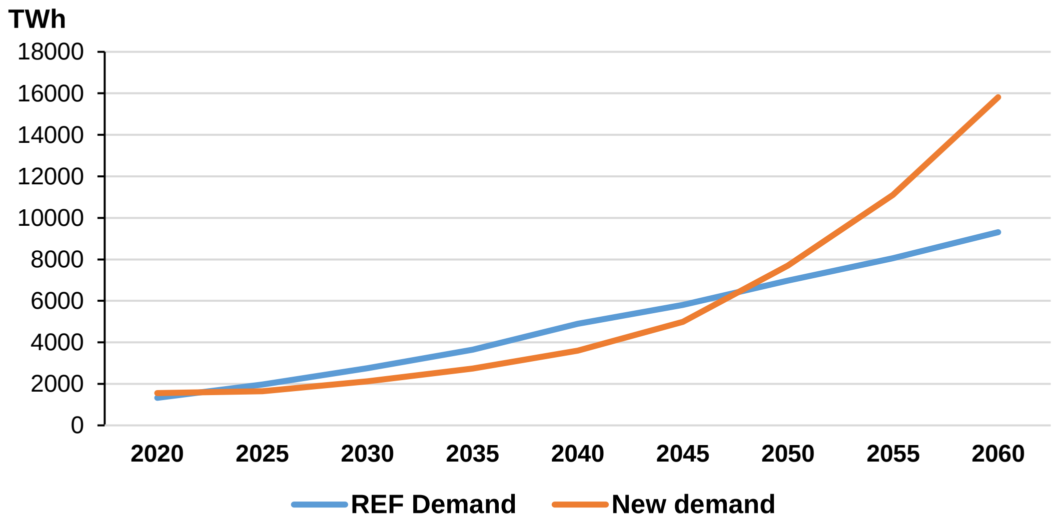


Figure 26: Development in new electricity demand

The electricity demand used to build scenarios in the earlier section is named Reference (REF) demand, whereas this electricity demand is called new demand. Till 2045, New demand is lower than the Reference demand, and later, new demand surpasses the reference demand (Figure 26). With this new electricity demand development, again, three scenarios, one BAU scenario without any emissions constraint and two net zero emissions scenarios with emissions stabilising at 200 MT respectively in 2050 and 2060 are developed and simulated in the same way as described in REF demand case. These three scenarios are BAU-New demand, NZ50-New demand, and NZ60-New demand. As demand is higher, we have increased the upper bound on nuclear and solar PV potential from 2050 onwards. Without that, achieving net zero emissions is impossible, and the model becomes infeasible. So additional demand in net zero emissions scenarios will be met by deploying more nuclear and solar PV capacity. This is because the potentials of other options like wind onshore/offshore or CCS are more uncertain/unknown.

We only present and compare the costs of achieving NZ 50 and NZ60 scenarios in reference demand and new demand case. As demand is higher, the energy system cost of achieving net zero emissions in 2050 or 2060 is more expensive than the reference demand case. Higher demand will be met by deploying more solar and nuclear options, and more storage will also be needed. Therefore, the investment will be higher, whereas other costs like fuel and O&M will be lower than achieving net zero emissions in the REF demand case in 2050, however, more expensive in NZ60 scenario(Figure 27).

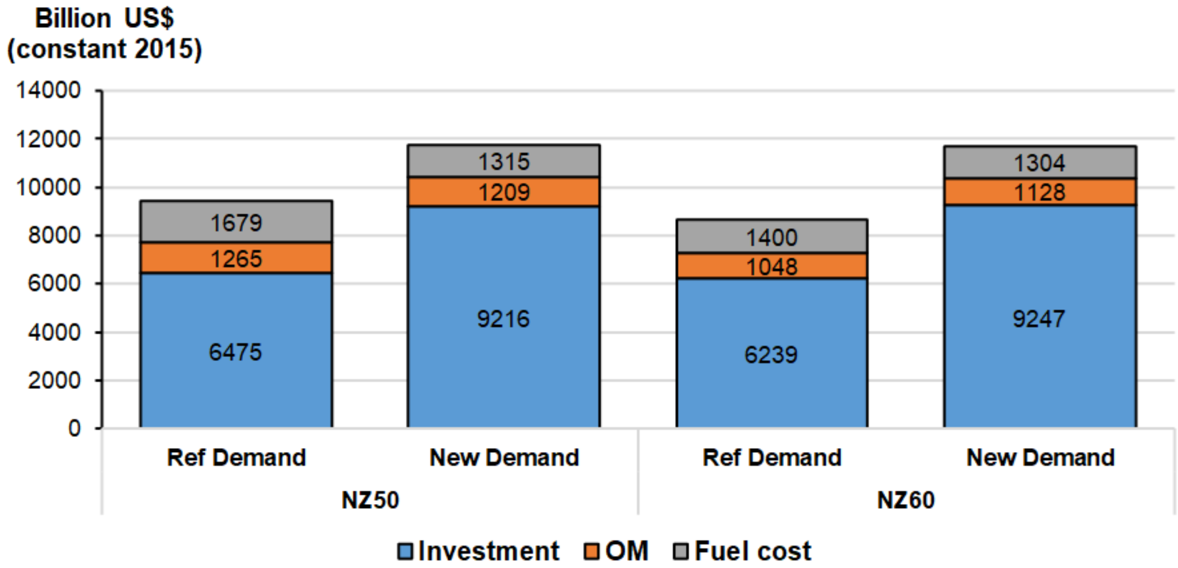


Figure 27: Comparing (undiscounted) costs of achieving net zero emissions for REF and New Demand

Chapter 8. Summary and policy recommendations

By developing optimal net zero pathways for the Indian power sector, this project attempted to identify 1) least cost energy technologies that would be key in achieving 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, and 3) their economic implications (investment requirement and energy supply costs). 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 in the following decade.
- Solar and wind combined contribute 85% and 90% of the total generation capacity in 2050 and 2060 respectively, in line with similar studies in other countries/regions.
- 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 hours daily, longer hour (6-hour) battery storage is a flexibility solution.
- Other carbon-free/low carbon technologies such as large hydro, coal + CCS, and nuclear also have a role to play in decarbonisation given India's huge electricity demand needs to be met.
- 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 coal plant will reach zero. However, deployment of coal+CCS could prevent the wrapping up of the 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. Currently, coal industry provides 13 million direct or indirect jobs.
- 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 USD if decarbonisation target is postponed to 2060.
- While the electrification of the end-use sector is an important tool to decarbonise the entire economy, higher electricity demand will increase the investment requirement and cost of power sector decarbonisation

Power sector decarbonisation needs a vast amount of solar and wind capacity. Currently available estimates on solar PV and wind-onshore potentials are old, and offshore wind potential has not even been assessed. The technology and the method of potential assessments have improved. For example, design improvements like taller towers can tap stronger wind resources at higher levels. At the same time, larger rotor allows wind turbines to sweep more area, capture more wind, and produce more electricity than a decade ago. Similarly, the average conversion efficiency of crystalline solar PV modules increased from 14.7% in 2010 to 20.9% in 2021 (IRENA, 2022), which has increased the electricity availability; there is a large potential for 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 the required quantity of potentials exists or not, India needs a reliable and advanced assessment of its solar PV and wind (onshore and offshore) potentials both for current and future as technologies will progress further. Otherwise, different pathways need to be developed. Also, the feasibility of deploying large capacities yearly in terms of land, materials, and manpower requirements must be investigated, and appropriate policies and measures must 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 a preliminary stage in India. A massive amount of work on technology, production, standards, and market development is needed. Also, the availability of raw materials for battery manufacturing needs 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), which aims to bolster critical mineral supply chains[46]. India has large pump-storage potential which the model finds less economical in competition with battery storage based on a rapid decline in battery cost. Work must be done to explore how to bring down costs of the pump-storage plant to avoid the dependence on one technology as a storage option. This will also reduce the over dependence of the minerals needed to manufacture batteries.

Decarbonisation of power system needs conventional coal-based capacity to decline after 2030, and the coal demand from the conventional power plant to reach zero by 2050 if decarbonisation is achieved in the same year. That needs the wrapping up of an industry that 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 a favourable technical and economic impact on the decarbonisation process. After signing the 123 agreement in 2008, India can import nuclear fuel and reactors. Faster development of nuclear capacity would ease the operation of the decarbonised power system and bring down the additional investment and costs.

India needs technological support from the international community on solar PV (further improvement), wind (especially offshore), CCS, nuclear, and storage technologies and better assessment of resources (especially solar

[46] https://indianexpress.com/article/explained/explained-sci-tech/explained-rare-earth-elements-india-global-alliance-supply-8070563/

and wind) and storage potentials. The government of India also needs to build local capacity on R&D, products manufacturing, certification, and standards, which needs 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) is needed to build a net zero power system. There 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. IRADe exercise shows that with the realisation of certain future low carbon technologies and cheaper finance, the Indian power sector can achieve Net zero emissions by 2050.

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