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to the Government of India

G20 भारत 2023 INDIA
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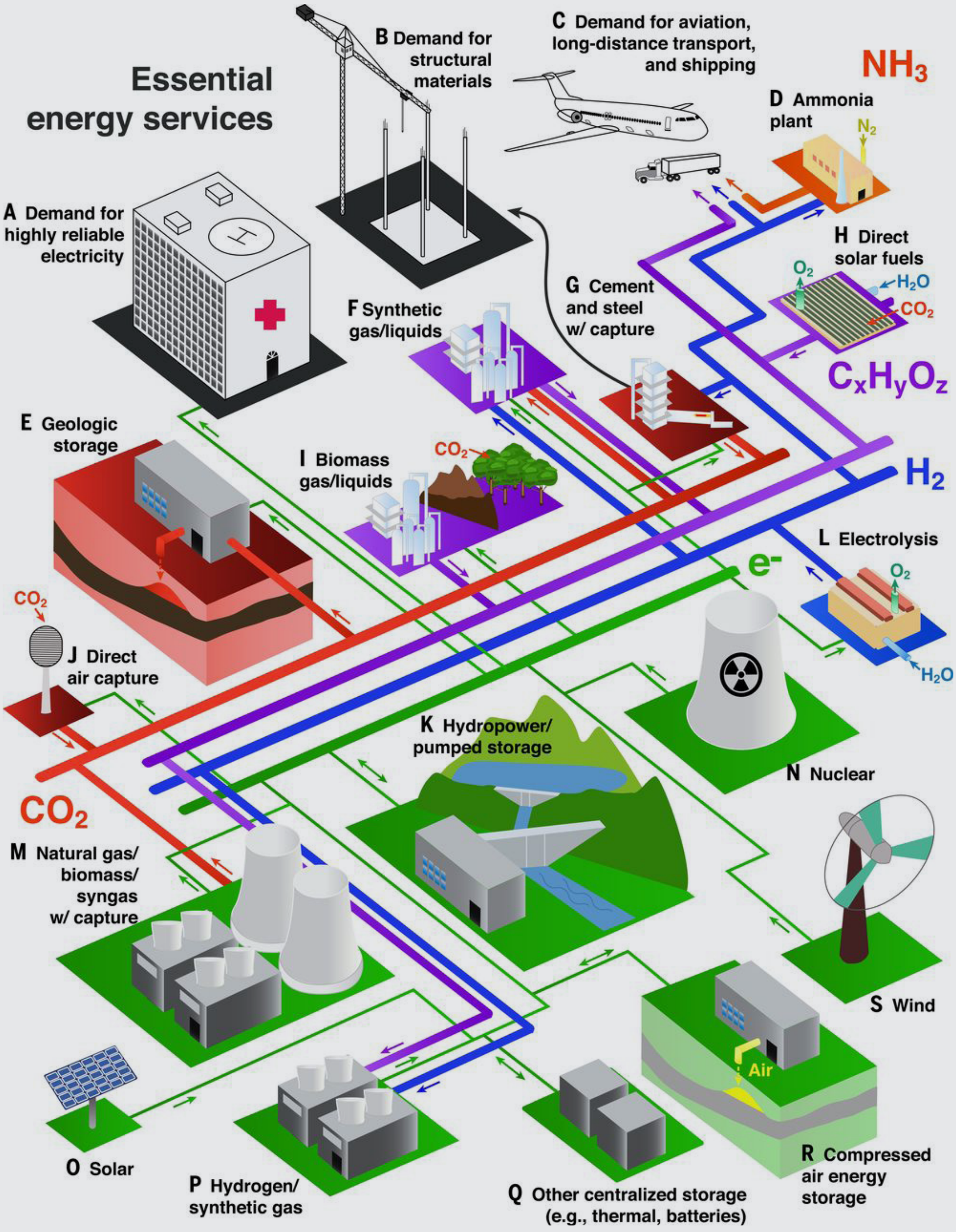
Synchronizing energy transitions toward possible Net Zero for India: Affordable and clean energy for all



Source: Davis et al (2018), Net-zero emissions energy systems, Science, 360, Reproduced with permission from AAAS.

Supported by:
Office of the Principal Scientific Adviser to the
Government of India and Nuclear Power Corporation of India Ltd.

Prepared by:
Indian Institute of Management Ahmedabad

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NPCIL
एनपीसीआईएल
राष्ट्र की सेवा में परमाणु
ATOMS IN THE SERVICE OF THE NATION
न्यूक्लियर पावर कॉर्पोरेशन ऑफ इंडिया लिमिटेड
Nuclear Power Corporation of India Limited

Synchronizing energy transitions toward possible Net Zero for India: Affordable and clean energy for all

Office of the Principal Scientific Adviser
to the Government of India

Supported by:
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and

Nuclear Power Corporation of India Ltd.

विद्याविनियोगाद्विकास:

Prepared by:
Indian Institute of Management Ahmedabad

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Disclaimer : The results presented in this report are outputs of the academic research conducted under the ESN project as per the contractual agreement. The academic work does not in any way represent our considered opinion for climate negotiations and also does not reflect the official policy or position of the Government of India. The information presented here is based on policies and regulations available in public domain by August, 2023.

MESSAGE

Climate change has become an existential threat to mankind and so eliminating carbon-di-oxide emission in conformance with IPCC recommendations has become a collective responsibility of the countries of the world. Whether that responsibility would be discharged or not is anybody's guess. Failure to do so could lead to mass scale miseries in addition to the potential possibility of 'population correction.' The brunt of this impact would be faced by poorer sections of population across the world. India being the largest part of humanity must become a developed country with minimum disparities as soon as possible and acquire enough resources to protect the population through appropriate measures even as we work hard to realise our global commitment to reach net zero by the year 2070. That in turn means that we should raise our per capita income/quality of life/Human Development Index (HDI) at least to a level comparable with advanced countries of the world before it is too late. In any case, taking our development to a level comparable with the advanced countries of the world has been our national aspiration.

IPCC has recommended that the global warming should be restricted to 1.5^{0C} above the temperature existing in preindustrial era to keep things in reasonable control. Its assessments predict this limit to be breached between 2030 and 2052 following the prevailing trends. It also recommended that staying below 1.5°C in 2100 will require cuts in GHG emissions of 45 percent below 2010 levels by 2030 and reach net zero by 2050. Several institutions and analysts, mostly outside India, have looked at potential scenarios for approaching global net zero. India has been a key focus area of many such studies, considering its size, rapidly growing economy, and significantly higher climate change threat potential. Rather than looking at vacating the carbon space at an accelerated pace as a part of correcting its disproportionate use by advanced countries, most of these studies tend to under estimate India's energy needs. Some groups in India also tend to tow such lines and promote a pathway to net zero disregarding the need to build adequate resilience to face climate change impact which would invariably require India to develop its infrastructure that is on par with advanced countries, capable of mitigating climate change impact and consistent with the size of India's population. This should happen as early as possible. This requires financial resources and energy is an integral component of rapid economic growth. Rapid development/economic growth and rapid decarbonisation, the two contra-indicators, must be simultaneously realised in India.

It was in this context that the need for independent domestic studies in this critical area was strongly felt. I am happy that such studies are becoming available of late. Clearly this is a complex problem requiring modelling of many interrelated issues involved. Multiple studies involving different approaches and assumptions clearly help in creating a more holistic understanding in this matter. The present report by IIM Ahmedabad is an important contribution in this context. Such studies should help guide our development plans and strategies in more robust manner keeping Indian interests in focus.

How much minimum energy should India need? All advanced countries have a HDI of 0.9 -0.95. Clearly the energy access should be better than the threshold at which such HDI can be attained. This report estimates India's energy needs between 19,000 -23,000 TWh for a HDI of 0.9 and an assumed stabilised population of 1.5 billion. While there could be significant scatter in these estimates, an important point to recognise is that these numbers are significantly larger that assessed renewable energy potential in the country. A large enough role of nuclear energy is thus inevitable for realisation of net zero without compromising development. Nuclear being the only clean energy baseload supply of significance is also important to keep tariff to electricity consumers under check which otherwise could become significantly larger with higher level of integration of variable renewable energy. Having recognised the importance of nuclear, its rapid scale up to the required levels is a challenge that the country and its policy makers must brace up to.

The clean energy transition on the demand side is expected to see even more churns. Many pathways and technologies, some yet to be developed, are expected to appear on the scene. While some of these would be for energy conversion to match energy sources with end use appliances, others could be technologies required at the demand end. Modelling their deployment in a complex competitive economy dynamic over a long period of five decades or so is indeed a major challenge. India must decide her own strategies and priorities based on sound logic and assessments rather than being driven by vendors appearing at different points of time. There are many examples to the contrary. Our not paying enough attention to CSP, given the importance of grid scale energy storage and high temperature for direct hydrogen production is but one such example. Going forward, unfolding of the complex maize of clean energy transition could throw up many such decision points where we should be guided by holistic understanding generated through this and many such detailed energy studies and not faulter to the detriment of our national interests.

Taking India to a developed country status while realising the clean energy transition is a critical challenge. We should recognise that India can meet it leveraging a time targeted implementation strategy informed and guided by comprehensive energy studies and technological insights as well as a well thought through domestic development effort carefully supplemented by well-designed international co-operation. Well-designed strategies would enable optimum investment needs, they would also free us from hefty continuously growing energy import bill.

Finally, I would like to compliment Prof. Amit Garg and his colleagues for putting together this very useful and important study.

Anil Kakodkar
Chancellor, Homi Bhabha National Institute,
Chairman, Rajiv Gandhi Science and Technology Commission
Former Chairman, Atomic Energy Commission

डॉ. वी.के. सारस्वत
Dr. V.K. Saraswat
सदस्य
Member
Tele : 23096566, 23096567
Fax : 23096603
E-mail : vk.saraswat@gov.in

सत्यमेव जयते

G20 भारत 2023 INDIA

भारत सरकार
नीति आयोग, संसद मार्ग
नई दिल्ली - 110 001
Government of India
National Institution for Transforming India
NITI Aayog, Parliament Street,
New Delhi - 110 001

MESSAGE

Climate change is posing unprecedented challenges on human and natural systems. Exhaustive efforts are being practiced globally to limit the earth's annual mean surface temperature rise to 1.5°C above pre-industrial level by end century, as articulated in the Paris Agreement. The Hon'ble Prime Minister of India's announcement for reaching net-zero by 2070 was hailed as an important milestone for global climate action. India is currently the only G20 country on track to meet its nationally determined contributions (NDCs). As the targets to decarbonize intensify, a quantitative analysis is needed to understand optimal paths forward to reach net-zero emissions in the next five decades. Further, energy transitions require diligent and meaningful dialogue on the pathways of adopting clean technologies based on indigenous demand and supply context. I am glad that the Indian Institute of Management Ahmedabad has taken note of this challenge and carried out a multifaceted analysis on this subject.

India's current primary energy mix constitutes more than 80% fossil based energy resources. Coal is expected to keep playing a crucial role in meeting India's developmental and energy needs for the next few decades. However, as India progresses to achieve high Human Development Index (HDI) levels, similar to most developed countries by 2047, while working towards achieving its net-zero 2070 goal, energy production and consumption needs to undergo fundamental changes. The report focuses on the same and deliberates that there is no silver bullet solution for mitigating carbon emissions. There are technologies that are anticipated to play an outsized role. Renewable energy - solar, wind supported by battery storage systems and nuclear technologies are a good example of that.

The study investigates seven alternate scenarios, four of which assess the potential net-zero 2070 pathways through various energy mixes. These scenarios explore different clean technologies such as renewable energy, nuclear, carbon capture, utilization and storage, hydrogen, biomass and energy efficiency measures to achieve net zero while optimizing for energy costs. Keeping energy and electricity costs affordable to ensure equitable access is one of the primary objectives, undertaken. The study also discusses the investment needs thereof and making low cost finance available to deploy these technologies.

I congratulate all those who have contributed to preparation of this report and hope that it serves as a useful resource for all relevant stakeholders.

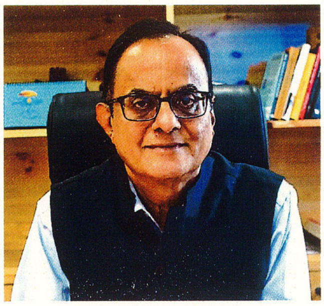
(Dr. V K SARASWAT)

New Delhi
13.09.2023

अजय के. सूद
भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
Ajay K. Sood
Principal Scientific Adviser to the Govt. of India

सत्यमेव जयते

विज्ञान भवन एनेक्सी
मौलाना आजाद मार्ग, नई दिल्ली - 110011
Vigyan Bhawan Annexe
Maulana Azad Road, New Delhi - 110011
Tel. : +91-11-23022112
Fax: +91-11-23022113
E-mail : sood.ajay@gov.in
office-psa@nic.in
Website : www.psa.gov.in



Message

I am happy to see the final report of the study on "*Synchronizing Energy Transitions towards Possible Net-Zero for India: Affordable and Clean Energy for All*", carried out by the Indian Institute of Management Ahmedabad and funded jointly by my office and the Nuclear Power Corporation of India Limited (NPCIL). The funding and continuous monitoring of this study reinforces our joint commitment for instituting high-quality research towards meeting a low-carbon economy. This study was sanctioned on 10th November 2021 and included Net Zero 2070 target for India after the announcement to this effect by the Hon'ble Prime Minister on 2nd November 2021 at COP26.

The Project Review and Monitoring Committee (PRMC) has rigorously reviewed this report in three meetings and has accepted this final report. I would like to thank them for their continuous monitoring and support of the project.

The study identifies the complexities of achieving the net-zero target for India. Not only would it require a diversity of technological interventions but also average investments of US$40-50 billion annually over the next five decades for these energy transitions. I am informed that the internationally benchmarked models (setup for India) used for this study incorporate over 500 technologies spread over 75 end-use sectors and services, capturing all energy sources and carriers. The study involves zero-carbon and low-carbon technologies such as renewable power, nuclear power, fossils with CO_2 capture utilization and storage, bioenergy, and hydrogen. The study highlights that there is no silver bullet solution for India towards Net-Zero energy transitions based on current scientific understanding of technological landscape. Myriad technologies must co-exist in India's energy basket.

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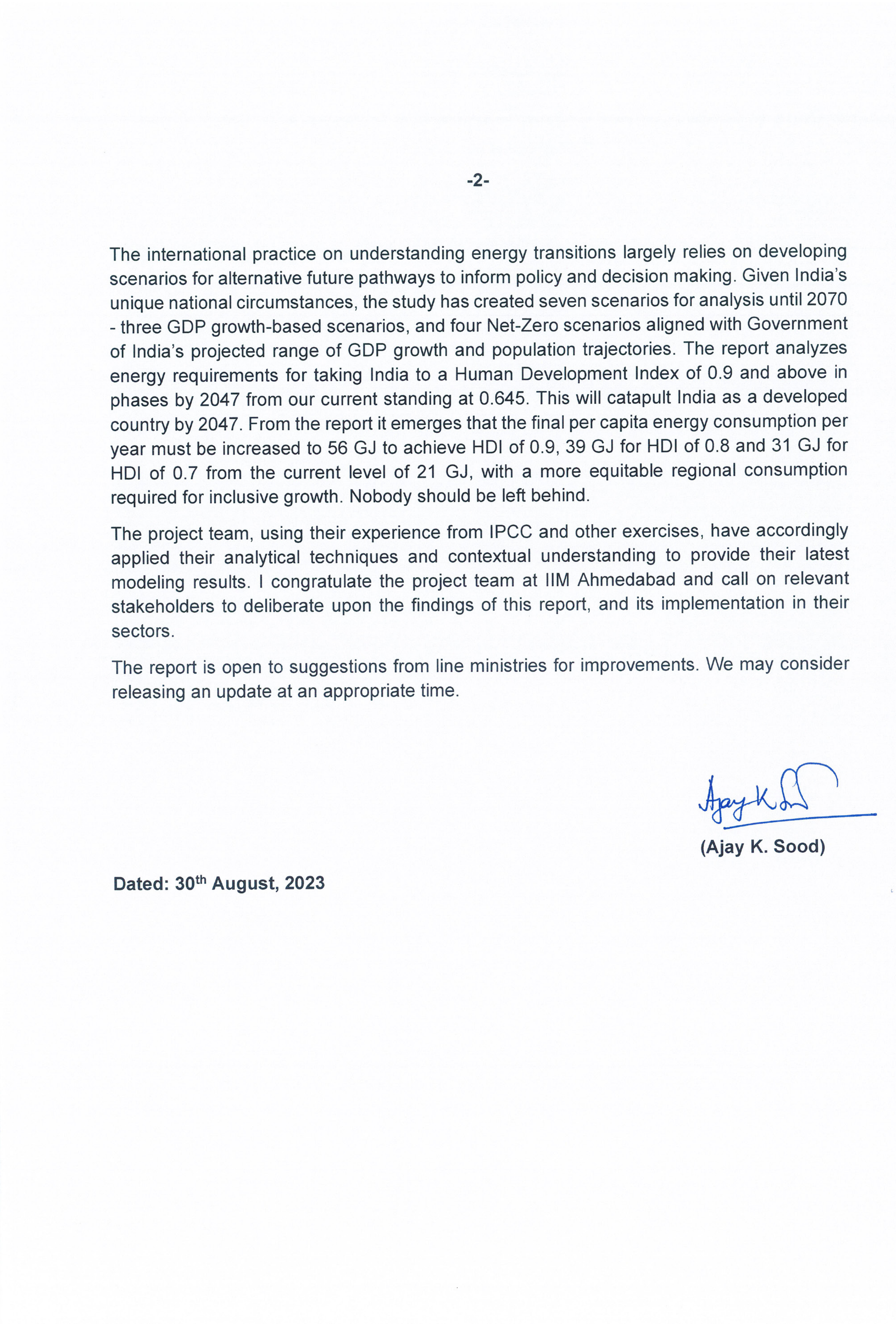

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The international practice on understanding energy transitions largely relies on developing scenarios for alternative future pathways to inform policy and decision making. Given India's unique national circumstances, the study has created seven scenarios for analysis until 2070 - three GDP growth-based scenarios, and four Net-Zero scenarios aligned with Government of India's projected range of GDP growth and population trajectories. The report analyzes energy requirements for taking India to a Human Development Index of 0.9 and above in phases by 2047 from our current standing at 0.645. This will catapult India as a developed country by 2047. From the report it emerges that the final per capita energy consumption per year must be increased to 56 GJ to achieve HDI of 0.9, 39 GJ for HDI of 0.8 and 31 GJ for HDI of 0.7 from the current level of 21 GJ, with a more equitable regional consumption required for inclusive growth. Nobody should be left behind.

The project team, using their experience from IPCC and other exercises, have accordingly applied their analytical techniques and contextual understanding to provide their latest modeling results. I congratulate the project team at IIM Ahmedabad and call on relevant stakeholders to deliberate upon the findings of this report, and its implementation in their sectors.

The report is open to suggestions from line ministries for improvements. We may consider releasing an update at an appropriate time.

Ajay K

(Ajay K. Sood)

Dated: 30th August, 2023

डॉ. अजित कुमार मोहान्ती
Dr. Ajit Kumar Mohanty

भारत सरकार
Government of India

अध्यक्ष, परमाणु ऊर्जा आयोग
व
सचिव, परमाणु ऊर्जा विभाग
Chairman, Atomic Energy Commission
&
Secretary, Department of Atomic Energy

MESSAGE

Climate change poses a big challenge to humanity today. The recently released synthesis report of the Intergovernmental Panel on Climate Change says that the window of action towards limiting the temperature rise is closing rapidly and decarbonization actions need to happen now.

India is one of the fastest-growing economies in the world but has a low gross domestic product per capita, low per capita energy, and electricity consumption as well as low GHG emissions per capita. Though India's energy demand is increasing, its per capita energy consumption may still remain below the world average for the next two to three decades.

India faces twin challenges of meeting the rising energy demands of a developing economy and ensuring an economy-wide transition to a low-carbon energy mix leading to a net zero energy mix by 2070. As emissions from the use of fossil fuels remain the largest source of greenhouse gas emissions in the country, a massive restructuring of the energy sector is needed. This requires integrated planning across all sectors, and harnessing of all low-carbon energy technologies and emission reduction mechanisms so that affordable and reliable energy is available to everyone during the process of transition and after achieving net zero.

This comprehensive study looks into minimizing the cost of power at the consumer end while working out an optimum mix of all sources of power aiming at net zero emission for India. The study estimates carbon dioxide emissions under seven future scenarios designed toward achieving net zero by 2070. One of the key findings of this study is that clean, affordable electricity can be achieved in a pathway focusing on nuclear power. Such a scenario also shows the lowest residual emissions.

Ajit Kumar Mohanty

(Ajit Kumar Mohanty)

अणुशक्तिभवन, छत्रपति शिवाजी महाराज मार्ग, मुंबई - 400 001, भारत • Anushakti Bhavan, Chhatrapati Shivaji Maharaj Marg, Mumbai - 400 001, India
दूरभाष/Phone:+(91) (22) 2202 2543 • फैक्स/Fax: +(91) (22) 2204 8476 / 2284 3888
ई-मेल/E-mail: chairman@dae.gov.in

पी० एम० प्रसाद
अध्यक्ष-सह-प्रबंध निदेशक
P. M. Prasad
Chairman-Cum-Managing Director

कोल इण्डिया लिमिटेड
COAL INDIA LIMITED
(A MAHARATNA COMPANY)
A Govt. of India Enterprise
"COAL BHAWAN"
Premises No. 04 MAR, Plot No. AF-III
Action Area - 1A, New Town, Rajarhat
Kolkata - 700 163

MESSAGE

India has set an ambitious aim of realizing Net Zero emissions by 2070 even as the country's energy requirement is on an expansion mode. India is already making serious efforts towards climate change adaptation and mitigation. Plans have been drawn to generate 500 GW of power, by 2030, which is around 50% of India's energy consumption through non-fossil fuel sources.

However, NITI Aayog and even independent international agencies estimate that coal's use in India is set to peak by early to mid-2030s despite India growing fastest in renewable energy capacity among major economies of the world. The focus should be to meet increasing energy demand and reducing carbon emissions and carbon intensity. Many pathways are being pursued towards this goal the latest being Hydrogen. While solar continues to steal the limelight the real game changer would be economically viable battery storage system. Also, the true test of transition towards Net Zero is not merely shifting from one fuel to another but to see whether it provides enough energy for those who have little access to it. Transition would be incomplete unless energy equity is attained.

I am pleased to learn that Indian Institute of Management Ahmedabad has completed a study on "Synchronizing Energy Transitions towards Possible Net-Zero in India" led by Prof. Amit Garg and his team of researchers. This is aptly relevant and contextual in the present scenario. I am sure the first-of-its-kind economy wide report on India's Net Zero India's commitment proves to be a valuable source of analysis and insights.

Best Wishes and Congratulations!

(P.M. Prasad)
28/08

Kolkata
28.08.2023

Foreword

On February 17, 2021, during a meeting of a committee constituted by Niti Aayog to discuss certain issues related to nuclear power, it was decided to "convene a group of experts for conducting a comprehensive study with rigorous methods for minimizing the cost of power at the consumer end and to work out an optimum mix for all sources of power, aiming for Net Zero emission to be realized by a definite year." I was tasked to take it forward. I compiled a list of experts from India who had been assisting the International Panel on Climate Change in drafting reports and examined their academic credentials. I shared this information over the telephone with Dr. V. K. Saraswat, member Niti Aayog, and Prof Vijay Raghavan, the then Principal Scientific Adviser (PSA). After reviewing the academic credentials of Prof Amit Garg, Indian Institute of Management Ahmedabad, we decided to invite him to make a presentation on the subject. We had a video meeting on June 9, 2021, where Prof Garg made a detailed presentation.

During our discussions, it was acknowledged that to address climate emergency, it is necessary to plan for an energy system transition to reduce carbon emissions and it has to be done without negatively impacting the pace of development of the country. By the middle of 2021, there were calls for setting a target date for Net Zero. Many countries were proposing 2050 as the target date. In the past, India chalked its own path on various issues, and it was expected that India would do so even now.

For studies directed at energy system transition, integrated models have been developed by the research community, and the output of studies depends on the model and also on input data. We noted that for studies related to India, the role of nuclear power is constrained at the data input stage itself. For example, in a paper published by Deshmukh[1] et al., one of the assumptions is, "Due to uncertainty in their future deployment, and their current targets are low, we did not consider new nuclear or hydro capacity in the main scenarios but include them in sensitivity scenarios." The paper favors only wind and solar but remarks, "Other options such as expanding nuclear and hydropower capacity may hold large potential but may cost more and have lower public acceptance." Many other publications, including those originating from India, have come up with a very insignificant role for nuclear in India's future energy mix because of assumptions made at the input stage.

Therefore, during modeling, it is very important to start with realistic assumptions. And, of course, one has to select a model that is comprehensive and includes all drivers such as capital cost, water and land requirements, indigenous technological capability, and element limitation factors, and differentiate between technologies available today and those under development.

All these issues were discussed, and it was decided to request Prof Garg to formulate and submit a project proposal for funding by the office of PSA. Prof Garg organized a team of experts and submitted a proposal in August 2021. The proposal was finalized after some iterations and sanctioned on November 10, 2021. It was funded by the office of PSA, with one-third funding provided by the Nuclear Power Corporation of India Limited.

While the sanctioning of the project was being processed, the Prime Minister of India announced India's long-term goal of reaching a Net Zero energy mix by 2070 at the climate summit held in Glasgow in November 2021. This was later included in the formal submission by India to UNFCC in August 2022. It was taken on board by Prof Garg in the analysis presented in this report.

Recent academic studies recognize the role of baseload sources such as nuclear in grid management, for providing security of supplies, and in reducing the capital needed for the energy system transition as well as improving affordability for consumers. This includes studies

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[1] Deshmukh, R., Phadke, A., & Callaway, D. S. (2021). Least-cost targets and avoided fossil fuel capacity in India's pursuit of renewable energy, *PNAS, 118*(13), e2008128118.

by Sepulveda et al.,[2] Nuclear Energy Agency,[3] and International Energy Agency.[4] Since the commonly used metric levelized cost of electricity (LCOE) generation has no parameter to account for the intermittency of renewable sources, it tends to overestimate the economic efficiency of renewable energy and the extent of overestimation increases with an increase in their penetration. Therefore, metrics such as value-adjusted LCOE (VALCOE) have been proposed. For one case (stated policy scenarios for India in 2050), the results of VALCOE have been reported as follows. For nuclear, LCOE and VALCOE remain the same at 65 USD/MWh, but for solar, LCOE is 15, while VALCOE is 55 USD/MWh.[5] With the increasing penetration of variable renewables, there is a growing realization that while renewable sources are needed for decarbonization, firm dispatchable sources such as nuclear and fossil with carbon capture and storage (or use) have to be a significant part of the energy mix. Electricity has to be generated and provided to consumers wherever they are located and whenever they need it. This results in high integration costs for renewables because of their variability and non-dispatchability. The current practice of socializing the integration cost of renewables is a hidden subsidy.

The objective of this report is to bring out all these aspects for the benefit of the public and policymakers and build scenarios for an energy mix that provides affordable and clean energy for all citizens living in a well-developed India. However, in academic studies, one includes scenarios that cover extreme situations and one scenario covered in this report is energy requirements under low economic growth (NDCL). Current policies of the Government of India are aimed at achieving a high economic growth rate and hence a high HDI. The review committee doesn’t view the low economic growth scenario (NDCL) as a possibility. During discussions with the review committee, it was made clear by the investigators that the low economic growth scenario is included only for the sake of comparison and from an academic perspective. Also, investigators have included the per capita final energy consumption needed to achieve an HDI of 0.9, but details have been worked out only for an HDI of 0.8. As has been forecast by some studies[6], India might achieve an HDI of 0.9 before 2070, and therefore detailing that has to be the topic for a future study. Low economic growth might not enable India to achieve the intended HDI and hence the future study, while postulating different economic growth scenarios, should also aim to bring out the resulting HDI.

Meeting the twin objectives of decarbonization and economic growth is challenging. The complexity of this challenge can be gauged from the Energy White Paper published by the UK[7] wherein authors state, “We have modelled almost 7,000 different electricity mixes in 2050, for two different levels of demand and flexibility, and 27 different technology and cost combinations.” I expect this report to motivate researchers to take up further Net Zero studies and bring out ideas for the design of policies for achieving an optimum energy mix.

I thank all members of the Project Review and Monitoring Committee for lively discussions.

R B Grover
Emeritus Professor
Homi Bhabha National Institute, Mumbai
Chairman, Project Review and Monitoring Committee

27 November 2023

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[2] Sepulveda, N. A., Jenkins, J. D., de Sistemes, F. J., & Lester, R. K. (2018). The role of firm low-carbon electricity resources in deep decarbonization of power generation. *Joule*, *2*, 2403–2420.

[3] Nuclear Energy Agency, OECD. (2022). Meeting climate change targets: The role of nuclear energy. NEA No. 7628.

[4] International Energy Agency. (2022, January 24). *Energy transitions require innovation in power system planning*. Retrieved August 15, 2022, from https://www.iea.org/articles/energy-transitions-require-innovation-in-power-system-planning

[5] IEA (2023). *World energy outlook*, p. 301.

[6] India’s Human Development Index: components, methodological issues and forecasting, Gaurang Rami, Routledge (Taylor & Francis Group), London, In book entitled ‘THE ROUTLEDGE HANDBOOK OF POST-REFORM INDIAN ECONOMY’ Edited by Rajesh Raj S. N. and Komol Singha, 2021, 978-0-367-42870-9 (hbk), 978-1-032-11145-2 (pbk), 978-0-367-85574-1 (ebk).

[7] Department for Business, Energy & Industrial Strategy and Department for Energy Security & Net Zero. (2020, December 18). *Energy white paper, Powering our net zero future* (p. 44) https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future/energy-white-paper-powering-our-net-zero-future-accessible-html-version.

Acknowledgments

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The authors acknowledge the support received from Padma Shri Prof. Ajay Kumar Sood, Principal Scientific Advisor (PSA) to the Government of India, and Padma Shri Dr. K. Vijay Raghavan, FRS, former PSA to the Government of India, in initiating this work of national importance.

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The authors are grateful for the support and advice provided by the Project Review and Monitoring Committee (PRMC) for the ESN Project, including Shri B. V. S. Sekhar (NPCIL), Shri S. C. Chetal (Former Director, Indira Gandhi Centre for Atomic Research), Dr. K. Balaraman (NIWE), Dr. Rajeev Sukumaran (CSIR-NIIST), and Dr. Bharat Bhargava (Ex-Director General at the ONGC Energy Centre).

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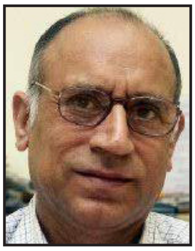
The authors also express their thanks to our research colleagues Mr. Sanjay Kumar Jain, Dr. Jyoti Maheswari, Mr. Alok Kushabaha, Ms. Namrata Ghosh, Ms. Pavithra V., and Ms. Rutva Patel for providing research support, and Ms. Dhara Thakkar and Mr. Jigar Shah for their administrative support towards the successful completion of this work. The authors thank Mr. Paresh Amleshwarwala for support received in designing of this report.

- Authors

Members of the Project Review and Monitoring Committee



Dr. Ravi Grover

Chairman, PRMC

Dr. Grover is an emeritus professor at Homi Bhabha National Institute, Mumbai. He is the founding vice-chancellor (during initial years he was designated as director equivalent to vice-chancellor) of the Homi Bhabha National Institute, a member of the Atomic Energy Commission, chairman of the Board of Research in Nuclear Sciences, a fellow of the Indian National Academy of Engineering, and World Academy of Art and Science.

Dr. K. Balaraman

Dr. Balaraman is the former director general of the National Institute of Wind Energy (NIWE). His vast experience of more than 3 decades is spread across the gamut of clean energy transition, sustainable energy and power system engineering right from planning to the real time operation.

Dr. Bharat Bhargava

Dr. Bhargava is the former director general of the ONGC Energy Centre. He has more than 50 years' experience in energy sector working on different aspects of clean energy technologies and more particularly on solar energy technologies and hydrogen energy in a research laboratory, industry, and the Government. is one of the main architects of the National Solar Mission, launched in 2010.

Shri S. C. Chetal

Shri Chetal is a mechanical engineer with a long career at Indira Gandhi Centre for Atomic Research from where he superannuated as Director. Subsequently, he was Mission Director of the 800MW Advanced Ultra Supercritical Thermal Plant R&D Project. He is presently Senior-Adviser BHEL R&D.

Shri B. V. S. Sekhar

Shri Sekhar is the associate director (CP&CC), Nuclear Power Corporation of India Ltd. (NPCIL).

Dr. Rajeev Sukumaran

Dr. Rajeev Sukumaran is Senior Principal Scientist and Head of the Biofuels and Biorefineries Section at CSIR's National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram. He is member of the Kerala State Biotechnology Commission and CSIR's Domain expert group on biofuels.

Ms. Remya Haridasan

Ms. Remya Haridasan is working as a Scientist in the Office of the Principal Scientific Adviser to the Government of India. Before joining Office of PSA, she has worked in Bhabha Atomic Research Centre, Mumbai for 7 years in the design and testing of control systems for nuclear power plants. In her current role at the Office of PSA, she is working in the areas of Science and Technology Policy and Governance.

Authors (Alphabetically)

Prof. Amit Garg (Principal Investigator)

Amit Garg is a Professor at IIMA and also National Investment & Infrastructure Fund (NIIF) Chair in Environment, Social & Corporate Governance (ESG). He specializes in energy, climate change, and sustainable development issues. His current research interests include carbon and climate finance, energy businesses, corporate accounting of greenhouse gases, energy and environment modeling, water–energy nexus, and preparing businesses for climate change challenges.

Dr. Omkar Patange

Dr. Omkar Patange is a research scholar with IIASA. He received his Ph.D. in Public Systems from the Indian Institute of Management Ahmedabad (IIMA), India. His research interests include mitigation strategies for deep decarbonization of energy and allied systems, their social and environmental impacts, and the institutional and governance challenges emerging from energy system transitions.

Prof. Saritha Sudharmma Vishwanathan

Dr. Saritha Sudharmma Vishwanathan currently works as an Assistant Professor at the Kyoto University in Japan. Previously, she worked at the National Institute for Environmental Studies (Japan) as a postdoctoral research fellow. She received her fellowship in management, majoring in Public Systems and Public Policy from IIMA. Her research focuses on energy–water–environment integrated assessment modeling, socio-technical transitions, institution and policy analysis.

Prof. Tirthankar Nag (Co-Principal Investigator)

Prof. Tirthankar Nag teaches strategic management, research methods, managing consulting engagements, and developing infrastructure businesses in IMI Kolkata. He has also worked with CESC in distribution planning. He has provided advisory services to Indian and international organizations in the energy sector, including World Bank, UNEP, DFID, USAID, and ADB.

Dr. Udayan Singh

Dr. Udayan Singh received his Ph.D. in Environmental Engineering from the University of Virginia. Udayan's research interests include decarbonization avenues for the energy sector, particularly through CO_2 sequestration and CO_2 removal.

Dr. Vidhee Avashia (Project Co-ordinator)

Dr. Vidhee Avashia is a post-doctoral researcher at the IIMA and co-chair of the Adaptation Working Group of the iGST. She holds a Doctorate in Management (Public systems) from IIMA. Her current research areas include adaptation policies, development, and climate change adaptation interactions in urban spaces, as well as GHG inventory and climate change mitigation.

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List of Abbreviations

2G:	Second generation
AIF:	Alternative investment funds
AIM:	Asia-Pacific Integrated Model
BAU:	Business as usual
BECCS:	Bioenergy with carbon capture and storage
BESS:	Battery energy storage systems
BNEF:	Bloomberg New Energy Finance
BRSR:	Business responsibility and sustainability report
CAGR:	Compound annual growth rate
CCS:	Carbon dioxide capture and storage
CCU:	Carbon dioxide capture and utilization
CCUS:	Carbon dioxide capture, utilization, and storage
CDR:	Carbon dioxide removal
CdS:	Cadmium sulfide
CdTe:	Cadmium telluride
CEA:	Central Electricity Authority
CEEW:	Council on Energy, Environment and Water
CERC:	Central Electricity Regulatory Commission
CIGS:	Copper indium gallium selenide
COP:	Conference of Parties
CPIs:	Carbon pricing instruments
CSTEP:	Center for Study of Science, Technology and Policy
CUF:	Capacity utilization factor
DLS:	Decent living standard
EBP:	Ethanol-blended petrol
EC:	Energy consumption
EI:	Education index
EIER:	Energy return on energy invested
EJ:	Exajoule
EMDCs:	Emerging markets and developing countries
EPS:	Electric Power Survey
EROI:	Energy return on (energy) investment

ESCerts:	Energy saving certificates
ESG:	Environmental, social, and governance
ESY:	Ethanol supply year
ETS:	Emission trading system
EU:	European Union
EVs:	Electric vehicles
FCI:	Food Corporation of India
FDI:	Foreign direct investment
FEC:	Final energy consumption
FGD:	Flue gas desulfurization
G20:	Group of Twenty
GDP:	Gross domestic product
GHG:	Greenhouse gas
GJ:	Gigajoule
GRI:	Global Reporting Initiative
GST:	Goods and services tax
GW:	Gigawatt
HDI:	Human development index
HI:	Health index
IAEA:	International Atomic Energy Agency
ICAR:	Indian Institute of Sugarcane Research
IEA:	International Energy Agency
IFCs:	International finance corporations
IFSCA:	International Financial Services Centres Authority
II:	Income index
IIBX:	India International Bullion Exchange
IIP:	Index of industrial production
IIT:	Indian Institute of Technology
INDC:	Intended nationally determined contributions
INR:	Indian rupee
IPCC:	Intergovernmental Panel on Climate Change
IRADE:	Integrated Research and Action for Development
ISO:	International Organization for Standardization
kWh:	Kilowatt hours
LBNL:	Lawrence Berkeley National Laboratory

LCA:	Life-cycle assessment
LCOE:	Levelized cost of electricity
LE:	Life extension
LPG:	Liquefied petroleum gas
LTS:	Long-Term Strategy
MDBs:	Multilateral development banks
MIT:	Massachusetts Institute of Technology
MJ:	Megajoule
MOEFCC:	Ministry of Environment, Forest and Climate Change
MRV:	Monitoring, reporting, and verification
MSMEs:	Medium, small, and micro enterprises
MW:	Megawatt
NDC:	Nationally determined contribution
NEP:	National Electricity Plan
NIMS:	National GHG Inventory Management System
NIWE:	National Institute of Wind Energy
NPCIL:	Nuclear Power Corporation of India Limited
NREL:	National Renewable Energy Laboratory
NTPC:	National Thermal Power Corporation Limited
NZ:	Net zero
OECD:	Organization for Economic Cooperation and Development
OEM:	Original equipment manufacturer
OMCs:	Oil market companies
PAT:	Perform, Achieve and Trade
PHWR:	Pressurized heavy water reactor
PLF:	Plant load factor
PMG:	Permanent magnet generator
POSOCO:	Power System Operation Corporation Limited
PPAC:	Petroleum Planning and Analysis Cell
PPP:	Purchasing power parity
PV:	Photovoltaic
R&M:	Renovation and modernization
RE:	Renewable energy
RECs:	Renewable energy certificates
RLDC:	Regional Load Despatch Centre

SAM:	System advisory model
SASB:	Sustainability Accounting Standards Board
SDGs:	Sustainable Development Goals
SEBI:	Securities and Exchange Board of India
SEC:	Specific energy consumption
SFRs:	Sodium-cooled fast reactors
SMR:	Small modular reactor
T&D:	Transmission and distribution
TERI:	The Energy and Resources Institute
TFEC:	Total final energy consumption
TWh:	Terawatt hours
UIDAI:	Unique Identification Authority of India
UN:	United Nations
UNDP:	United Nations Development Programme
UNFCCC:	United Nations Framework Convention on Climate Change
USA:	United States of America
USD:	United States Dollar
UTs:	Union Territories
VRE:	Variable Renewable Energy
WACC:	Weighted Average Cost of Capital
WG3:	Working Group III of IPCC

Executive Summary

From a global perspective, India, home to one-sixth of the world's population, is unique and defined by its solidarity with the developing world. Developing nations in Asia, Africa, the Caribbean, and Latin America look up to India as a frontrunner in addition to being one of the largest nations in managing its low-carbon, inclusive development growth through the use of clean, affordable, and reliable energy systems with the help of low-cost finance.

Energy requirements

Linking the human development index (HDI) with the final energy consumption (FEC) provides a means of estimating a country's minimum energy requirements to ride the HDI ladder. As per the Human Development Report 2021-2022, India's current HDI is 0.633, placing it in the medium-HDI group. The high HDI presently ranges between 0.70 and 0.799, and the very high HDI is above 0.8 (with a maximum possible value of 1.000). India aspires to become a developed country by 2047, and the ensuing 25 years starting India's 75th independence year (2022) and 2047 have been declared as Amrit Kaal by the Government of India. India's HDI. Therefore, must become comparable with that of the advanced countries of the world by 2047. Today, the top 28 countries have an HDI better than 0.9, which could be our HDI target (UNDP, 2022). There could be significant differences in the total energy needs corresponding to HDI values of 0.8 and of 0.9. In fact, more energy is required for transiting to 0.9 from 0.8 than for the increment between an HDI of 0.7 and 0.8. We evaluate these likely FEC values to reach various levels of HDI.

HDI has three components: income (per capita), education (mean years of schooling), and health (life expectancy at birth). Global trends indicate that income is closely linked to per-capita energy consumption, particularly for countries with medium to high HDI levels. We, therefore, study the relative contributions of the three indices (energy, education, and health) to HDI, analyzing them at the Indian state and union territory (UT) levels. We estimate the minimum energy (and electricity) requirements at the final consumption point needed to achieve a high HDI, a very high HDI, and an HDI of 0.9 in India. It is important to note that as the energy mix changes because of emerging trends (e.g., climate change constraints such as Net Zero (NZ)), newer technologies such as low-carbon hydrogen from fossil hydrocarbons with CCUS, direct splitting of water to get green hydrogen, advanced photovoltaics, and advanced nuclear technologies such as small modular reactors (SMRs), the national energy requirements may change. We analyze these future trends by running alternate scenarios. We have deployed a national technology-centric Asia-Pacific Integrated Model (AIM)/Enduse model, an internationally recognized economics–energy–environment modeling framework to simulate the energy mix and emissions projections for NZ assessments. We have improved on AIM/Enduse India Version 3.3 (developed by the IIMA team) in conjunction with another bottom-up internationally used model, TIMES, and developed as TIMES-India by us. Several Indian research teams have developed variants of NZ scenarios through their respective models (e.g., TERI, CEEW, IRADE, IIT Delhi, IIT Mumbai, and CSTEP). The FEC–HDI assessment has been corroborated by these models through soft linkages.

In the early 2000s, a country could achieve a very high HDI with an FEC of 50 GJ/capita/year (equivalent to 14,000 kWh/capita/year). By 2010, the required FEC had decreased to 40 GJ/capita/year (about 11,000 kWh/capita/year), and by 2020, it had further decreased to 35 GJ/

capita/year (about 97,00 kWh/capita/year) (Garg, 2020). These transitions occurred due to a combination of global energy efficiency gains and increased electrification. Currently, India's FEC is at 21 GJ/capita/year (about 5,850 kWh), with electricity contributing about 18% to final energy consumption (compared to about 25% share in industrialized countries) (IEA, 2021). According to the International Energy Agency (IEA), electricity is projected to account for 37% of the total FEC (TFEC) for the USA, 35% for India, 39% for the EU, 38% for Japan, and 46% for China in 2050 (IEA, 2022b). Meanwhile, in 2021, the share of hydrogen reached almost 2.5% of the FEC – this, however, is not green hydrogen largely (IEA, 2022d). The production of green hydrogen is expected to reach 16 - 24 Mt per year by 2030 (IEA, 2022d). Achieving NZ targets could boost these figures further since more electrification using low-carbon electricity would be needed, and also for producing green hydrogen. Our modeling indicates that electricity consumption will increase gradually to 29–32% of TFEC for India by 2070 under the NDC scenarios and 47–52% of TFEC for India NZ by 2070, different across the various scenarios analyzed. A study by CEEW projects the share of electricity in the TFEC of India to rise to 31% by 2050 (Chaturvedi & Malyan, 2022).

Exploring the links between the HDI and FEC at a state level in India, we compare data from 2011 and 2019. The FEC range for Indian states is 2.4– 91 GJ/capita/year, indicating that the HDI growth in India is happening at a more pronounced rate than in other economies with comparable per-capita FEC, as analyzed in the IPCC AR6 WG3 report. However, none of the Indian states or UTs have achieved very high HDI levels yet, and the energy consumption is bound to increase by 1 to 2 orders of magnitude to facilitate this across states. The time interval studied (2011–19) shows greater equity between Indian states as the ratio of the highest and lowest values across all development metrics (health, income, and education) and energy access has reduced. Our findings show that a very high HDI of 0.800 may be achieved at a minimum per-capita energy consumption of 37 GJ/year. The per-capita energy consumption is an estimated 56 GJ/year for achieving an HDI of 0.9 and above, depending on climate change impacts on energy use, a higher electrification share in the energy mix, higher urbanization, more equitable consumption by all, newer technologies such as low-carbon and green hydrogen, advanced photovoltaics, and small modular reactors (SMRs) for nuclear power. Since the current state-level range of FEC per capita is wide (2.4–91 GJ), the mean is projected to increase in the future. If we assume a future population of 1.5 billion, India's total FEC could range from 14,000 to 18,000 TWh for an HDI of 0.8 and at least 20,000 TWh for an HDI of 0.9 in terms of energy requirements nationwide. This is similar to the estimates presented by Bhattacharya et al. (2022). Depending on electrolyzer efficiency and relative share of hydrogen versus electricity, this could range from 19,000 to 23,000 TWh.

The per-capita electricity consumption in 2070, considering an average HDI of 0.800 for India, is projected to range from 5,100 to 8,400 kWh/year across different scenarios and from 10,400 to 13,200 kWh/year for an HDI of 0.900.

The health index (HI) ranges from 0.703 to 0.876 (with an average of 0.80 for India) across states, indicating that it has entered the inelastic range and that considerable improvement in the HDI may not be possible through improvement in the HI. However, it should be noted that states with a lower HI must strive to reach the national average HI of 0.8. The education index (EI) ranges from 0.481 to 0.726 (0.59 national average) across states and UTs. The average years of schooling in India is 6.5 years, compared to the global expectation of 14 years. Therefore, the EI falls in the elastic range, and improving it could lead to a faster enhancement of the national HDI. The income index (II) is also in the elastic range, with some states having a very low per-capita income. The national average per-capita income is USD 6,681 (PPP) and, in nominal terms, was INR 1.26 lakhs in 2019, INR 1.27 lakhs in 2021, and INR 1.5 lakhs in 2022. In comparison, the global average in nominal terms was approximately INR 10 lakhs/capita/year in 2021. Therefore, the growth of Indian per-capita income would undoubtedly propel India's HDI to higher levels.

In the past, HDI improvements in India were primarily driven by improvements in life expectancy, but most states have now reached a point where increases in income and years of schooling would deliver the most "bang per buck." Among all Indian states and UTs, Bihar, Assam, Manipur, Tripura, Uttar Pradesh, Madhya Pradesh, Jharkhand, West Bengal, Mizoram, and Orissa have per-capita energy consumption in the bottom one-third. Their average per-capita electricity consumption (lowest of 167 kWh/capita/year for Bihar and highest of 2,387 kWh/capita/year for Goa among states, and 1,877–13,800 kWh/capita/year for UTs) is also low. Providing more energy and electricity per capita, therefore, would enhance the national HDI. Thus, as electrification increases (especially in Bihar, Uttar Pradesh, Madhya Pradesh, Rajasthan, and Assam—states with high population and low energy access currently), there is an opportunity to improve the national HDI to 0.7 by 2025, 0.8 by 2035–40, and 0.9 by 2045–50. All further analysis has been undertaken for an HDI value corresponding to 0.8. The dependence of the Indian economy on coal means that energy demand and energy sector emissions will continue to grow. However, in NZ scenarios wherein more nuclear power is deployed (up to 331 gigawatts (GW) maximum, against 7.48 GW currently), GHG emissions per kWh could reduce to 2 g/kWh in 2070 from the current 765 g/kWh. Under the NZ scenario with a higher renewable energy share (281 GW solar and 150 GW wind), the GHG emissions per kWh could reduce to 5 g/kWh in 2070.

Low-cost electricity for end users under NZ 2070 in India

We have explored how India can achieve clean and affordable electricity under four NZ pathways. To achieve NZ energy systems by 2070, the electricity sector will need to decarbonize well before that year.

The cost of power for end users is estimated through the levelized cost of electricity (LCOE) across scenarios. Generally, LCOEs at the generation point and at the consumption point are related through average transmission and distribution losses in the national power grid and local distribution; system costs (grid balancing costs, flexibility in operations, grid-based storage, infrastructure, smart metering, connection costs) have not been directly included here. Transmission and distribution (T&D) losses were 20.66% in 2018–19 (CEA, 2020a). State-level differences exist, and the range of average T&D losses was 12.56–34.94% across the main power-consuming states (CEA, 2020a). Furthermore, the profile/utilization costs, which increase because of the variability of the VRE output, also bring in variation in the LCOEs at the generation point (OECD, 2019). The 69th Meeting of the Forum of Regulators of India held in September 2019 noted that current state-level data suggests that a total additional burden of grid integration of renewable energy (RE) would be INR 1.11/kWh of the balancing cost and INR 1.02/kWh of the stranded capacity cost, totaling INR 2.13 per kWh, while the storage costs may range up to INR 4.18 per kWh (FoR, 2020).

Moreover, when looked at from the cost-to-consumer point of view, the system costs for nuclear energy are expected to be lower than those imposed by the variability of RE (OECD, 2019). Since RE, especially solar and wind, is variable, uncertain, location-constrained, non-synchronous, and modular in nature, the system effects and the system costs make the grid integration challenging. The system effects are in terms of a) profile costs (increase in the generation cost of the overall electricity system in response to the variability of the VRE output), b) balancing costs (increasing requirements for ensuring the system stability because of the uncertainty in the power generation), c) grid costs (increase in the costs for transmission and distribution due to the distributed nature and locational constraint of VRE generation plants), and d) connection costs (costs of connecting a power plant to the nearest connecting point of the transmission grid). System effects would increase the landed costs of power to the consumer as the share of RE increases based on the inclusion of profile, balancing, grid, and connection costs that can no longer be socialized. However, the benefits from the use of RE would come in terms of decentralized, distributed generation for locations and purposes where gird integration is challenging.

One of the key findings of this study is that clean, affordable electricity at lowest LCOE can be achieved in Net Zero pathways, especially with a focus on nuclear power and renewable power. Widespread electrification of end-use sectors, especially transport and residential, and eventually low-carbon and/or green hydrogen production will lead to a rapid increase in electricity demand after 2050 but not a corresponding increase in the carbon footprints of the power sector.

For this study, we have attempted to map out India's future energy requirements under seven alternate scenarios: low-economic-growth scenario (NDCL), medium-economic-growth scenario (NDCM), high-economic-growth scenario (NDCH), NZ 2070 scenario with a thrust on nuclear power (NZ1), NZ 2070 scenario with a thrust on fossil fuels with carbon capture, utilization and storage (CCUS) (NZ2), NZ 2070 scenario with a thrust on renewable energy (RE) (NZ3), and integrated NZ 2070 scenario (NZ4). All four NZ scenarios take medium-economic growth projections. The low low-growth scenario is included for the sake of comparison and to provide an academic perspective. While we have not worked out the linkage of the low-growth scenario to HDI, it is not likely to enable India to reach its ambition of becoming a developed country. NZ scenarios have been worked out assuming a target HDI of 0.8. and doing the same for an HDI of 0.9 has to be a part of a future study. Figure S.1 describes the emissions trajectory under various scenarios.

Under NZ scenarios, the emission intensity of electricity generation decreases to around 1–105 gCO2/kWh from the current 765 gm/kWh, along with a substantial reduction in LCOE. The nominal LCOE for the NZ 2070 scenario (with a thrust on nuclear energy) stabilizes 40% (including T&D losses) below the LCOE for the 2020 medium-growth nationally determined contribution (NDC) scenario. This LCOE is projected to be the lowest among all the scenarios. The reduction in LCOEs is observed due to factors like reduced investment costs of solar, and wind, higher utilization of nuclear energy, reduced T&D losses and reduced interest rates (WACC is assumed to decrease from 9.5% today to around 5% in 2050). The cumulative emissions under NZ1 are also the lowest across all scenarios, followed by those under NZ3.

Short-term implications (up to 2030)

Figure S.2 shows the assessment of India's projected performance against its NDC target on reducing the GHG intensity of GDP between 2005 and 2030 under all the scenarios considered in this study. It can be noted that except for a slow growth scenario and the scenario with thrust on fossil fuels with CCUS (NZ2), the targeted decoupling of GHG and GDP is achievable. If GDP growth is strong, decoupling would be also strong since GHG emissions grow by almost the same percentage year on year. If GDP growth is lower, decoupling will also be weaker as GHG emissions have a minimum level since minimum economic activities have to be continued in any country. Again, higher GDP growth may not necessarily result in proportionately higher GHG emissions. Emission growth may also be subdued by government policies and measures such as for energy efficiency, renewable, bioenergy, and ethanol. Table S.1 presents the assessment of the share of non-fossil sources in electricity generation. While NZ scenarios are targeted toward 2070, the trajectories by 2030 show the achievement of the NDC target of 50%. Thus, this indicates that India may push for a higher economic growth supported by a higher share of non-fossil sources of electricity to achieve its NDC targets by 2030.

Figure S.1: CO_2 emissions under across all seven scenarios

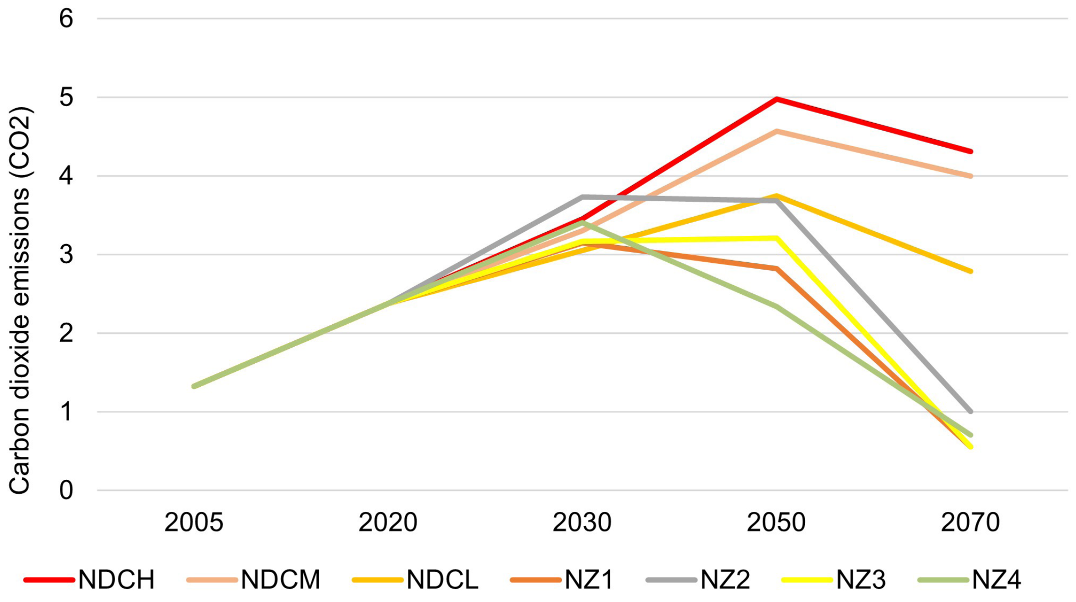


Figure S.2: India's performance on GHG intensity of GDP under various scenarios

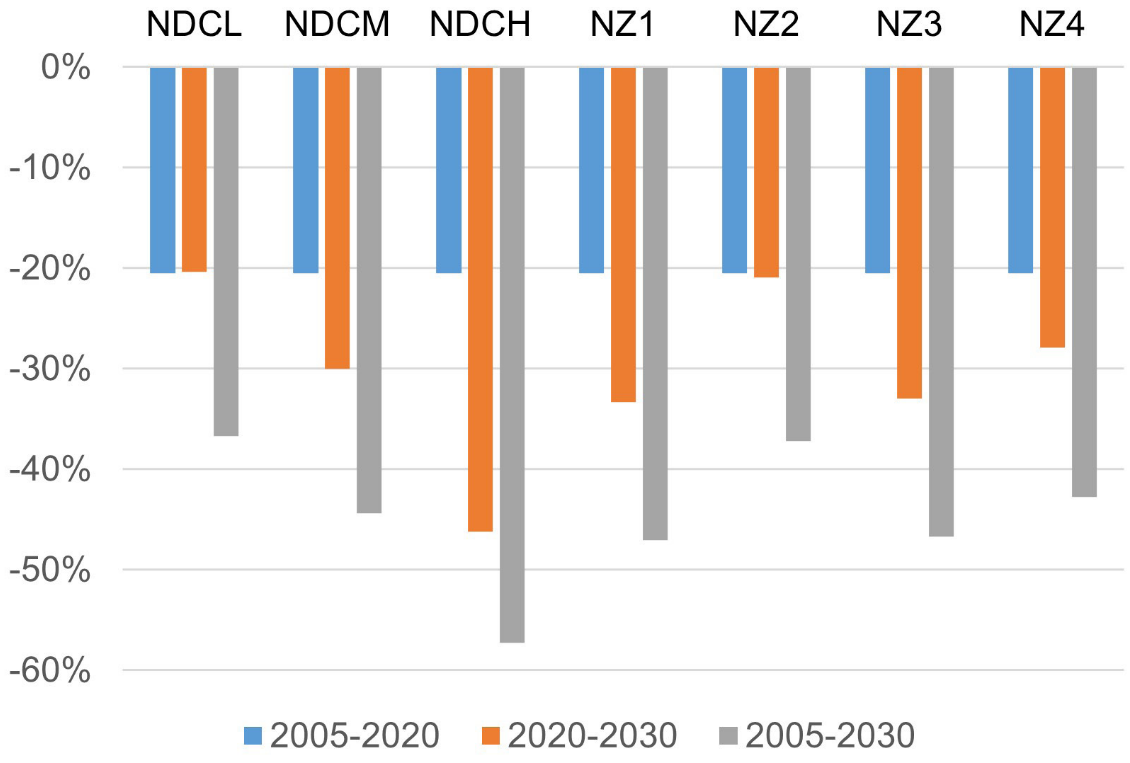


Table S.1: India's performance on share of non-fossil sources in electricity generation under various scenarios

	Share of non-fossil sources in electricity generation (%)						
Year	NDCL	NDCM	NDCH	NZ1	NZ2	NZ3	NZ4
2005	35%	35%	35%	35%	35%	35%	35%
2020	38%	38%	38%	38%	38%	38%	38%
2030	56%	46%	43%	70%	54%	71%	65%

The present load curve in India peaks at around 230 GW, while the total generating capacity is 456 GW. The projected load curve is expected to reach a higher level of 335 GW in 2030. We estimate the load curve to reach 670 GW in 2070 (Figs 6.6 - 6.9) and 946 GW for NZ1 and NZ2 and 964 GW for NZ3 and NZ4 under alternate trajectories (Figs 6.10 - 6.13). Figures 6.6 - 6.9 illustrate the load curve under the medium peak demand projections (the dark blue line in Fig 6.5). However, if we use the present CAGR till 2022 with CAGR reductions factored to project loads in 2070 (following the yellow trajectory in Fig 6.5), we arrive at Figures 6.9 - 6.13. These two sets have peak loads of 670 GW (Figs 6.6 - 6.9) and 946 GW/964 GW in 2070 (Fig 6.10 - 6.13), although the total installed capacity in 2070 is projected to range anywhere between 951 GW to 1149 GW (Table S.1). These load curves present two alternate assessments of total loads in 2070. Additional capacity for a peak load of 946 GW for NZ1 and NZ2 and 964 GW for NZ3 and NZ4 indicated in Figs 6.10 – 6.13 could be appropriate fuel/technology depending upon the scenario and future policy thrust. Energy modeling that tracks economy and energy transition towards Net Zero and evolution as well as penetration of technology is a complex problem with many potential inflections that could disrupt any model behavior. Subjective assumptions, constraints, and policy evolution are inevitable and could lead to large variations in results. The actual realization of the future could be somewhere in between 670 GW and 964 GW, or even something beyond. Our results are, therefore, policy indicative and not policy prescriptive.

The study notes that the current net load curve assumes a characteristic "duck" shape, with a decrease during the day, especially when solar generation begins, and an increase in the demand profile in the evening. The global push toward decarbonization has put pressure on fossil-fuel-based electricity generation capacities. Moreover, coal power plants demonstrate inflexibilities associated with quick ramping and minimum load operations. Recent notifications from the Government of India (GoI) have further decreased acceptable levels of minimum load operation of coal plants to accommodate renewable integration. In the case of natural-gas-based plants, inadequate gas supply has led to low-capacity utilization factors. Deployable storage technologies typically have shorter durations, around four hours per day, which helps in balancing shorter-duration demand through intraday energy arbitrage. Hydropower, with its quick ramping capabilities, is more amenable to peak load balancing during VRE integration.

In this context, the scenarios in this study witness the full absorption of available nuclear capacities as a base load for integrating VRE sources. Our findings indicate that in the projected base case in 2030, up to 50 GW of RE curtailments/storage may be required. Alternatively, the RE may be used for hydrogen generation. Direct splitting of water to generate hydrogen could become potentially more attractive route soon. Hydrogen supply and demand from small and medium enterprises (SMEs) could be appreciable for a developing country like India. Research indicates that India may witness steady growth in the share of electricity in energy demand with electric vehicles (EVs), and the share is expected to reach 25% by 2047. The share of electricity in energy demand is estimated to be 20.6% in 2030, compared to 18.3% in 2021. A larger share of electricity in the energy mix may increase the demand by 51 GW, with the need for examining net capacity assumptions. With further demand-side management, it may be possible to shift 50 GW of load to solar hours, thereby avoiding RE curtailment. Time-of-day tariffs may also help flatten the load curve further, as seen in a few high-HDI countries. Finally, all the scenarios considered demonstrate full absorption of projected nuclear capacities by 2030 in the short term.

Bioenergy is also one of the sources that the Government of India has been pushing to move towards a cleaner energy systems. In this modelling exercise, the bioenergy manifests in different forms. The solid fuel or biomass is reflected and modelled under the electricity sector (biomass to power route). Further, the BECCS assessments also include biomass to energy flows. The biogas is reflected in the residential sector of the model in terms of PNG and CNG blending.

The transport sector has one of the highest energy demands in terms of end use. Thus, replacing transportation fuel, even partially, with green fuel such as ethanol or biogas would help reduce national GHG emissions. However, achieving the GoI's ethanol blending target needs a paradigm shift in ethanol production and distribution. The current ethanol production capacity stands at 426 crore liters from molasses-based distillation and 258 crore liters from grain-based distillation. With ethanol demand for blending purposes expected to reach 722–921 crore liters by 2025 at a 20% blending rate, there will be a huge capacity gap that needs to be filled. Therefore, sugarcane-based ethanol cannot be the only source of ethanol in transport.

Additionally, focusing heavily on sugarcane-based ethanol production has negative environmental impacts. Uttar Pradesh, Maharashtra, and Karnataka are the primary producers of sugarcane and ethanol. A life-cycle assessment (LCA) of sugarcane-based ethanol production in these states revealed that sugarcane farming contributes the highest amount of GHG emissions to the ethanol supply chain, followed by transport, while the least emissions come from ethanol production (fermentation-related emissions are biogenic and hence not accounted for as per the IPCC guidelines). Uttar Pradesh, Maharashtra, and Karnataka have respective emission footprint of sugarcane-based ethanol of 0.34, 0.85, and 0.68 kgCO_2e/liter of ethanol, while petrol emits approximately 2 kgCO_2e/liter in direct comparison. Because substantial amounts of continued supply of ethanol will be required to achieve the 20% blending target set by the GoI for 2025, relying only on sugarcane-based ethanol will not bridge the gap and may also lead to negative environmental impacts. Hence, the GoI is promoting grain-based ethanol generation for fuel-blending purposes. To meet the blending targets, the government has allowed the use of surplus stocks of maize and rice available with the Food Corporation of India (FCI) for ethanol production. However, it is essential to be conscious of fuel–food conflicts in these processes. Investing in second-generation (2G) ethanol production could, therefore, be another viable option. The Indian Oil Corporation recently launched a 2G ethanol plant at its Panipat refinery, which is expected to produce 3 crore liters of ethanol annually using 2 lakh tons of agricultural waste. The emission implications of such 2G production need to be assessed; however, the major source of CO_2 emissions would be the transport of agricultural waste/surplus stock. Policies such as sub-mandates for 2G ethanol, uniform pricing mechanisms, and long-term procurement policies may be used to build demand for 2G ethanol.

India also needs a longer-term vision of what comes after the 20% target is achieved. The scenarios could be many and varied. One of the options is to allow higher blending rates in states that produce higher quantities of ethanol, thus reducing transportation needs and related emissions. However, an increased blending mandate would require a switch in automobile technology (upgrading certain vehicle parts) and bringing in flex-fuel vehicles.

Long-term implications (up to 2070 NZ India)

The composition of the power-generating profile and power generation varies across the seven scenarios considered in this study. Table S.2 describes the electricity generation capacity across all seven scenarios. The model results presented here have been reconciled with 2005 and 2020 actual numbers, while the results for 2030 and 2050 have been validated with other available studies and fall in the same broad range.

Table S.2: Electricity generation capacity (in GW) under all scenarios in the long term for peak load projection of 670 GW in 2070

Scenario	Year	Biomass	Coal (includes lignite)	Coal with CCUS	Gas	Gas with CUCS	Hydro (includes pumped storage)	Nuclear	Solar	Wind	Other	Total
	2005*	1.1	71	0	16	0	32	3.36	0.5	7	0	131
	2020**	10	206	0	25	0	51	6.7	37	39	1	375
NDCH	2030	34	227	47	82	10	53	11	166	63	19	712
	2050	42	194	92	132	11	65	75	370	70	24	1075
	2070	57	163	98	157	49	69	90	540	100	25	1348
NDCM	2030	35	220	13	95	3	53	11	149	58	16	653
	2050	33	170	25	189	32	67	75	320	70	23	1004
	2070	30	135	25	155	16	67	80	540	80	22	1150
NDCL	2030	22	186	2	95	2	57	18	108	53	10	553
	2050	35	132	12	115	13	63	35	180	70	20	675
	2070	23	96	6	105	14	64	40	180	80	17	625
NZ1	2030	16	123	29	55	0	46	30	281	70	9	659
	2050	43	69	44	40	21	61	265	281	70	23	917
	2070	51	0	29	0	21	117	331	304	100	0	953
NZ2	2030	24	204	29	97	7	43	30	201	70	11	716
	2050	39	404	140	13	178	45	75	251	70	20	1235
	2070	35	0	207	0	126	91	78	233	169	12	951
NZ3	2030	16	122	29	47	0	45	30	301	70	10	670
	2050	18	77	29	172	2	53	75	551	200	28	1205
	2070	13	0	26	0	50	117	207	486	250	0	1149
NZ4	2030	13	123	29	90	0	42	29	281	71	10	688
	2050	41	77	29	166	12	45	95	405	281	15	1166
	2070	23	0	26	0	101	56	178	410	282	12	1088

Note: * *Numbers are based on the Energy Statistics 2007 for financial year 2005-06 and Growth of Electricity sector in India, CEA, 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at around 14 GW.*

*** Numbers are based on CEA's General Review 2022 and installed capacity reports upto December 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at 47.8 GW.*

In the NZ1 scenario (with a thrust on nuclear energy), the generating capacity of nuclear is estimated to gradually build up to 331 GW in 2070, with a much faster rate beyond 2040. In the NZ2 scenario (with a thrust on fossil fuels with CCUS) and the NZ3 scenario (with a thrust on RE), nuclear capacity is projected to be 78 and 207 GW, respectively. In the NZ2 scenario, coal capacity with CCUS is expected to reach 207 GW by 2070. In the NZ3 scenario, the RE capacity is projected to reach 486 GW for solar and 250 GW for wind by 2070. A CEEW study on India's Net-Zero energy transitions has projected the share of solar energy in the generation mix to increase to 26% in 2050 and 46% in 2100 (Chaturvedi & Malyan, 2022). A study by Shell-TERI implications of the 2070 Net-Zero target on the energy transformation needs by 2030 puts the share of solar in total electricity generation between 18% to 60% by 2031 (Shell-Teri, 2023). A large part of this would require either storage or green hydrogen generation. Table S.3 provides information on emissions, electricity generation, and LCOE for 2070 across scenarios.

Table S.3: Peak annual emission, annual emissions, electricity generation, and nuclear capacity in 2070

	NDCH	NDCM	NDCL	NZ1	NZ2	NZ3	NZ4
Peak annual CO_2 emissions ($btCO_2$)	4.9	4.6	3.8	3.1	3.7	3.2	3.4
Residual emissions in 2070 ($btCO_2$)	4.3	4.0	2.8	0.55	1.0	0.56	0.70
Generation in 2070 (TWh)	5,025	4,070	3070	4,398	4,743	4,271	4,958
Nuclear capacity in 2070 (GW)	90	80	40	331	78	207	178
Share of electricity supplied from nuclear in 2070 (%)	13	14	10	50	12	36	27
LCOE (INR/kWh) in 2070	3.40	2.97	2.53	2.76	3.60	3.00	3.38

If India plans to phase down coal in the next three decades, it will need to build adequate infrastructure for alternative sources such as nuclear power, in addition to flexible grid infrastructure and storage to support the integration of RE. Furthermore, the coal phase-down will require undertaking significant imports of critical minerals to fulfill the needs of RE and battery storage sectors. Therefore, the mining sector is expected to face substantial challenges. Recent inferred discovery and future development of lithium reserves in Jammu and Kashmir, Korba, and Rajasthan could possibly change the critical mineral scenario for India in the future. However, the quantity and quality of the resources available are yet to be ascertained. The Government of India has recently released a list of 30 minerals critical for India's economic growth and development (MoM, 2023). The parliament has also passed the Mines and Minerals (Development and Regulation) Amendment Bill, 2023, which allows auction of mining leases and composite licences for certain critical minerals like lithium, zirconium, and other atomic minerals, as well as copper, zinc, nickel and other deep-seated minerals to private sector (PIB, 2023).

Aluminum, chromium, cobalt, copper, graphite, iron, lead, lithium, manganese, nickel, vanadium, and zinc are among the most commonly used minerals across battery technologies. However, the type and quantity of minerals required for energy storage vary by technology and use. Moreover, there are supply concerns such as the environmental and energy-use impacts of increased extraction of mineral resources, as well as the relative vulnerability of developed countries to the supply of critical elements required for the clean energy transition.

Compared to the supply chain for fossil fuels, especially oil and natural gas, the supply chain for these raw materials is more geographically concentrated. Minerals critical for battery technologies such as nickel and cobalt have reserves in very few locations globally, making a case for resource nationalization. The demand for graphite, lithium, and cobalt is expected to increase exponentially, but the supply will also observe constraints since over 60% of graphite and cobalt production is concentrated in China and the Democratic Republic of Congo, respectively.

Lithium-ion batteries are a dominant technology currently as more energy can be stored for the weight of the battery, and can be useful for stationary and transportation purposes. Graphite demand will change in the future as lithium will replace it. Proven lithium resources are limited and will experience price increases. However, there is currently an enhanced thrust on exploring lithium in India and new reserves have been supposedly discovered in Jammu and Kashmir and Rajasthan. Hence, new research investments are coming into developing alternative technologies. Because of sodium's abundance and cost-effectiveness, along with its very suitable redox potential (similar to that of lithium), sodium-ion batteries have great potential to be a counterpart to lithium-ion batteries, including in stationary energy storage and EVs, by 2030. Furthermore, sodium batteries are expected to be much more cost-effective because of the global availability of sodium resources. Although the current market share of Na-ion batteries is smaller than that of Li-ion batteries, efforts are underway to make Na-ion batteries commercially feasible on a global scale.

The vanadium redox flow batteries are recyclable, leading to a reduced need for minerals. The largest deposits of vanadium are located in China, Russia, Australia, South Africa, and Brazil. Additionally, vanadium occurs in almost 65 minerals. Vanadium pentoxide (V2O5) is used as an electrolyte in redox flow batteries and is extracted from the titaniferous magnetite ore during steelmaking. Vanadium can also be extracted from the processing of aluminum from bauxite. Therefore, ash, slag, spent catalysts, or residues generated from the iron and steel industries, aluminum plants, and crude oil, tar, and coal refining and processing contain vanadium, which can be recovered. This means that vanadium availability is relatively distributed across the globe.

To reduce its dependence on the import of critical minerals whose large reserves are located in geopolitically volatile nations, India needs to invest in developing renewable and battery technologies that are based on domestically available mineral resources. This could also involve the use of vanadium-based flow batteries for stationary applications and EV charging infrastructure, as well as sodium-based batteries along with lithium-based batteries. As the demand for energy storage for clean transitions increases, it becomes increasingly important for India to develop technologies for the reuse, recovery, and recycling of critical minerals. Refurbishing, recycling, and mineral recovery will play a vital role in meeting future mineral demands and limiting import dependencies. However, the recycling of minerals comes with its own energy penalty – for example a study found that recovery of lithium from lithium batteries leads to 38-45% higher energy consumption compared to its primary production (Golroudbary et al., 2019).

If India intends to follow coal-dependent pathways, it will need to explore carbon dioxide technologies (CDRs) as well, such as bioenergy with carbon capture and storage (BECCS) and CCUS, to fully understand their long-term potential. However, the energy penalty for deploying BECCS at power plants would need a closer examination. CCUS must be powered via renewable grids to ensure their compatibility with long-term NZ targets. Challenges such as a mismatched operation scale, which may require clustering emitters near a suitable use or storage site to ensure cost-efficient capture and transport, as well as the risks of leakage, the need for monitoring and maintaining storage sites, and accompanying liabilities, could potentially hinder the deployment of CCUS. Without CDRs, moving toward NZ pathways will strand majority of the coal and gas assets after 2040.

Under all the NZ scenarios, nuclear power generation forms a substantial portion in 2070 331 GW under the NZ1 (with a thrust on nuclear energy), 78 GW under the NZ2 (Fossil fuel with CCUS), 207 GW under the NZ3 (renewable), and 178 GW under the NZ4 scenario. Because of trade bans and the lack of indigenous uranium, energy production from nuclear energy did not gain momentum in the past, but the import of uranium has been possible through the opening of international civil nuclear trade.

Further, globally, nuclear energy will play an important role in decarbonizing and achieving the NZ targets. A recent study noted that U.S. domestic nuclear capacity has the potential to scale from ~100 GW in 2023 to ~300 GW by 2050 (USDoE, 2023). Over 16 European countries are of an opinion to support nuclear power through their energy policies and green industrial subsidies. The EU government has agreed to allow EU incentives for green industries to certain advanced nuclear technologies (Reuters, 2023). China has approved new nuclear power projects to achieve its green energy transition goals (Zheng, 2022).

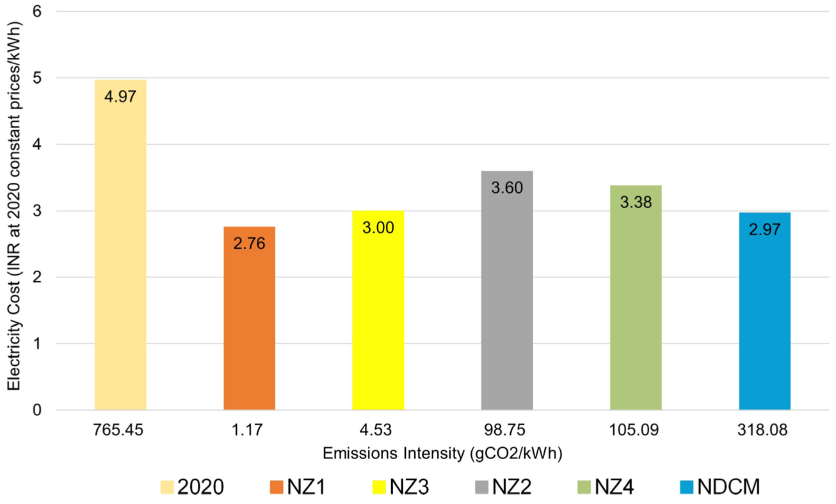
Low-carbon or clean hydrogen is normally perceived to be the prominent energy carrier in future. Renewables, nuclear, CCS, and hydrogen (among others) are projected to contribute toward NZ transitions under alternate scenarios based on technological developments and relative economics. Even so, the interquartile range for hydrogen's share in final energy is 1 - 6% overall and 2 -8% in the industry sector as per the IPCC Sixth Assessment Report. If costs come down more drastically, some expert elicitations suggest that this share may to increase as high as 40% (Bhattacharya et al., 2022). Hydrogen use may be considered as a spectrum- from unavoidable to uncompetitive, considering products such as methanol or hydrogenation of biodiesel. Low-carbon hydrogen production is imperative for these.

Figure S.3 shows the emission intensity of electricity and electricity costs across NZ scenarios for 2070. The LCOE decreases substantially in 2070, when the share of nuclear power increases in the national electricity mix. Conversely, the NZ2 and NZ4 scenarios show a slight increase in LCOE compared to the NDCM scenario. Under NZ1, the emission intensity of electricity generation approaches 1 from around 765 gCO2/kWh in 2021, leading to a substantial reduction in LCOE.

Furthermore, under the NZ2 and NZ4 scenarios, we observe residual carbon emissions compared to the NZ1 scenario. Thus, the costs of carbon would further increase the costs at the user end under NZ2 and NZ4 scenarios.

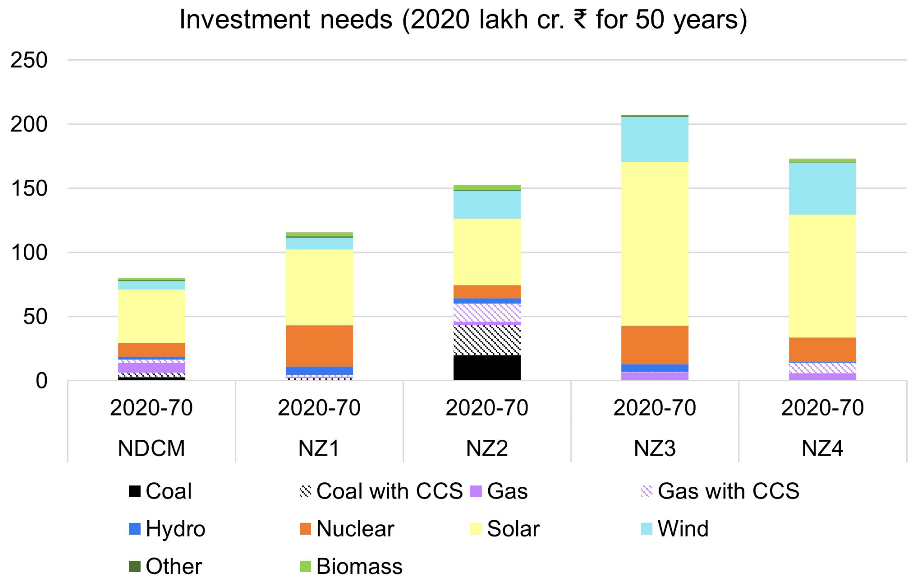
Achieving the necessary levels of nuclear power generation for India to achieve NZ emissions by 2070 would require significant investments in research, development, and large-scale deployment of nuclear technologies. For India, investments are an important dimension for moving toward NZ 2070. Figure S.4 provides the annual average investment needs required in the NDCM growth scenarios vs. in the NZ scenarios (NZ1 to NZ4) between 2020 and 2070. NZ1 brings down the cost of electricity below that in the NDCM scenario and reduces the emission intensity of electricity generation below 2 gCO_2/kWh. However, the additional investments required in NZ1 are approximately 130% above those in the NDCM growth scenario. Similarly, other NZ scenarios would require investments in the range of 100–180% above those in the NDCM growth scenario.

Figure S.3: Emission intensity and electricity costs across NZ scenarios in 2070



The investment numbers do not include the system costs (grid balancing costs, flexibility in operations, grid-based storage, infrastructure, smart metering, connection costs). Some of these would be common. However, some of these would be different across scenarios, such as the storage costs for BESS systems co-located with the solar and wind plants. However, the current sustainable finance guidelines in India do not consider nuclear as a part of its green deposits framework (RBI, 2023). Although the capital cost of nuclear power plants is currently high, at INR 15 crores/MW (about 1.5–2 times/GW than that of coal power), more investments in nuclear technology and achieving economies of scale are expected to reduce these costs. Nuclear power has comparatively very low variable costs and offers the advantages of not needing any CCUS compared to coal and gas for NZ and not needing any storage capacity and critical mineral imports compared to renewable power. Additionally, its plant load factor (PLF) could be as high as 80–85%, which is way above all other energy mix options. Our analysis projects the cost at the user end to be the lowest under NZ1 among all scenarios analyzed.

Figure S.4: Annual average Investment needs for electricity generation between 2020 and 2070 in all NZ and NDC scenarios



Overnight costs have not been included in these estimations. Capital investments in the electricity sector between 2020 and 2070 could be 30–70% higher than under the current medium-growth scenario (without the NZ target). However, if a carbon price is established in India soon, a drastic reduction in the carbon footprint of electricity to 1–105 gCO2/kWh in 2070 under NZ1 and NZ4 (with a thrust on nuclear and integrated) scenarios from the current level of 765 g/kWh could generate about 5 lakh crores in today's price, considering that in 2050, the carbon price in India will be INR 1,700/tCO2 or approximately USD 25/tCO2. For the carbon price, if we assume a discount rate of 5% and a carbon price that gradually increases from INR 250 to 1,250 per ton CO2 in 2020–30 to INR 2,000–5,000 per ton CO2 in 2050–70, the carbon revenue for instance in the NZ1 scenario would be between INR 5.5 and 14 lakh crores in terms of net present value (NPV). These funds could be deployed to fill the capital investment gap in achieving the nuclear thrust.

Recommendations

The scenario analysis in this study shows that a diverse energy system would be useful in managing cost to the consumers and effective load balancing. Results and inferences have been presented in detail in various chapters. We present some high-end recommendations for the Indian energy systems towards a Net-Zero based on our assessment.

Coal is projected to continue for the next two decades as the backbone of Indian energy system. However, slowly but surely, non-fossil energy (renewable and nuclear) needs to replace the fossil fuel share. Alternate scenarios capture their growth in 2050 and 2070.

Net-Zero is a challenge for India. Multiple transitions have to happen almost simultaneously across energy supply and end-use sectors.

Overall, all low-carbon technologies may be provided a level playing field and preferential treatment could be avoided for only select technologies through new, innovative finance and/or transition finance mechanisms. Life cycle assessment of each of the alternate energy system should be carried out, and incentives may be linked proportionately to the net mitigation provided by alternate technologies constituting the energy basket. This is particularly relevant in the case of hydrogen. Here, all forms of low-carbon hydrogen below a certain GHG intensity could be incentivized, instead of just green hydrogen. Clean hydrogen could also be produced using biochar grown from various bioenergy plantations, such as bamboo, rice stacks, cotton plant residue, and many other agricultural crop residues. Biochar demand generation from sectors such as steel making and agriculture itself could propel and incentivize supply. This would in turn incentivize farmers, supporting their incomes, industries established in rural areas, and the whole green ecosystem transitions in India.

Scaling up hydrogen technologies would require several policy and technological interventions. The current hydrogen intensity production from unabated fossil fuels is 10 to 14 kg-CO_2e/kg- H_2. With use of CCUS, this may reduce to nearly 2 - 3 kg-CO_2e/kg-H_2,which could itself represent a sizable reduction. Our results show that carbon intensity of 2 kg-CO_2e/kg-H_2 would be compatible with economy-wide Net-Zero emissions in 2070. This allowable emission intensity for hydrogen may be reduced in a phased manner over the next 2 - 3 decades. Emission intensity reduction gradually to around 4 kg-CO_2e/kg-H_2 in a decade and upto 2 kg-CO_2e/kg-H_2 in long term can be consistent with Net-Zero emissions. It looks, therefore, essential to support the production of hydrogen from various sources, including renewable energy, fossil fuels with carbon capture, utilization and sequestration (CCUS) technologies and nuclear energy currently, under the umbrella of clean hydrogen to speed up the availability of hydrogen in the market. This will ready the adoption of hydrogen as a carrier gradually in India and her energy basket. In addition, as hydrogen demand picks up, hydrogen supply will gyrate toward green hydrogen as technology matures and costs come down.

Regulatory changes also need to reflect hydrogen blending limits into natural gas networks. An analysis of the fugitive emissions from hydrogen transmission and distribution networks is also imperative because hydrogen could be more susceptible to leakage. Finally, we also recommend a screening program to explore naturally occurring hydrogen in India.

Uranium storage facilities are commissioned to allow for resilience to disruption of nuclear power. Institutional arrangements may be scaled up so that more nuclear power could be commissioned easily and early. This may include public private partnerships. Special economic zones could be set up in areas where nuclear power/hydrogen cogeneration can take place alongside industrial operators with large demand for these commodities.

Chapter 1

INTRODUCTION

1. Introduction

India is one of the fastest-growing economies in the world, supporting approximately 18% of the global population. Despite having the lowest gross domestic product (GDP) per capita, lowest FEC per capita, lowest power consumption per capita, and lowest GHG emissions per capita among the G20 countries, it is the fifth-largest economy in the world and the third largest emitter of GHGs (IEA, 2021;European Commission et al., 2018; UNFCCC, 2015).

In terms of the energy profile, India's average annual energy consumption per capita is one-third of the world average. Around 18% of the world's population consumes just 6% of the world's primary energy. Although 50 million households have been covered under the Ujjwala liquified petroleum gas (LPG) scheme and 100% of villages have been electrified, many households are still using solid fuels for cooking. India's energy demand is expected to double by 2040. Global total primary energy demand is expected to grow from 14314Mtoe in 2018 to 17723 Mtoe by 2040 (IEA, 2019) and India is expected to account for almost one-quarter of this growth between 2019 and 2040 (IEA, 2021). its per-capita energy consumption may still remain 40% below the world average. India's primary fuel for electricity generation is coal, which is abundantly available within the country. However, India is a net importer of oil and natural gas. Because of its heavy dependence on fossil fuels to meet the energy demands of a fast-growing economy, India's electricity systems will continue to depend on coal (IEA, 2015, 2018, 2021).

Despite all these challenges, India has consistently expressed its commitment to low-carbon development pathways and has actively participated in international climate negotiations. At the 21st Conference of Parties (COP-21), which led to the Paris Agreement, India joined the global commitment to limit the rise in global temperature "well below 2 °C" and committed to reducing the GHG emission intensity of its GDP by 33–35% by 2030 and to achieve about 40% cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030 (UNFCCC, 2015), which has since been enhanced to reducing the GHG emission intensity of its GDP by 45% and about 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030 with a NZ 2070 target by Prime Minister Narendra Modi at COP-26 in Glasgow (UNFCCC, 2022). According to the latest estimates, India is well on the way to fulfilling these climate commitments (IEA, 2015, 2018, 2021). Domestically, the GoI is dedicated to achieving affordable housing, health and education, clean energy and water access, food security, and a better standard of living for all its citizens in the near future, in line with the United Nations' Sustainable Development Goals (SDGs).

India's climate policies adopt a development-centric approach (MoEFCC, 2021) to strike a balance between its climate change commitments, economic growth, and development. However, achieving "net-zero (NZ)" emissions from the energy systems in the latter half of this century, primarily from a fossil-fuel-dependent electricity sector, will pose additional challenges in balancing global climate targets with domestic development goals. Hence, a detailed study of future energy systems in terms of the FEC is needed to meet the goals of high HDI, energy security, technology–fuel mix, electricity load profiles, low cost of electricity for consumers, and other impacts of our mitigation strategies under different policy scenarios.

The objective of this study is "to conduct a comprehensive study with rigorous methods to minimize the cost of power at the consumer end while working out an optimum mix for all sources of power, aiming at NZ emission to be realized by a definite year." This study attempts to answer the following questions. Figure 1.1 shows the research flow for this study.

a. What are the current linkages between the FEC, GDP, and HDI? How would the FEC change if India aims to achieve a very high HDI?

b. What would be the energy demand for India around 2070 under different mitigation policy scenarios? How will the energy transitions affect the electricity sector and technology–fuel mix in the demand sectors of future energy systems?

c. What is the current annual average load profile of the Indian power grid, and how could it change because of more RE integration and more nuclear power?

d. How could ethanol facilitate the transition toward cleaner energy? What impacts would blending ethanol with fossil fuels have on GHG emissions?

e. What could be the impacts on material mining undertaken to meet the large-scale deployments of solar, wind, nuclear, and battery storage technologies?

Figure 1.1: Research framework

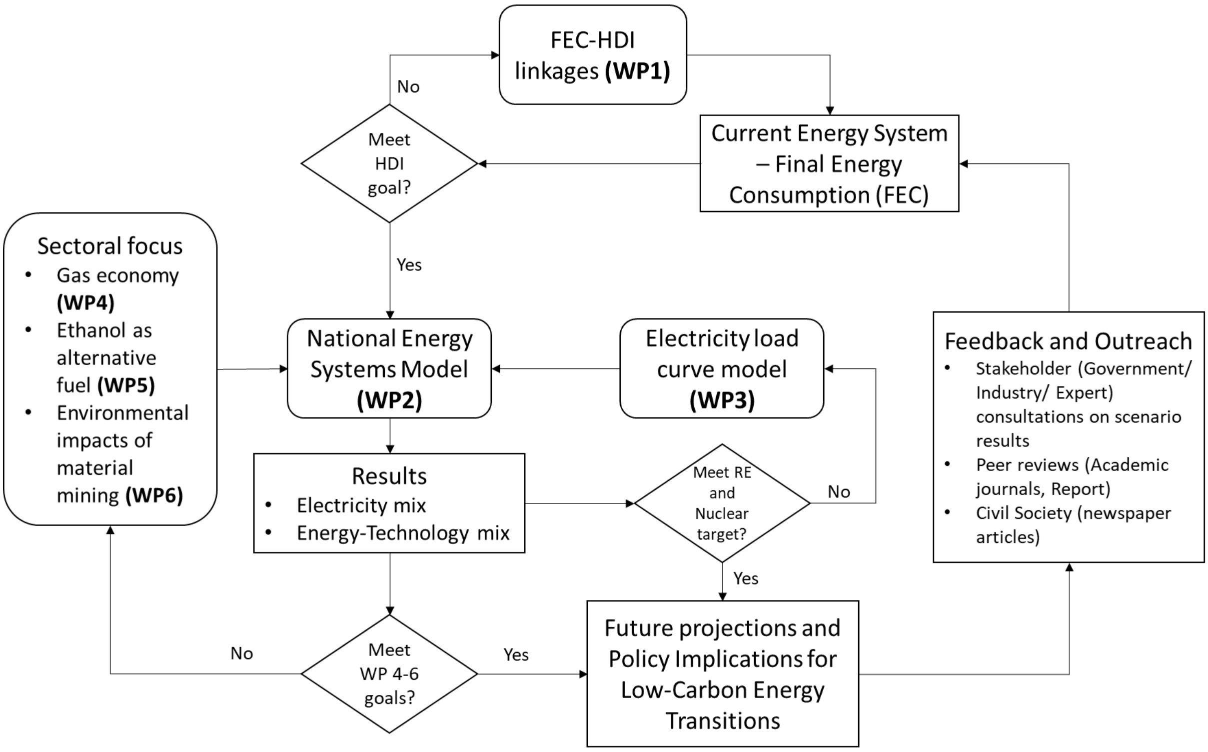
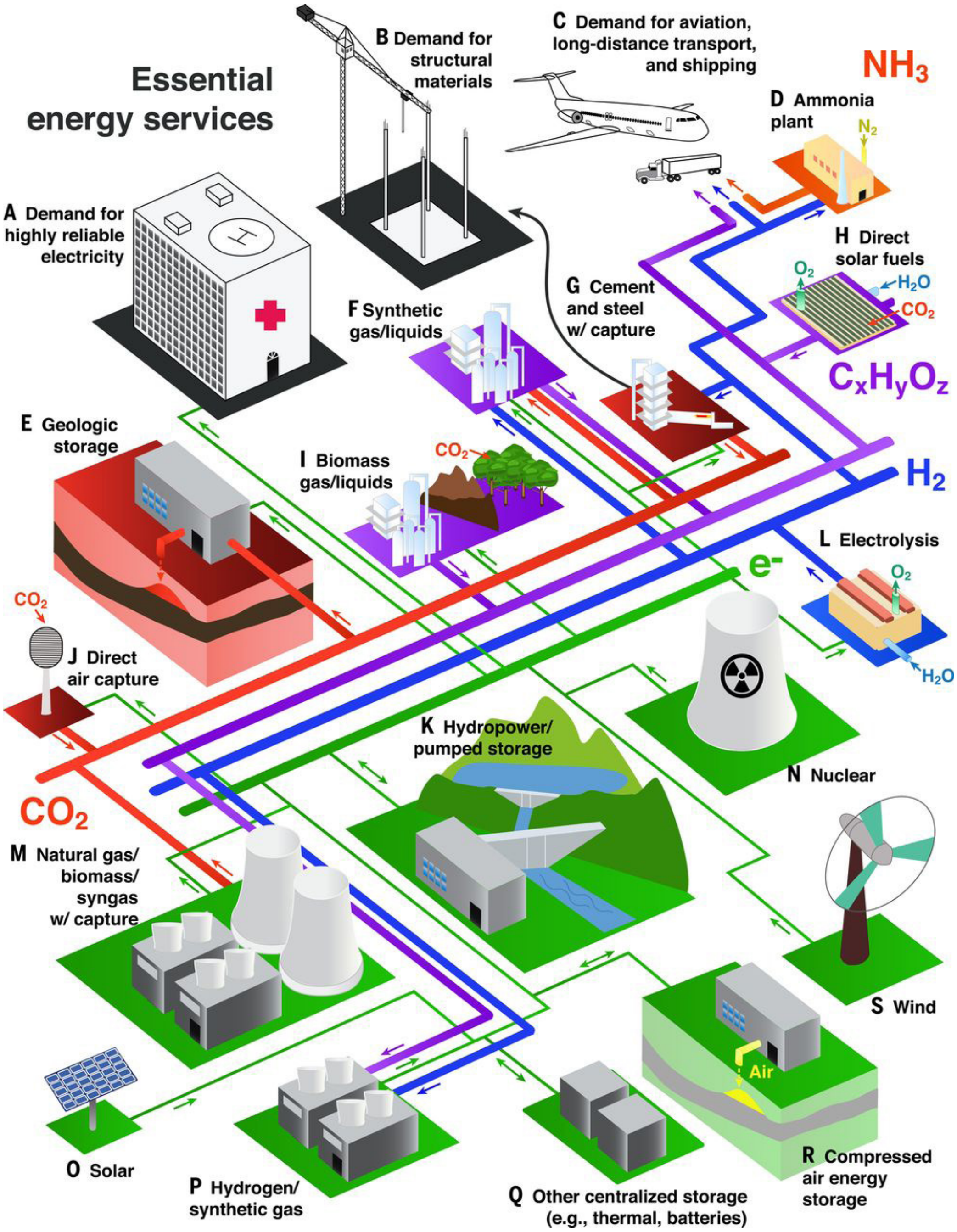


Figure 1.2: A broad schematic of net-zero energy systems and its linkage to this.



Source: *Davis et al (2018), reproduced with permission from the publisher.*

The IPCC Sixth Assessment Report characterizes the elements of a net-zero energy system, which is summarized in Figure 1.2. There are several key highlights of such a system. First, electrification would need to be expanded from around 20% of FEC to 50% of FEC. A high rate of electrification, coupled with low-carbon electricity grid will drive down emissions while improving healthcare and education. Second, several new energy carriers will emerge in future.

In our research context of this report, Element A is covered under Chapter 2 of this report. Chapters 3-5 present scenario analysis for elements E, I, L, M, P, O and S. Chapter 6 emphasizes load balancing with focus on elements K, R and Q. Chapter 7 focusses on element N.

Chapter 2

DEVELOPMENT AND ENERGY NEEDS

2. Development and Energy needs

The most recent report of the Intergovernmental Panel on Climate Change (IPCC) provides valuable insights into synergies and tradeoffs of decarbonizing energy systems and achieving key societal goals such as promoting human health and reducing poverty (Clarke et al., 2022). The report highlights that improved energy access and electrification contribute to the attainment of societal priorities, as measured by the HDI. HDI is a widely used indicator suggested by the United Nations Development Programme. It is a composite metric that considers per-capita income, literacy rate (education), and life expectancy (health). As per the Human Development Report 2021-2022, India has an HDI of 0.633 (with a maximum possible value of 1.000), which corresponds to a medium level of human development. Our report targets to increase India's HDI to high levels (0.7–0.79) and eventually to very high levels (0.8 and above) in the coming years. Some studies suggest this could happen over the next three to five decades (Bhattacharya et al., 2022; Rami, 2021). Therefore, it is imperative to understand the impacts of increases in the HDI, both historical and projected, on energy and electricity consumption.

There has been significant research on linking energy consumption with the HDI. Initial work by the UNDP showed that very high levels of HDI were achievable with an annual per-capita energy investment of 100 GJ in 1975, which reduced to 60 GJ in 2005 and further to 50 GJ in 2012. Clarke et al. (2022) used updated data to show that this threshold had fallen to 40 GJ/capita in 2019, with multiple countries achieving very high HDI at even lower per-capita energy consumption. Bhattacharyya et al. (2022) found that efficiency improvements in the electricity and hydrogen economy may bring down the energy needs to 41.2–48.6 GJ/capita/year for India to reach high HDI levels. On the basis of historical observations, it is also seen that different priorities become influential at different levels of development. For instance, when a country's HDI is below 0.5 or in the so-called elastic region, human development is more strongly coupled with education and health. On the other hand, in very developed economies, HDI is largely correlated with increases in per-capita incomes (Reddy, 1999). More recent work by Zahid et al. (2021) highlighted the need for increased penetrations of RE to hasten HDI growth at similar levels of energy consumption. This can be observed because of the direct linkages of low-carbon energy with healthcare (Dholakia, 2018) and education (Mehmood, 2021). Thus, more recent research has also started to incorporate linkages between HDI and GHG emissions, in addition to per-capita energy consumption.

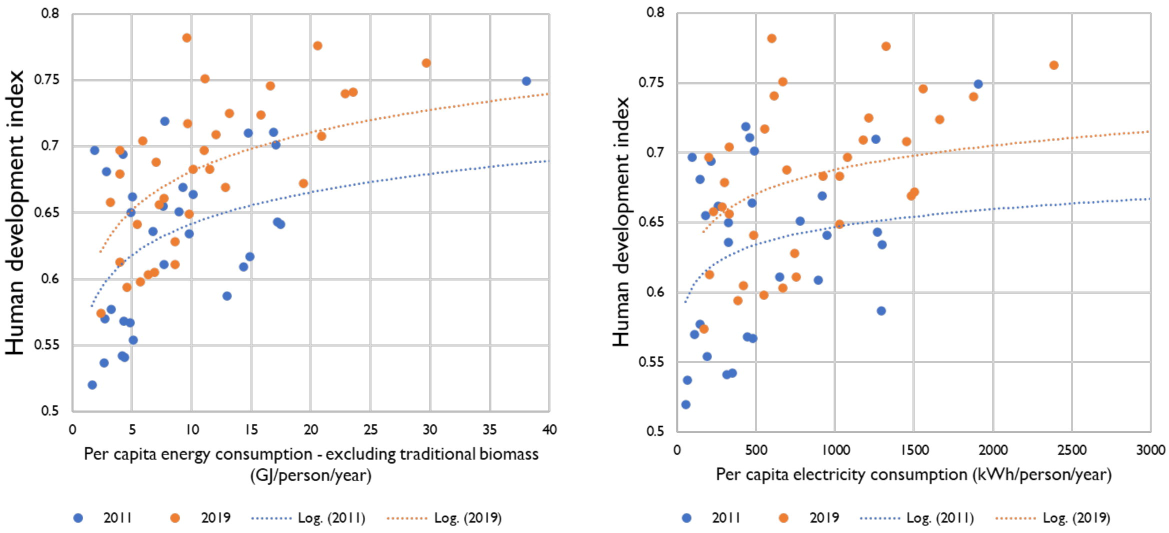
Several analyses have been performed using analytical formulations. However, nearly all such analyses consider national HDIs. Given the wide levels of differences in development in India at sub-regional levels, it is prudent to conduct a similar analysis across different states. For instance, the IEA World Energy Outlook shows that the average per-capita FEC in Bihar is less than 10 GJ/year (IEA, 2021). Another reason to evolve these analyses is that they have largely used per-capita energy consumption. However, the IPCC also points to electrification as a key parameter here, which should also be accounted for. The detailed methodology used for this assessment is described in Annexure 1.

2.1 India HDI: Energy linkages

The key feature of this analysis is to report the HDI vs. energy consumption and understand the temporal trends. Figure 2.1 shows the plot of HDI vs. per-capita energy and electricity consumption for all the states and UTs. For the sake of data completeness, only 2011 and

2019 data have been reported here. The state-level trends in the HDI also follow a logarithmic pattern, as in the case of national-level data for both final energy and electricity consumption (Bhattacharyya et al., 2022; Clarke, L. et al, 2022). Notably, the HDI values of none of the states fall in the saturation region of the graph because the highest HDI was 0.75 in 2011 and 0.78 in 2019. Thus, none of the Indian states or UTs have achieved very high HDI levels yet. Therefore, any increase in energy access would likely lead to growth in human development parameters for all the states and UTs. The results show an increase in human development from 2011 to 2019.

Figure 2.1: State-level HDI in 2011 and 2019 vs. (left) per-capita energy consumption and (right) per-capita electricity consumption.



An important trend observable in Figure 2.1 is that no states had low HDI (below 0.55) in 2019. In 2011, five states, i.e., Bihar, Uttar Pradesh, Rajasthan, Odisha, and Madhya Pradesh, had an HDI of less than 0.56. However, significant improvements in education and healthcare indices have substantially improved the HDI equity across various states. Moreover, improved equity in the energy parameters between states has also been observed. For instance, the ratio of the maximum and minimum per-capita electricity consumption across states was 40 in 2011, which has been reduced to 13 in 2019.

Another important trend visible in these graphs is the reduced energy thresholds for achieving high HDI between 2011 and 2019. Both graphs show increased human development at a corresponding level of energy consumption between 2011 and 2019. For instance, on the basis of the trend analysis in 2011, it can be seen that a per-capita energy consumption of 15 GJ/annum is likely to result in an HDI of 0.65. In 2019, a similar energy input would result in an HDI of 0.70. Almost a jump of 0.05 HDI in absolute levels has been observed in eight years at a comparable level of per-capita energy consumption. This increase in HDI is much more pronounced for Indian states than at the international level, where an HDI increment of only approximately 0.01 is seen between 2012 and 2017 at a similar energy level. This is likely due to the availability of more efficient energy access through electrification and LPG connections (e.g., the Ujjwala scheme) across India, especially in rural areas. Similar results are seen for electricity consumption as well, where an increase of 0.05 units of HDI at a per-capita electricity consumption of 1,500 kWh/person/year is observed. Furthermore, a jump of almost 0.04 HDI in eight years is observed at a comparable level of per-capita electricity consumption. This is important because this value is close to India's per-capita electricity consumption (1,255 kWh/

person/year). Hence, if electricity access can be improved in all states, especially in lower-consuming ones, to the current average levels, a high HDI can be achieved even at the present threshold energy levels. This is also important from a climate change mitigation perspective since 70% of GHG emissions come from coal combustion in the power sector, leading to a very high indirect linkage of HDI and GHG emissions.

2.2 Deciphering HDI components

The HDI parameters are a function of the highest and lowest values of respective variables globally. Because India's life expectancy (70 years) is higher than the lowest life expectancy (approximately 54 years), the health index (HI) values are comparably higher. There is a significant difference between the achievement of nationwide human development goals. For instance, the average HI in 2019 was 0.80 (0.77 in 2011), and the HI is higher than the HDI in most states. These increased values of the HI are seen because of increased life expectancy in India.

In contrast, the educational index (EI) is much lower than the HDI across states. In 2011, the average EI was at designated low levels of the HDI (0.55), which improved to 0.59 in 2019, but there is still substantial scope for improvement. Particularly, the national mean number of schooling years is averaged at 6.5 years, but it is as low as 4.6 years in Bihar. For females, the national mean is 5.4 years, while it is 2.9 years in Bihar. The global aspirational value for schooling is 14 years. Therefore, in countries with a very high EI, the current per-student investment is USD 8,000 annually, achieved through private/parental finance (UN, 2019). Hence, it is crucial to decompose the HDI components to understand where the push is required for improving HDI levels.

Improved equity across all indicators has been observed between 2011 and 2019. The relativeness ratios, i.e., the ratios of maximum and minimum values of an indicator, show a reduction over the years, indicating a positive trend. The HDI relativeness ratio of 1.44 in 2011 became 1.36 in 2019 at all-India levels. Moreover, the HI ratio improved to 1.25 in 2019 from 1.28 in 2011, the EI ratio changed from 1.62 in 2011 to 1.50 in 2019, and the II ratio reduced from 1.57 in 2011 to 1.49 in 2019. The energy inequity has also reduced between 2011 and 2019. In 2019, the FEC ranged from 2.37 to 91 GJ/capita/year across states, while the national average was 19 GJ/capita/year in 2019 and 14.8 GJ/capita/year in 2011. The lowest per-capita electricity consumption in 2011 was observed in Bihar, at 55 kWh/capita/year, which increased to 167 kWh/capita/year in 2019. For per-capita energy consumption, the maximum-to-minimum ratio was 51 in 2011, which improved to 38 in 2019. Similarly, for per-capita electricity consumption, the ratio decreased to 82 in 2019 from 175 in 2011.

Thus, an immediate scope for moving toward high HDI and eventually very high HDI for India is to reduce the disparity between high-performing and low-performing states, for instance, increasing energy access in states that currently consume 50% less per-capita energy compared to the national average.

Once the key trends have been observed, the analytical formulations discussed in Annexure 1 can be used to calculate the regression coefficients. The slope of this regression is critical in identifying the parameter most influenced by increases in energy consumption and, therefore, the most valuable returns (in terms of HDI increase) against the investments for each sector. Table 2.1 shows the key regression parameters here. Note that the coefficients here are negative because of the negative sign of the left-hand side in front of the "HDI" parameter.

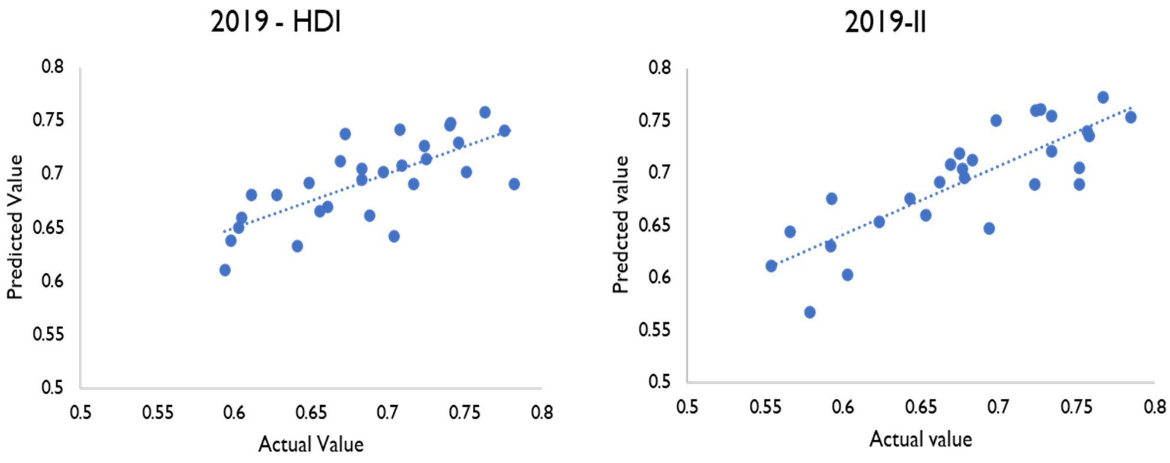
Table 2.1: Key regression outputs for HDI–energy and HDI–electricity relationships

2011 data	HDI	HI	EI	II
Energy coefficient	-0.26	-0.25	-0.16	-0.25
R	0.46	0.51	0.27	0.46
Electricity coefficient	-0.11	-0.09	-0.11	-0.01
R	0.34	0.45	0.36	0.27
Energy coefficient	-0.65	-0.25	-0.70	-0.89
R	0.58	0.43	0.48	0.72
Electricity coefficient	-0.18	-0.08	-0.30	-0.44
R	0.35	0.18	0.28	0.49

The first key conclusion here is that the energy coefficients for all the parameters were relatively similar in 2011. Thus, any increase in energy investments would accrue nearly equitably in the HDI, HI, and II. However, in 2019, the absolute value of the energy–II coefficient was much higher than other indices, implying a greater impact of improvements on the HDI outcomes. In fact, Reddy (1999) concluded that beyond a certain point in development (say after HDI > 0.65), the coupling of income with the HDI goes strongly. In other words, improvements in income are the most predictable way of improving human development as societies move to situations where basic human needs are already met. This is evident from the low level of the energy–HI coefficient, which implies that benefits from health improvements might have stagnated insofar as their influence on the overall HDI.

It is noteworthy that the goodness of fit for our state-level analysis is much lower than for national-level analyses. For instance, the *R*-value of 0.58 is lower than that calculated by Steinberger and Roberts (2010), who obtained an *R*-value of 0.82 for national-level data. This is due to several reasons. As already noted, interstate transport of electricity and liquid fuels across states is much higher than international transport. As such, the consumption data might not be exactly representative of the actual in-state consumption. Furthermore, the lower number of observations (~30) in comparison to international data (~190) could affect the fitness of this analysis. That said, we plotted the predicted values against the actual values of our regression in Figure 2.2. The results show that although the *R*-values are small, there is an acceptable match between the predicted and observed values.

Figure 2.2: Comparison of the predicted value obtained via regression with the actual value of (left) HDI and (right) income index.



Source: Actual data was obtained from https://globaldatalab.org/shdi/shdi/, and the predicted values are the authors' analysis.

2.3 Sub-national HDI assessment

Although Figure 2.1 shows the overall trends in HDI vs. energy, understanding trends in individual states is also essential. Several important trends are noticeable here. Table 2.2 highlights that several states that are in the bottom 33% of HDI are also in the bottom 33% of individual components within human development (HI, EI, and II) until 2019. These states are Assam, Bihar, Chhattisgarh, Jharkhand, Madhya Pradesh, and Uttar Pradesh. Per-capita energy consumption in these states is also within the bottom 33%, i.e., below 6 GJ/annum. This signifies a state-level relationship between the per-capita energy consumption and individual human development parameters, in addition to the composite HDI. Notably, for some of these states, such as Jharkhand and Madhya Pradesh, electricity generation does not rank within the bottom 33%. This suggests a greater linkage for per-capita energy consumption than electricity consumption with HDI. This could be due to various reasons, such as the key source of electricity generation in these states is coal, which might result in higher levels of air pollution that are detrimental to human health.

For instance, Gohlke et al. (2011) found that increased coal consumption in many regions globally led to lower life expectancy and higher infant mortality. There is significant literature on the environmental externalities of coal-based electricity generation. Another study on Delhi and other Indian cities indicates that a shift from coal or even an increase in the efficiency of the electrostatic precipitators may bring down these externalities (Dholakia et al., 2013). More recently, Cropper et al. (2019) reported that urban air pollution from Indian coal-fired power plants causes an estimated 80,000 deaths in 2015, which may increase 4–5 times if coal use increases by 2050. While multiple researchers have conducted cost–benefit analyses, the “value of statistical life” varies from USD 150,000 to USD 5,000,000 in these studies, causing a wide variance in the economic estimates of the mortality costs.

Moreover, electricity generation in a particular state might not be entirely representative of the state’s consumption. Both Jharkhand and Madhya Pradesh are locations of high-capacity power transmission corridors. Therefore, when studying state-level trends, per-capita electricity production is not a good indicator of human development compared to the FEC. While these states are typically characterized by lower energy consumption, recent years have seen a comparatively higher level of incremental energy use (between 2011 and 2019) in some of these states. For instance, Chhattisgarh, Rajasthan, Odisha, and Madhya Pradesh have a percapita energy consumption of 77%, 68%, 56%, and 52%, respectively. This increase in energy consumption has been instrumental in improving human development parameters, even though they are significantly below the national average. For instance, Chhattisgarh’s EI and II both increased by 0.06 points during 2011–2019.

In addition, some states/UTs with very high human development metrics do have high energy consumption as well. This is particularly the case in highly urbanized regions, with high petrol and LPG consumption. For instance, Delhi, Goa, Lakshadweep, and Puducherry are all ranked in the top 33% across all human development parameters as well as per-capita energy consumption. Puducherry - for instance – has a higher per-capita energy consumption because of industrial consumption which is much higher than the national average (CRISIL, 2019a). Similarly, Goa has shown a very high urban electrification rate coupled with substantial urbanization (CRISIL, 2019b). However, this is not necessarily the case in all states. For instance, Kerala is ranked within the top 33% in all human development parameters and the highest in education and health parameters. This has largely been achieved through public spending on healthcare and education facilities. However, the per-capita energy consumption is approximately 10 GJ/

annum and the per-capita electricity consumption is 600 kWh/a, which are both lower than the national average (Kutty, 2000).

India's annual per-capita income has more than tripled from USD 1,786 PPP (INR 0.33 lakhs) in 1990 to USD 6,681 PPP in 2019 (INR 1.26 lakhs). The HDI formula uses a log of PPP values. Thus, the influence of income diminishes as a country/region moves from developing to developed. Hence, the states where income improvements could effectively lead to HDI improvements are states where the log of PPP value is less than 9 or, in other words, where per-capita income is less than USD 7,600/year PPP. These states include Bihar, Chhattisgarh, Jharkhand, Madhya Pradesh, Manipur, Meghalaya, Odisha, Tripura, Uttar Pradesh, and West Bengal. The UTs have the highest per-capita incomes, e.g., Chandigarh with over USD 16,000 PPP. For these UTs, the impact of income on the HDI values has stagnated and is not likely to lead to an increase anymore. One key opportunity here is that as women move into the workplace, their income increases will drive the increase in the national average. The trend is currently linear, with women income being 11% lower nationwide.

The average HI in 2019 was 0.80, while it was 0.77 in 2011. The HI is higher than HDI in most states, leading to a national average HDI of 0.645, because of the gains in life expectancy in India. India's life expectancy is 70 years, compared to 54 years in Sub-Saharan Africa. As these indices are calculated relative to the highest and lowest values, the HI shows improvement. The lagging states must work on improving the HI, but the overall national HDI may not improve much by improving the HI alone.

Assam, Bihar, Chhattisgarh, Jharkhand, Madhya Pradesh, and Uttar Pradesh are ranked in the lowest 33% in all individual parameters (HI, EI, II) and have energy consumption below 6 GJ/capita/person (the national FEC average was approximately 21 GJ/capita/year in 2019). The literature evidences that an electricity generation increase alone may not correspond to an HDI increase. Chhattisgarh, Rajasthan, Odisha, and Madhya Pradesh have a per-capita energy consumption of 77%, 68%, 56%, and 52%, respectively. Chhattisgarh's EI and II both increased by 0.06 points during 2011–2019.

A key observation regarding the decoupling of the HDI–energy linkage is seen in the case of northeastern states. Many of these states have achieved higher human development at comparably lower energy consumption (Table 2.2). For instance, Mizoram and Manipur were ranked among the top 33% of states among various human development parameters in 2011 and 2019. However, their per-capita energy and electricity consumption were ranked within the bottom 33%. The largest state in the region, Assam, has traditionally had low energy consumption as well as human development metrics (Nayak, 2012). It is likely that increased energy investments in these states may propel economic opportunities to increase the per-capita income, the key deterrent to HDI in this region.

Table 2.2: State-level data on HDI, HI, EI, II, energy, and electricity for 2011 and 2019

2011	Energy GJ/person/a	Electricity kWh/Person/a	HDI	HI	EI	II
Andaman and Nicobar Islands	17.04	491.35	0.7	0.86	0.57	0.7
Andhra Pradesh	12.94	1,291.15	0.59	0.74	0.47	0.59
Arunachal Pradesh	5.06	260.17	0.66	0.73	0.62	0.63
Assam	2.71	110.88	0.57	0.71	0.5	0.53
Bihar	1.64	53.63	0.52	0.7	0.42	0.47

2011	Energy GJ/person/a	Electricity kWh/Person/a	HDI	HI	EI	II
Chandigarh	17.21	1,269.24	0.64	0.82	0.5	0.65
Chhattisgarh	4.86	477.78	0.57	0.73	0.47	0.53
Dadra and Nagar Haveli	66.13	9,436.74	0.69	0.8	0.63	0.64
Delhi	14.73	1,255.47	0.71	0.79	0.64	0.71
Goa	38.05	1,906.15	0.75	0.83	0.68	0.74
Gujarat	14.38	893.67	0.61	0.74	0.49	0.63
Haryana	17.44	947.29	0.64	0.77	0.53	0.65
Himachal Pradesh	9.3	917.2	0.67	0.79	0.58	0.65
Jammu and Kashmir	4.87	322.03	0.65	0.78	0.56	0.63
Jharkhand	4.34	444.61	0.57	0.75	0.48	0.51
Karnataka	7.67	651.26	0.61	0.77	0.49	0.61
Kerala	7.75	436.39	0.72	0.86	0.65	0.67
Lakshadweep	16.85	458.18	0.71	0.82	0.6	0.73
Madhya Pradesh	4.17	348.76	0.54	0.69	0.44	0.52
Maharashtra	8.94	778.93	0.65	0.79	0.57	0.62
Manipur	1.87	94.93	0.7	0.79	0.66	0.65
Meghalaya	6.75	326.59	0.64	0.75	0.54	0.63
Mizoram	4.22	216.51	0.69	0.76	0.6	0.73
Nagaland	2.88	146	0.68	0.76	0.61	0.69
Orissa	4.4	312.08	0.54	0.71	0.44	0.51
Puducherry	56.57	10,496.55	0.74	0.83	0.68	0.71
Punjab	10.14	472.16	0.66	0.78	0.55	0.68
Rajasthan	5.11	191.09	0.55	0.72	0.42	0.56
Sikkim	8.39	2,145.38	0.64	0.8	0.54	0.6
Tamil Nadu	7.59	181.56	0.66	0.8	0.56	0.63
Telangana						
Tripura	1.49	356.55	0.62	0.76	0.56	0.55
Uttar Pradesh	2.68	65.56	0.54	0.67	0.46	0.51
Uttaranchal	9.76	1,298.71	0.63	0.77	0.55	0.6
West Bengal	3.27	143.51	0.58	0.76	0.47	0.53

2019	Energy GJ/person/a	Electricity kWh/Person/a	HDI	HI	EI	II
Andaman and Nicobar Islands	23.55	611.46	0.741	0.861	0.651	0.727
Andhra Pradesh	9.79	1,027.89	0.649	0.772	0.535	0.662
Arunachal Pradesh	7.67	284.63	0.661	0.807	0.547	0.653
Assam	3.97	204.63	0.613	0.751	0.541	0.567
Bihar	2.37	167.12	0.574	0.75	0.481	0.525

Chandigarh	20.55	1,325.02	0.776	0.82	0.726	0.785
Chhattisgarh	8.58	754.51	0.611	0.725	0.531	0.593
Dadra and Nagar Haveli	91.89	13,800.01	0.663	0.805	0.568	0.638
Delhi	16.59	1,558.93	0.746	0.814	0.675	0.757
Goa	29.71	2,387.39	0.763	0.85	0.68	0.767
Gujarat	19.36	1,502.53	0.672	0.784	0.556	0.698
Haryana	20.9	1,454.26	0.708	0.795	609	0.734
Himachal Pradesh	13.15	1,213.24	0.725	0.796	0.652	0.734
Jammu and Kashmir	7.04	693.25	0.688	0.802	0.586	0.694
Jharkhand	5.69	548.89	0.598	0.753	0.512	0.554
Karnataka	11.53	923.66	0.683	0.817	0.584	0.669
Kerala	9.62	599.89	0.782	0.86	0.725	0.752
Lakshadweep	11.1	669.55	0.751	0.825	0.683	0.752
Madhya Pradesh	6.34	667.44	0.603	0.73	0.509	0.592
Maharashtra	11.05	1,076.94	0.697	0.818	0.611	0.677
Manipur	3.99	198.28	0.697	0.822	0.668	0.617
Meghalaya	7.32	328.21	0.656	0.792	0.572	0.623
Mizoram	5.89	329.23	0.704	0.763	0.634	0.723
Nagaland	3.97	301.82	0.679	0.806	0.598	0.65
Orissa	6.88	417.91	0.605	0.755	0.518	0.566
Puducherry	22.87	1,877.55	0.74	0.834	0.671	0.724
Punjab	15.83	1,662.83	0.724	0.804	0.622	0.758
Rajasthan	8.58	742.31	0.628	0.763	0.505	0.643
Sikkim	9.65	551.97	0.717	0.825	0.616	0.723
Tamil Nadu	12.03	1,179.17	0.709	0.831	0.627	0.683
Telangana	12.81	1,482.77	0.669	0.786	0.564	0.675
Tripura	3.19	229.27	0.658	0.813	0.591	0.593
Uttar Pradesh	4.59	384.03	0.594	0.703	0.515	0.579
Uttaranchal	10.13	1,025.97	0.683	0.771	0.61	0.678
West Bengal	5.45	484.79	0.641	0.8	0.546	0.603

Data sources listed in Annexure 1.1

The data for 2019 has been validated against the State Energy Efficiency Index, BEE (2022)

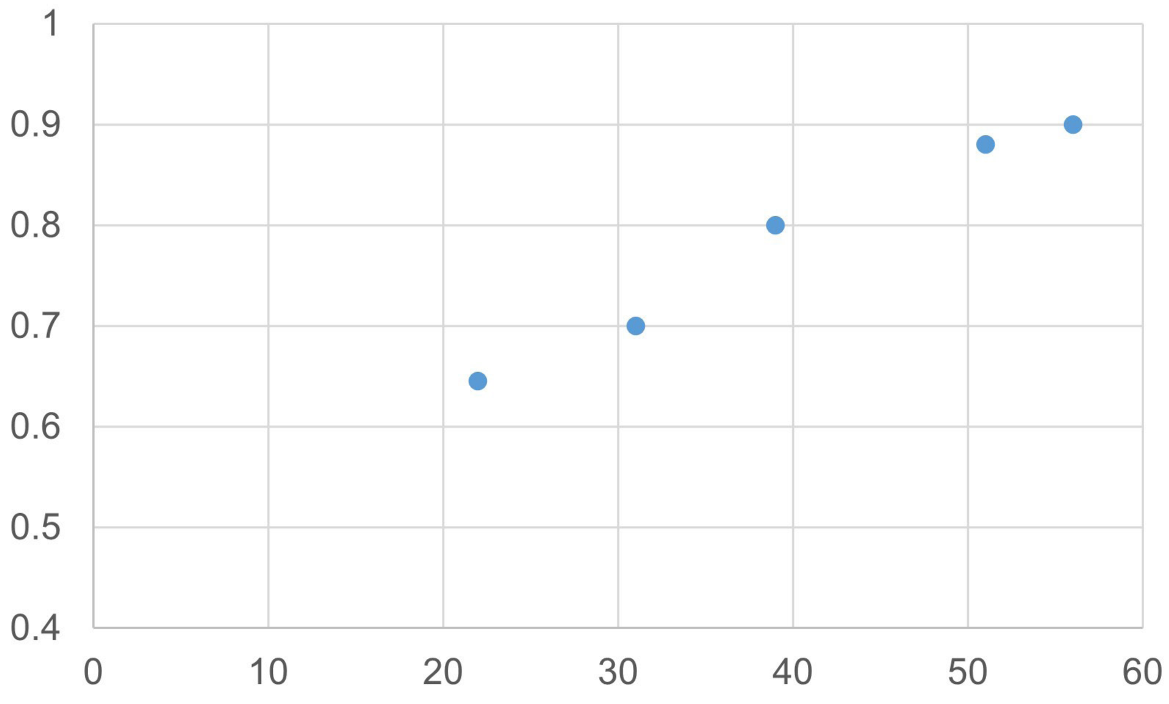
Many Indian states have been able to achieve high levels of HDI (0.7 and above) at much lower levels of energy of 10–15 GJ per capita annually (Rao et al., 2019) because of robust investments in healthcare and education. However, in later work, Millward-Hopkins et al. (2020) attributed these differences to different definitions of a "decent living standard" (DLS). On the basis of this, they conclude that an energy standard of 13–18.4 GJ per capita annually may be necessary. They also conclude that a lower DLS in some Indian regions may imply that some parts of the population are not receiving a threshold energy requirement. Finally, as several Indian states move to high and very high levels of HDI, key priorities are also changing.

Thus, here, a critical evaluation of the variable (income, education, or health) that leads to the highest optimal growth in human development at the lowest energy inputs has been performed.

2.4 How much energy do we need for development?

The assessments undertaken here suggest that for India achieving a high HDI is possible at 29 GJ/capita/year and that a very high HDI is possible at 37 GJ/capita/year (10,300 kWh/capita/year). Bhattacharya et al. (2022) concluded that a very high HDI might be achieved at an estimated 41.2–48.6 GJ/capita/year (11,000–13,000 kWh/capita/year). If we assume India's population to be 1.5 billion, this translates to total TFEC aspirations of 7,200 TWh in 2019 and 18,900–22,300 TWh/y by 2070. Estimates from our study indicate total TFEC aspirations of 15,400 TWh/y (@4% growth/year, possible by 2070). Similar estimates on TFEC by CEEW are 18,000–24,000 TWh/y. These differences may stem from electrolysis energy requirements for hydrogen generation and also different analytical formulations used across these studies. The assessments undertaken here also have sufficiency considerations, i.e., measures undertaken to avoid the demand for energy. Our work estimates a level of energy requirement for India that would be sufficient to achieve high HDI and very high HDI early but does not impose any direct upper bound on energy consumption per capita, which would depend upon the energy basket for achieving a NZ 2070 through our four alternate pathways in this report. Similar trends have been observed for the HDI and per-capita electricity consumption. Our regression results show that per-capita FEC would be 31 GJ/year, 39 GJ/year and 56 GJ/year for reaching HDI of 0.7, 0.8 and 0.9. Considering a population of 1.5 billion by the mid-century, this translated to 14,000-18,000 TWh/year for an HDI of 0.8 and 19,000-23,000 for an HDI of 0.9 (Figure 2.3). Future scenarios discussed in Chapter 3 may have variable uses of energy carriers such as hydrogen. This would mean that the energy requirement would be highly influenced by electrolyzer efficiency, and also the dominant form of hydrogen production (nuclear, renewables or fossil fuels with CCUS).

Figure 2.3: Threshold FEC for target HDI levels compared to current HDI of 0.645



IPCC AR6, 2022 (Clarke et al., 2022, pp. 613–746) results show that even if the FEC remains the same, a higher share of electricity in the FEC results in a greater HDI. Thus, electricity access to all and average consumption levels (affordability) become important here. India's contribution of electricity to the FEC is currently close to 18%, compared to 21% for the USA (https://yearbook.enerdata.net/; WEO, 2020). Therefore, as greater electrification occurs (especially in Bihar, Uttar Pradesh, Madhya Pradesh, Rajasthan, and Assam—states currently with high population and low energy access), there is an opportunity to improve the national HDI to 0.7 by 2025, 0.805 by 2035–40, and 0.9 by 2045–50. Doubling the electricity per capita/year consumption could lead to an increase in the HDI by at least 0.2 points in the next five years in Bihar, where per-capita electricity consumption is also very low, i.e., <200 kWh/year.

Moreover, the most "bang per buck" spent may be obtained by investing in education in Bihar, Chhattisgarh, Madhya Pradesh, Jharkhand, Odisha, Rajasthan, Uttar Pradesh, and West Bengal, along with several north-eastern states, as these states are in the "elastic" range of growth for education.

The energy linkage with GDP may not be considered exact because of large-scale trade of products as well as remitted wages for several Indian states (e.g., Kerala). In 2011, the value of imported goods to the GDP was 31% which reduced to 21% in 2019. While some of these are in the form of energy/fuel imports that are accounted for by the PPAC source, others such as materials are not accounted for in this analysis. To disaggregate this, Akizu-Gardoki et al. (2018) have showed the decoupling of energy footprint and HDI—permanent or temporary—in 89 countries. However, they have concluded that decoupling is more difficult for India as it is a net-exporter country in terms of embodied energy (only 14% such countries have shown decoupling). To carry out this analysis, we would require detailed state-specific economic input-output tables and its characterization factors to life cycle inventory. A subset of that data is available from the Reserve Bank of India, which may be adapted in future work but its conversion may be difficult because the trade metrics vary (21 metrics by the RBI and 26 metrics internationally).

Chapter 3:

Climate Change, Energy Profile, and NZ Futures

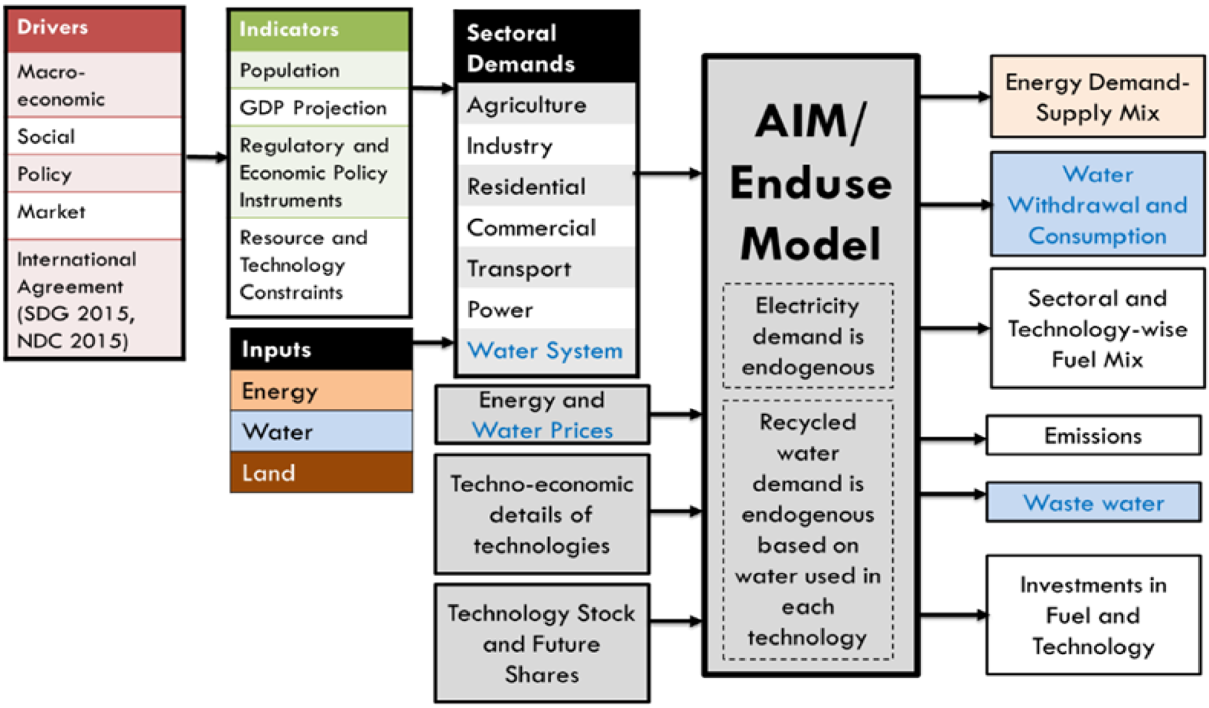
3. Climate Change, Energy Profile, and NZ Futures

The national energy system can be divided into three parts: primary energy supply, secondary conversion processes, and FEC in demand sectors. This chapter provides a description of the energy systems' analytical framework using the Asia-Pacific Integrated Model (AIM)/Enduse-India and TIMES-India models to evaluate the energy demands, technology–fuel mix, and emission intensity under the current policies and alternative deep decarbonization scenarios.

3.1 Modeling framework

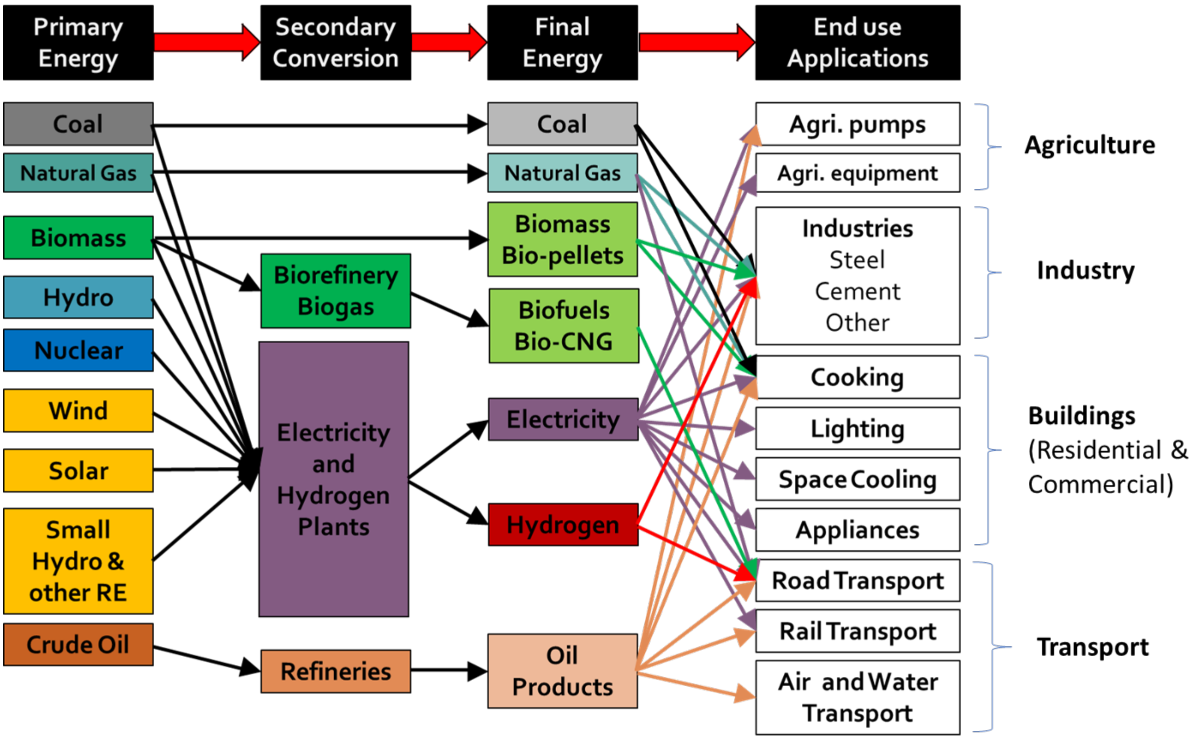
We used the AIM/Enduse-India model (Figure 3.1) to capture the energy and environment systems of major sectors in India to observe the impact of multiple objectives (energy and climate security) of existing and future policies (energy efficiency, addition of renewables), energy supply (power), and end-use sectors (industry, etc.). The model provides a techno-economic perspective at the national level with sectoral granularity. It has been developed to report primary and final energy mixes, emissions from the energy system, electricity generation capacity additions, and related costs for various sectors (Vishwanathan et al., 2017, 2018; Vishwanathan & Garg, 2020). For this study, we have extended the model to 2070. The model has been set up for five major sectors (energy supply, agriculture, industry, buildings, and transport) along with their respective services, technologies, and discount rates. Electricity demand is endogenously estimated in the model. So, the model estimates sector-wise end use demands and selects the set of power technologies based on economics, technical efficiency, and capacity constraints. The model has been calibrated from 2000 to 2015 and runs in annual time steps until 2070.

Figure 3.1: Modified AIM/Enduse Water–Energy–Land (W-E-L) modeling framework



We have also used the TIMES-India model (Figure 3.2) to authenticate and verify the results from the AIM/Enduse-India model and to estimate the LCOE, including its fixed and variable costs, in all the seven scenarios (explained in detail in subsequent sections).

Figure 3.2: TIMES-India Reference Energy System (RES)



Source: Adapted from Patange, 2022

3.2 Scenario description

Emissions are the product of complex dynamic energy systems driven by forces such as demography, socio-economic indicators, technology development, lifestyle changes, in addition to rural and urban transformations. While the evolution of emissions projections for India in the past has been linear, however the future scenarios will be highly uncertain. A 'scenario is a coherent, internally consistent, and plausible description of a possible future state of the world. It is not a forecast; each scenario is one alternative image of how the future can unfold' (IPCC, 2000). It should be noted that this study is academic in nature meant to explore a range of scenarios based on certain modelling and policy assumptions. These are not policy prescriptive. The study does not predict India's emission pathways as there are varied dynamic forces at play at national as well as global level.

To complement the energy modelling we undertook additional modelling to project the future load curves. The model uses annual maximum demand only for two years – 2030 and 2070. For 2030, the demand is in line with that of CEA, 20th EPS and Draft NEP as outlined in the document. For 2070, the two scenarios have been worked out based on EPS CAGR. The technology capacities have been derived from the energy model based on technology selection. The load curves are created to provide a sense of proportion. For 2070, it is mentioned that these are policy indicative and not policy prescriptive. The detailed methodology for load curve modelling is described in Annexure 5. Section 5.2 (Balancing Load and Supply) of the Annexure 5, provides the explanation of how we estimate the future load curves for each technology and how these are aligned with the energy model.

For this study, we have attempted to map out India's future energy requirements under seven alternate scenarios. These scenarios include three NDC commitment scenarios with three separate economic growth trajectories—low-economic-growth scenario (NDCL), medium-economic-growth scenario (NDCM), and high-economic-growth scenario (NDCH)—and four NZ 2070 scenarios—NZ 2070 with a thrust on nuclear power (NZ1), NZ 2070 with a thrust on fossil fuels with CCUS (NZ2), NZ 2070 scenario with a thrust on RE (NZ3), and integrated NZ 2070 scenario (NZ4). All four NZ scenarios take medium economic growth GDP projections (Section 3.3).

3.2.1 NDC scenarios

The NDC scenarios consider ongoing developmental policies along with mitigation and adaptation strategies mentioned in the National Action Plan for Climate Change (NAPCC) (MOEFCC, 2008) and NDC (MoEFCC, 2015, 2021). They assume the continuation of energy, forestry, agriculture, industry, transport, and climate policies since 2000. The scenarios adopt short- and medium-term policy interventions related to energy, technology, and services in every major sector. They consider India's contributions in response to the COP decisions 1/CP.19 and 1/CP.20 from 2021 to 2030 in every major sector. The scenario results in a reduction of emission intensity by 33–35% in 2030 from the 2005 level and sets a target of attaining 40% of energy from renewable sources by 2030 by enhancing the existing policies in selected priority areas (MoEFCC, 2015), including the following:

- Introducing new and efficient technologies in the power sector (thermal power plants
- Promoting RE generation and increasing the share of alternative fuels in the overall fuel mix
- Reducing emissions in the transportation sector
- Promoting energy efficiency in industry, transportation, and building sectors

The model is set up for energy supply (power) and four major end-use sectors, along with their respective services, technologies, reference years, and discount rates. These sectors include agriculture, power, industry, and buildings. The maximum shares for the base year are taken from various government and research publications. We estimate the shares for the projected years on the basis of population, economic growth, and sectoral transformation and using current policies. Various driving forces influence water supply and demand for a service, which include sectoral demand (population and economic growth) and a set of technologies (new, improved, replacement).

The low economic growth scenario is an exploratory scenario with an assumption of overall CAGR of 4.45% between 2020 and 2070 (the growth rate is lower than 4% between 2040 and 2070). Each of the sectoral energy and electricity demand is estimated based on the low economic growth rate assumed for this scenario. Hence, there is reduced demand of electricity based on the decreased sectoral demands when compared with medium and high scenarios. Again, these demands are not based on growth predictions but are plausible projections of an assumed low growth scenario. The study does not claim the model outcome as a predictions/probabilistic outcome.

3.2.2 NZ scenarios

On November 2, 2021, the Honorable Prime Minister of India announced India's NZ 2070 targets at COP26 (Glasgow). The normative NZ scenarios present a narrow but achievable pathway for India's energy sector to achieve NZ CO_2 emissions by 2070. These scenarios are designed to simultaneously meet key energy-related United Nations SDGs, in particular by achieving universal energy access by 2030 (SDG7), major improvements in air quality (SDG

3), and meeting the climate change agreements (SDG13). For India, this is consistent with limiting the global temperature rise to 2 °C and below 2 °C without a temperature overshoot (with a 50% probability), in line with reductions assessed in the latest IPCC WGIII AR6.

There are many possible paths that can be taken to achieve NZ 2070 CO_2 emissions at a national level; however, there exist barriers and uncertainties that may affect them. For India, a lot will depend on the pace of innovation in emerging technologies, the extent to which citizens are able or willing to change their behavior, the availability of sustainable alternatives in addition to the extent and effectiveness of technology transfers and support, financial investments, and capacity building through international cooperation. In this study, the NZ scenario pathways assume the deployment of optimum available technologies and mitigation options dictated by costs, technology maturity, policy preferences, and the market on the basis of India's socioeconomic conditions. We have analyzed four different pathways focusing mainly on the power sector, which is the main subject of this study.

a) NZ 2070 with a thrust on nuclear power (NZ1): This scenario follows the Paris Agreement targets. It assumes the expansion of nuclear capacity over the years. Meanwhile, for coal-based plants (includes lignite), we assume i) the retirement of old, inefficient thermal plants, ii) retrofitting of young power plants, and iii) the addition of CCUS based on geophysical-economic feasible conditions for existing coal-based capacity.

b) NZ 2070 with a thrust on fossil fuels with CCUS (NZ2): This scenario follows the continuation of coal use with new capacity assumed to be supercritical and ultra-supercritical boiler technologies deployed along with CCUS facilities. We also assume i) retirement of old, inefficient plants, ii) retrofitting of young power plants, and iii) higher decarbonized electrification in industry, transport, and building sectors. This scenario considers hydrogen production as well.

c) NZ 2070 with a thrust on RE (NZ3): In this scenario, we follow the Paris Agreement targets and assume additional growth of renewables with storage. Flexible operating capacities are assumed to handle VRE across the grid with storage capacities. No new coal technologies are installed after 2020. We assume i) retirement of old, inefficient plants and ii) retrofitting of young power plants with CCUS.

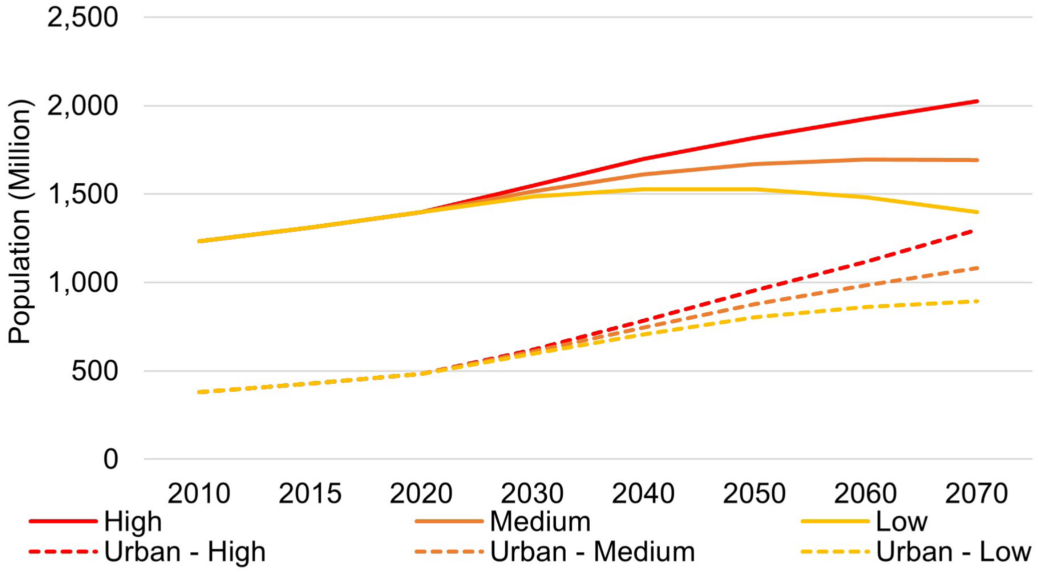
d) Integrated NZ 2070 scenario (NZ4): This scenario is an extension of NZ3, assuming some fossil fuel phase down across all sectors.

Further details on the model inputs are available in Annexure 2, and modeling formulations for AIM/Enduse-India and TIMES-India models are in Annexures 3 and 4, respectively.

3.3 Scenario drivers

We use a top-down method to estimate the service demand on the basis of population, GDP, and urbanization rate. The details on the population profile and GDP are provided below. We follow the future projections for population and urbanization presented in the UN Population Database, 2022 (Figure 3.3).

Figure 3.3: India population and urbanization projections



Note: The dotted lines represent the rate of urbanization, and the solid lines represent the population growth.

Source: UN Population Database, 2022

The model estimates electricity demand based on the technologies selected in each sector. The technology selection is based on a combination of technical efficiencies, technology costs, energy prices and energy constraints in the model. The sectoral demand (agriculture demand, industry demand, transport demand, building energy demand) in each sector is calculated exogenously based on gross-value added estimates of each sector. We have assumed the mitigation policies across three economic growth scenarios— high, medium, and low—to capture the country's economic growth (Figures 3.4 and 3.5). We have assumed the mitigation policies across three economic growth scenarios— high, medium, and low—to capture the country's economic growth (Figures 3.4 and 3.5).

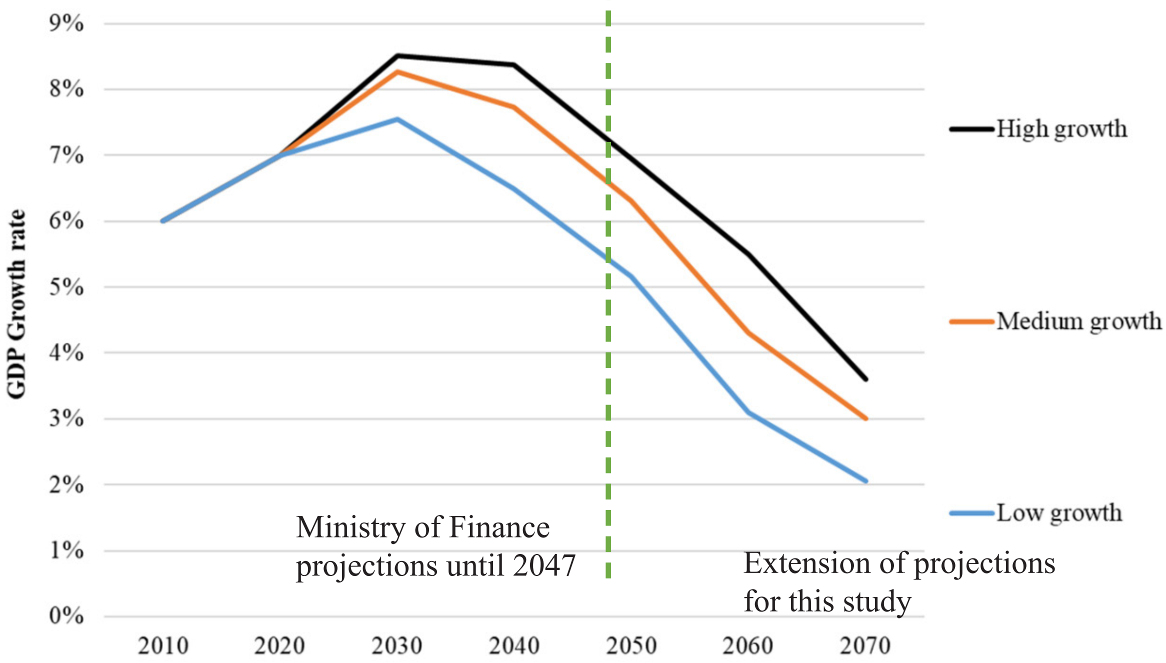
a) NDC high (NDCH): The NDCH growth scenario follows high growth rates of approximately 8% and 6% between 2020 and 2030 and between 2030 and 2040, respectively, which lower to 4% between 2040 and 2070. Overall, the compound annual growth rate (CAGR) between 2020 and 2070 is at 5.1%.

b) NDC medium (NDCM): The NDCM growth scenario follows a slightly high growth rate of approximately 7% between 2020 and 2030, followed by a medium rate of 6% between 2030 and 2040, which lowers to 4% between 2040 and 2070. Overall, the CAGR between 2020 and 2070 is at 4.8%.

c) NDC low (NDCL): The NDCL growth scenario follows low growth rates of approximately 6.1% and 5.2% between 2020 and 2030 and between 2030 and 2040, respectively, which lowers to 3.5% between 2040 and 2070. Overall, the CAGR between 2020 and 2070 is at 4.45%.

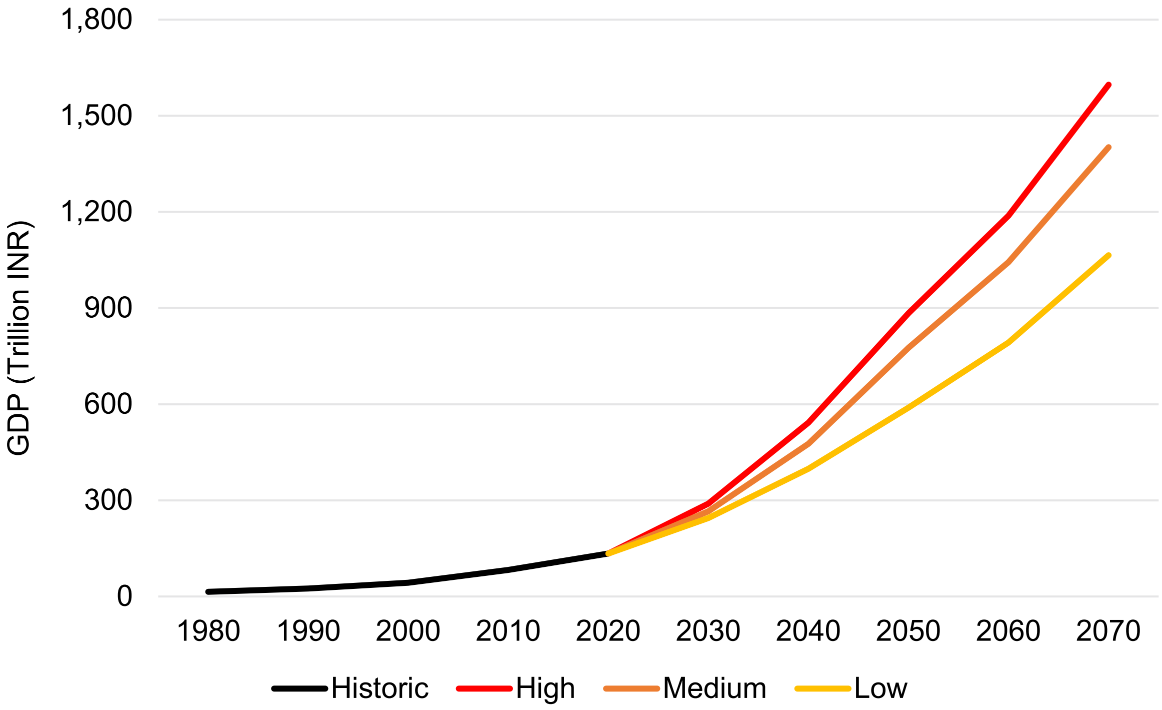
Sectoral demand may increase or decrease according to the market environment and customer demand. Historical trends have shown a decline in the share of the agriculture sector from 60% in 1950 to 14% in 2015–16 of the overall GDP and an exceptional rise in the service sector to 64% in 2015–16. The share of the industry in GDP is projected from the logistic regression of the past data and by assuming a long-run saturation level of 29–31% in 2050. Next, with the help of a similar logistic regression, the projection for the service sector is made in terms of its share in the balance future trajectory of non-industrial GDP (assuming a long-term saturation share of 61–63%). Branching in this manner ensures consistency with the total GDP and industry GVA projections. The share of transport in the balance non-industrial and non-commercial GDP is then projected in a similar way (assuming a 25% long-term saturation share). The projections for the GVA in the agriculture sector are automatically obtained as the final balance. To counter-validate for consistency, the projections for the net-irrigated area are made separately using logistic regression of past data. These are checked for correlation with the projections for the agriculture GVA.

Figure 3.4: Annual growth rate until 2070



Source: Ministry of Finance until 2047 (extended until 2070)

Figure 3.5: GDP projections used in this study



The industry sector constitutes seven energy-intensive aluminum, cement, chlor-alkali, fertilizer, iron and steel, paper and pulp, and textile plants, in addition to other manufacturing units. The share for agriculture is assumed to decrease in the next decade, while that of the industry will increase. Use of energy plantations and modern agriculture (e.g., biofuels, biogas, biochar etc.) would grow instead of biomass remaining as traditional use for cooking. The services share of GDP may slightly increase. These driving forces influence a combination of parameters based on which supply and demand for a service can be determined.

The model selects a set of energy technologies to minimize the total annual cost of fulfilling energy service demand while taking into account energy and emission constraints, technology diffusion, and other factors. The payback period represents the time required for the return on an investment, such as energy savings, to break even against costs such as capital costs, operational costs, maintenance costs, overhead costs, and other costs. The model considers technological changes such as 1) the recruitment of new technology at the end of the service life of older technology or to meet the increase in service demands, 2) improvements in the energy efficiency of existing technology, and 3) the replacement of existing technology with new technology, even if the existing technology remains in service but is stopped immediately because the new technology is due to a policy or is more cost-effective.

Sectoral demands considered here are for the following:

1) Industry

   The industry is divided into sub-sectors, viz, steel, aluminum, cement, paper and pulp, textiles, fertilizers, caustic soda, soda ash, and other industrial sub-sectors. This segregation is based on the energy-intensive industries selected in the PAT scheme.

2) Transport

   Passenger transport and freight transport across modes have been considered here.

3) Buildings

   For this study, household energy consumption is based on the following categories: cooking, lighting, cooling appliances, and others, including refrigeration and information and communication technology (ICT) services.

4) Agriculture

   Indicators such as yield change, water and energy needs for cultivation, the area under cultivation, and fertilizer use efficiency have been considered here.

Chapter 4:

SHORT-TERM RESULTS AND IMMEDIATE OPPORTUNITIES (UNTIL 2030)

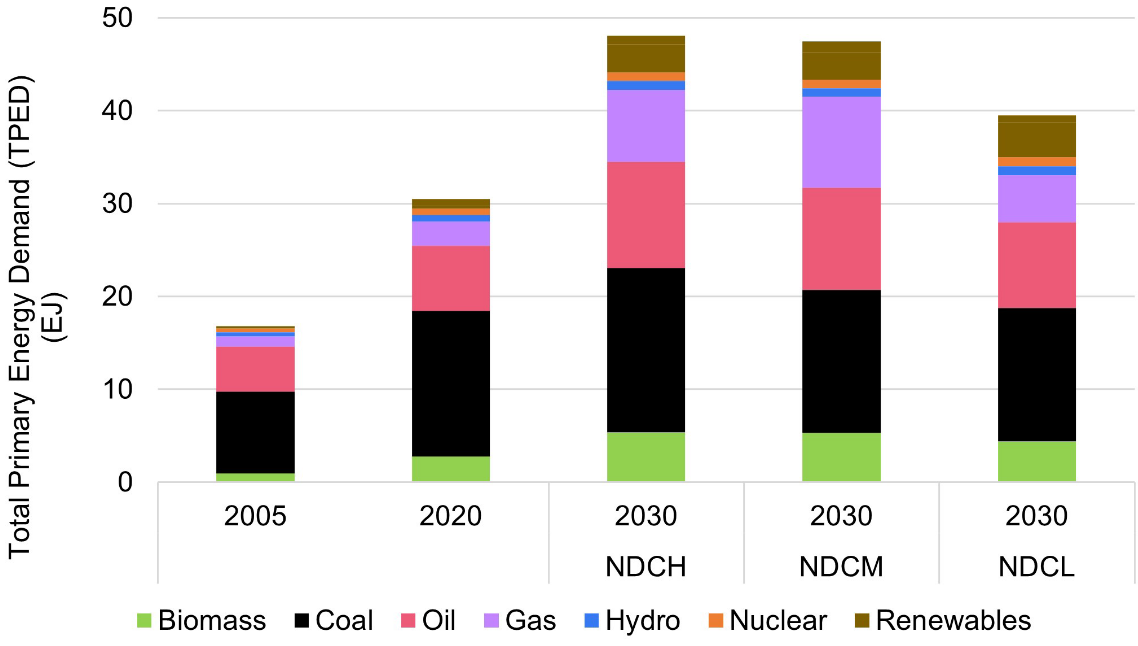
4. Short-Term Results and Immediate Opportunities (Until 2030)

This chapter presents an overview of the total primary energy demand, required power supply, the FEC in end-use sectors, and subsequent CO_2 emissions in the current decade under low, medium-, and high-economic-growth scenarios. It also illustrates the load curves and required grid flexibility, as well as the role of biofuel in these scenarios. We have further discussed the Kaya identity and India's performance to meet the updated NDC targets committed at COP26 in Glasgow.

4.1 Total primary energy demand (TPED)

We have projected the total primary energy demand under three economic growth scenarios (high, medium, and low) while considering the impact of policy response to energy security and economic uncertainty. India's economy rebounded strongly after the economic crisis of the COVID-19 pandemic in 2021. Primary energy growth is set to increase at a CAGR of 4.9% in the high-economic-growth scenario, 4.7% in the medium-economic-growth scenario, and 2.8% in the low-economic-growth scenario by 2030. Figure 4.1 presents the total primary energy demand by fuel in all sectors under NDCH, NDCM, and NDCL growth scenarios in the short term. The high-growth scenario focuses on increasing demand, which is met by the coal-intensive power sector. The medium- and low-growth scenarios are supported by coal (includes lignite), oil, and gas.

Figure 4.1: Total primary energy demand by fuel under NDCH, NDCM, and NDCL growth scenarios in the short term



The primary energy sources are consumed in the demand sectors (agriculture, industry, transportation, and buildings) either directly or after conversion into electricity. In all three scenarios, around 60 per cent of the energy demand is from the industry sectors, followed by the transport (17-18%), buildings (16%), and agriculture (5-6%) sectors.

4.2 Electricity generation capacity (GW)

As of January 2023, India's total power-generating capacity was 412 GW, with about 51.2% of coal-based thermal plants, 6% of natural-gas-based power plants, 11.3% of large hydro (includes pumped storage), 1.6% of nuclear, 10.1% of onshore wind, 15.5% of solar, and the remaining of bio-power and small hydro (CEA, 2023a). India's electricity generation has increased with an annual average growth rate of 5% between 2011 and 2021. As of May 2022, India's power generation was at 1,688 TWh, of which thermal (coal, gas, diesel) share was 74%, followed by large hydro at 9.3%, nuclear at 2.6%, and renewables at 13.6%. The PLFs of thermal power and nuclear plants were at about 56% and 81%, respectively (CEA, 2022). In 2018–19, the industrial sector consumed 43% of the electricity produced, followed by residential at 24%, agriculture at 17.6%, and the remaining share by transport (railways), public lighting, and others (CEA, 2020b).

India is the third-largest consumer of energy in the world, but its per-capita electricity consumption of 1,255 kWh/capita/year was way below the global average of 3,495 kWh/capita/year in 2021. India has the second-largest coal-based generation capacity after China. In 2019, while 100% of villages in India were connected to grid power, about 3% of the population lacked electricity access, and electrified cities/villages have reportedly suffered frequent power outages. The activity in India's power and refinery sectors is driven by increasing production to meet rising consumption and urbanization. Coal has fueled India's rapid increase in energy and electricity use in recent decades; however, India is now quickly expanding its renewable capacity as well. Current clean coal policies include 1) renovation and modernization (R&M) and life extension (LE) of existing old power stations, 2) retirement of old, inefficient power plants, and 3) addition of supercritical generation. This is in addition to ambitious renewable targets that have accelerated from 175 GW by 2030 in 2015 to 500 GW by 2030 in 2021 (CEA, 2021; UNFCCC, 2015).

Figure 4.2 and Table 4.1 present power generation capacity under high-, medium-, and low-growth scenarios until 2030. The annual growth rate in generation capacity between 2020 and 2030 is estimated to be 4.4% in the high-economic-growth scenario, 3.5% in the medium-economic-growth scenario, and 1.8% in the low-economic-growth scenario. In the high-growth-rate scenario, we observe the installation of CCUS technologies in coal and gas, while in the medium-growth-rate scenario, CCUS remains at a small scale. In the low-growth-rate scenario, with comparatively lesser energy demand, both coal and renewable capacities remain low as compared to the other two NDC scenarios.

Figure 4.2: Electricity generation capacity under NDCH, NDCM, and NDCL growth scenarios in the short term

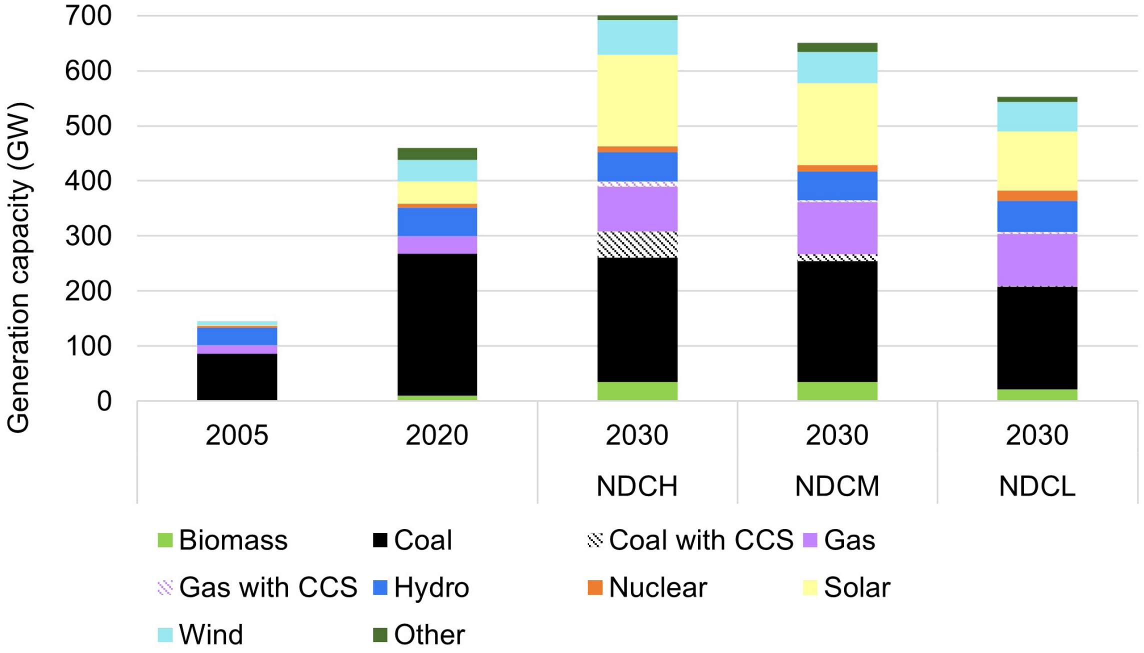


Table 4.1: Electricity generation capacity (in GW) under NDCH, NDCM, and NDCL growth scenarios in the short term

Scenario			NDCH	NDCM	NDCL
Year	**2005***	**2020****	**2030**	**2030**	**2030**
Biomass	1.1	10	34.38	34.85	22
Coal (includes lignite)	71	206	227	220	186
Coal with CCUS	0	0	47	12.5	1.83
Gas	16	25	81.68	95	95
Gas with CCUS	0	0	9.68	3.18	2.48
Hydro (includes pumped storage)	32	51	53.15	52.57	57.31
Nuclear	3.36	6.7	11	11	17
Solar	0.5	37	166	149	108
Wind	7	39	63	58	53
Other	0	1	19	15	10
Total	131	375	712	653	553

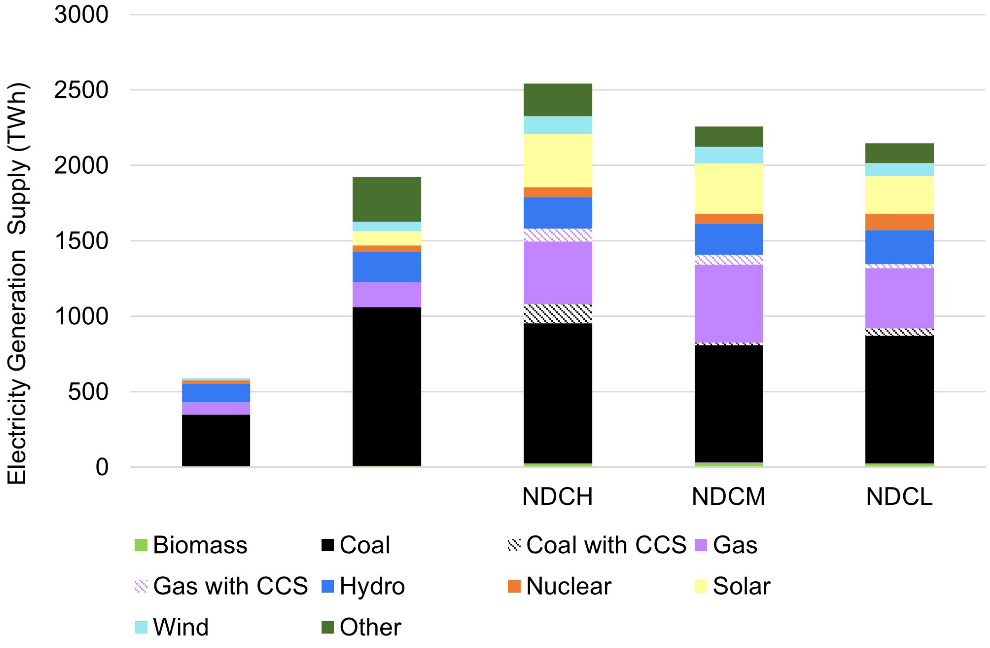
Note: ** Numbers are based on the Energy Statistics 2007 for financial year 2005-06 and Growth of Electricity sector in India, CEA, 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at around 14 GW.*

*** Numbers are based on CEA's General Review 2022 and installed capacity reports upto December 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at 47.8 GW.*

4.3 Electricity generation (TWh)

Figure 4.3 shows the trend and share of electricity generation from different growth sources until 2030. Between 2020 and 2030, the annual growth rate in electricity generation is estimated to be 2.8% in the high-economic-growth scenario, 1.6% in the medium-economic-growth scenario, and 1.1% in the low-economic-growth scenario. The coal share in electricity generation is projected to decrease from 71% in 2005 to 36%, 35%, and 39% in 2030, while the share of renewables is expected to increase from 4% in 2005 to 27%, 26%, and 22% in 2030 in high-, medium-, and low-growth scenarios, respectively. Natural gas, hydro, and nuclear power are expected to provide the required base load for renewable expansion.

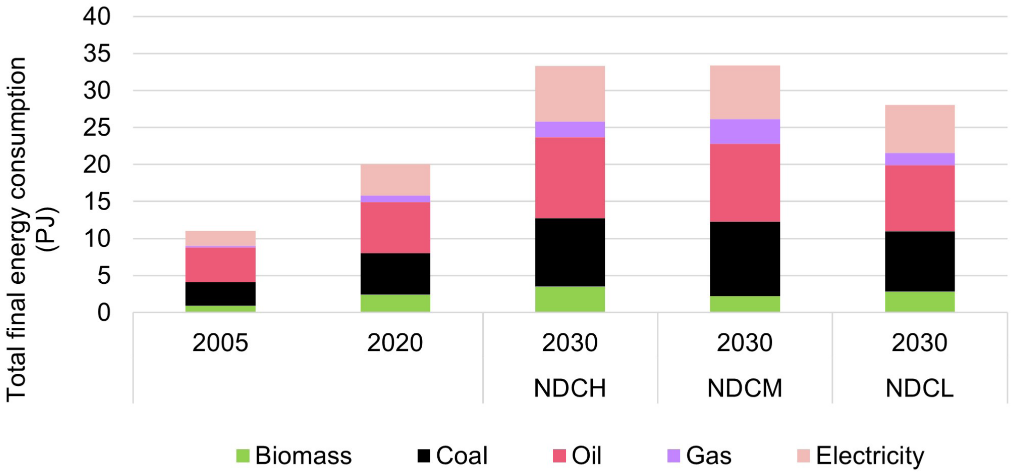
Figure 4.3: Electricity generation supply under NDCH, NDCM, and NDCL growth scenarios in the short term



4.4 Total FEC

The economy-wide FEC increased from 11 EJ in 2005 to 27–33 EJ in 2030 under different growth scenarios. Figure 4.4 presents the total FEC under NDCH, NDCM, and NDCL growth scenarios. Most of the coal is used in the industry sector for energy and industrial processes. Oil is primarily used in the transport and industry sectors, followed by the building and agriculture sectors. Natural gas is consumed by the industry sector, followed by the transport and building sectors. Electricity is majorly used by the building sector in 2030, followed by the industry, transport, and agriculture sectors. Electricity demand increases to 21–24% of FEC in the NDC scenarios in 2030. Agriculture, industry, transport, and building sectoral shares are observed to be approximately 5–6%, 60–62%, 17–18%, and 15–16%, respectively, under NDC growth scenarios in 2030.

Figure 4.4: Total FEC across sectors under NDCH, NDCM, and NDCL growth scenarios

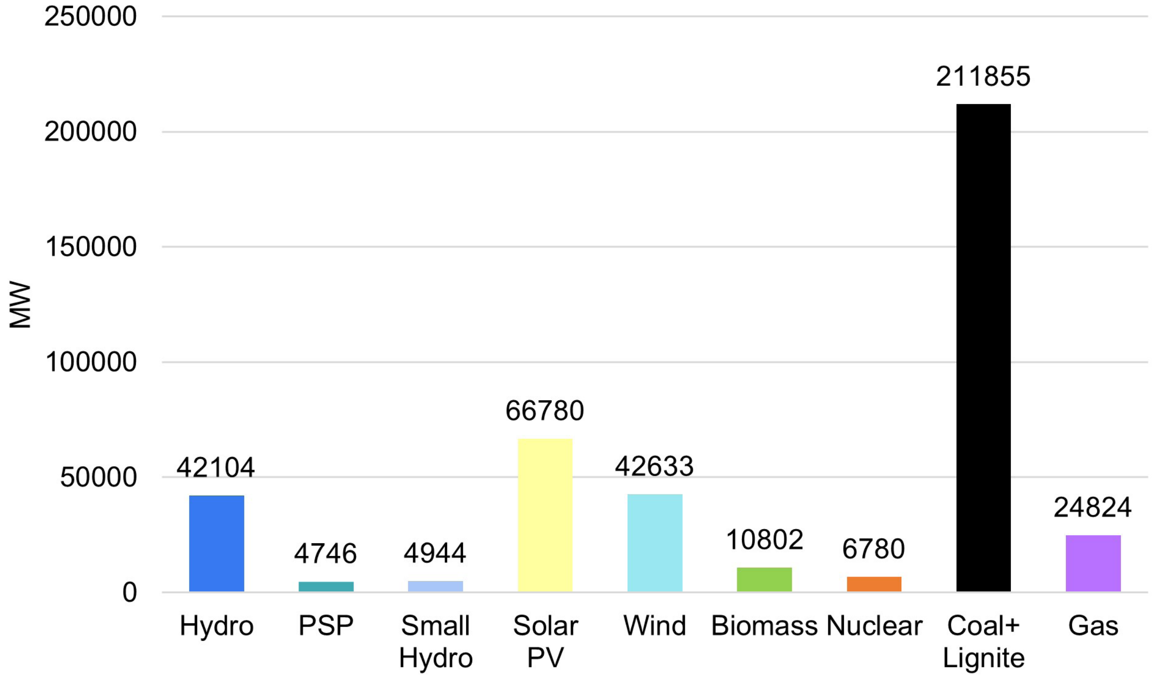


4.5 Load curves and grid flexibility

Power systems require a precise balance between demand and supply. Policy encouragements and mandates entail the running of RE generators with conventional generators such as coal, nuclear, and others serving the net/residual load. This arrangement includes variability from both the supply side due to RE generation and the demand side.

The experience of power grids around the world that have been aggressively expanding RE has revealed that operating the grids beyond 20% penetration of RE sources poses a significant challenge. As the amount of VRE sources interconnected to the system increases, the net load curve assumes a characteristic duck-shape, with a decrease during the day and a steep increase in the demand profile in the evening, making it challenging to maintain the generation–load balance. This leads to the need for capacities (current capacity as shown in Figure 4.5) that can be quickly ramped up or down to match the net load curve and maintain grid balance. In various projections, a maximum ramp-up rate of 379 MW/min and a maximum ramp-down rate of 422 MW/min have been reported for 2021–22 (CEA, 2019).

Figure 4.5: Installed capacity as of March 31, 2023



Note: Hydro Excludes 2136 MW of Hydro imports from neighboring countries and 589 MW Diesel based capacity

Source: Report on Optimal generation capacity mix for 2029-30 Version 2.0, Central Electricity Authority (CEA), MoP, April, 2023 (CEA, 2023a)

The variability of RE can be attributed primarily to three sources: variability over time of the day and across seasons, the uncertainty of outputs, and the specificity of location. The conventional generation sources are not designed to be flexible enough for their outputs to be adjusted in real time with system requirements, i.e., ramped up or down frequently because of efficiency and equipment constraints.

Several studies have examined grid operations, some from the technical stability point of view and others from the perspective of fuel mix optimization. The results from such studies necessarily do not converge because of the variation of time-based data sets—some use limited data, others use simulated data and various load profiling techniques. Also, studies include those with a technological focus and those exploring cost and financing.

Additionally, various types of models may be classified as a) investment models, b) operational models, c) soft-linked investment and operational models, d) operational models with investment rules, and e) optimization of investment and operations. This study does not look at investments as capacities across various scenarios. Given the capacities, the study examines VRE integration issues with the growth of renewables.

Though projection models vary in complexity levels, the main differentiating factor is the data used for these models. Several studies use solar or wind profiles procured from satellite data from NREL studies (Palchak et al., 2017), while others use profiles based on actual data. Some studies have noted differences between the two sources (Tongia, 2022). See Table 4.2 for a summary of relevant studies in the Indian context.

Table 4.2: Actual capacity (March 31, 2023) and projected capacity in 2030 in GW

Source	Capacity (as of March 31, 2023)	SCE, 17th Lok Sabha/ CEA	NREL	BNEF	TERI	LBNL
	2023	2022	2030	2030	2030	2030
Solar	66.78	280	250	204	229	307
Wind	42.64	140	200	109	169	142
Other RE	15.75	15				
Hydro	42.1	61	54	81	84	62
Coal (includes lignite)	211.85	267	170	234	238	229
Natural gas	24.83	25	49	25	25	25
Nuclear	6.78	19	11	33	17	19
Subtotal	410.73	807	734	686	762	784
Battery storage	0	27 (4 h)/108 GWh	16 (2 h) 68 (4 h)	N/A	60 (2 h)	15
Pumped storage	4.75	10	2	0	0	63/252 GWh
Load shifting		0	0	0	0	60
Total	415.47	844	804	686	822	862

Sources: 1) MNRE, Standing Committee on Energy (2021-22), 17th Lok Sabha, 2022

2) Palchak et al. (2017)

3) CEA (2020); CEA. (2023a)

4)Tongia (2022)

5) Abhyankar et al. (2021)

The above projections have divergences, especially between the CEA and BNEF scenarios. However, all these projections point to the increasing share of renewables and the issues that may arise for grid integration. The increasing share of renewables is the result of policy initiatives that are also mentioned in the Draft National Electricity Plan, which was released in September 2022 and projects the following capacities in 2031–32, as described in Table 4.3.

Table 4.3: Projected capacities in 2031–32 in GW

Source	Draft National Electricity Plan (GW)	Optimal Energy Mix 2030 (GW)
Solar	333	292.56
Wind	134	99.89
Other RE	19	19.85
Hydro	64	53.86
Coal	249	251.68
Natural gas	25	24.83
Nuclear	22	15.48
Subtotal	847	758.14
Battery storage	52	41.65
PSP	19	18.9
Total	917	777.14

Source: Central Electricity Authority, Ministry of Power, GoI, September 2022 ; CEA (2023a)

This study considers the estimates of the Standing Committee on Energy (SCE, 2021–22), 17th Lok Sabha, as a basis for ascertaining capacities in 2030, and these estimates are also similar to those in the draft NEP adjusted for the time between 2030 and 2031–32. The study selects this as the most acceptable estimate in the current time frame. The total projected capacities are within a similar range excepting Bloomberg's New Energy Outlook (BNEF) 2021. Notably, the study by the Lawrence Berkeley National Laboratory (LBNL) estimates possible load shifting by 60 GW in the agriculture and industrial sectors.

On the basis of load profile data, projected installed capacity and load, and other influencing parameters, future load curves are projected incorporating RE load, nuclear load, and baseload/peak load schedules. The study follows a four-step process:
1) Projection of demand using time series data
2) Load profile development for RE
3) Developing constituents of the load curve
4) Developing scenarios

See Annexure 4 for the detailed methodology.

Principles of economic dispatch considering load characteristics such as peak/base load have been explored subject to constraints of availability, ramping, other constraints, and constraints from bottom-up models. Load profiling for various types of loads and alignment with technology/fuel mix and cost data have been conducted. Scenarios have been developed in alignment with NDCH, NDCL, NDCM, NZ1, NZ2, NZ3, and NZ4, with projected peak demands until 2029–30.

The study uses maximum demand met and load data from various reports of POSOCO, CEA, and other sources. It also aligns peak load projections of EPS and CEA until 2029–30. In addition, it uses constituent load profile data from the Ministry of Power's MERIT[8] database. Load profile data is also available at IEA,[9] but the data cannot be downloaded.

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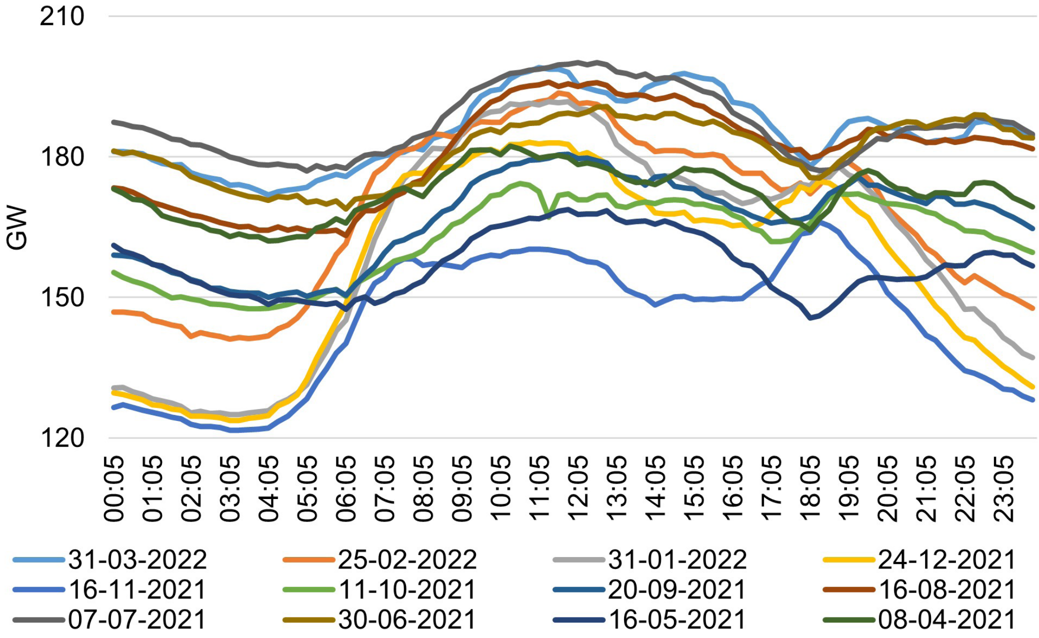
[8] Ministry of Power, GoI. (n.d.). https://meritindia.in/

[9] IEA. (2022, May 9). Real-time electricity tracker. https://www.iea.org/reports/real-time-electricity-tracker?utm_content=buffer58468&utm_medium=social&utm_source=linkedin-Birol&utm_campaign=buffer&tracker=true&from=2022-7-19&to=2022-8-18&category=demand&country=IND#more-european-union

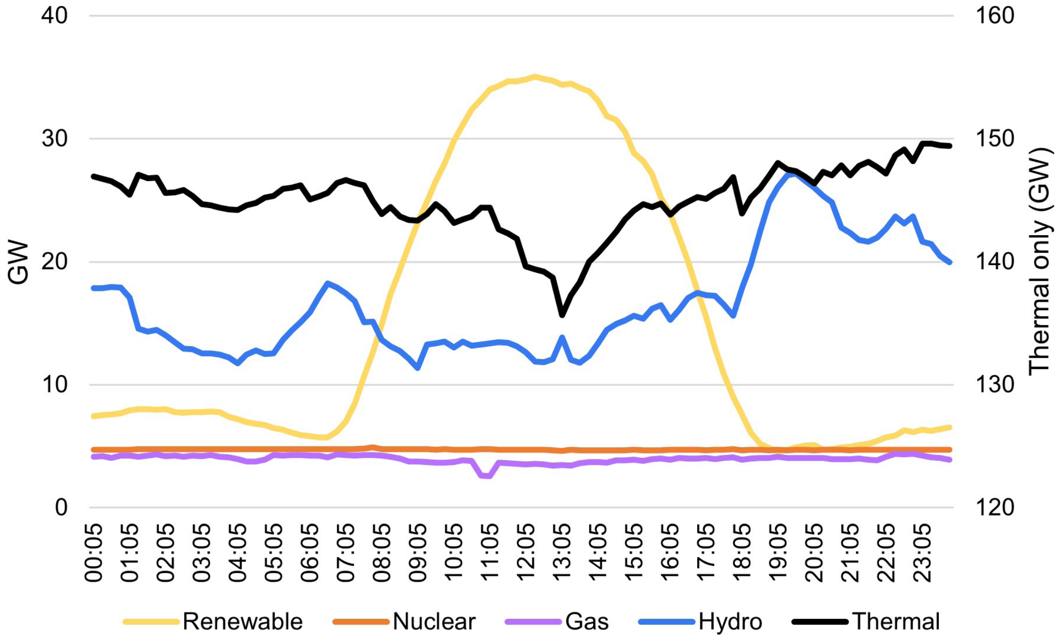
Figure 4.6 shows the load profile constructed from publicly accessible data for maximum monthly demand from 2018–19. Figure 4.7 shows the monthly maximum demand day for 2021–22. Additionally, the maximum daily demand and evening peak hour demand and energy met are also available. There is an established demand of approximately 122 GW, which can accommodate baseloads with an estimated variable load of 78 GW.

Figure 4.6: Load curve: Monthly maximum demand met day for 2021–22



Source: POSOCO monthly reports

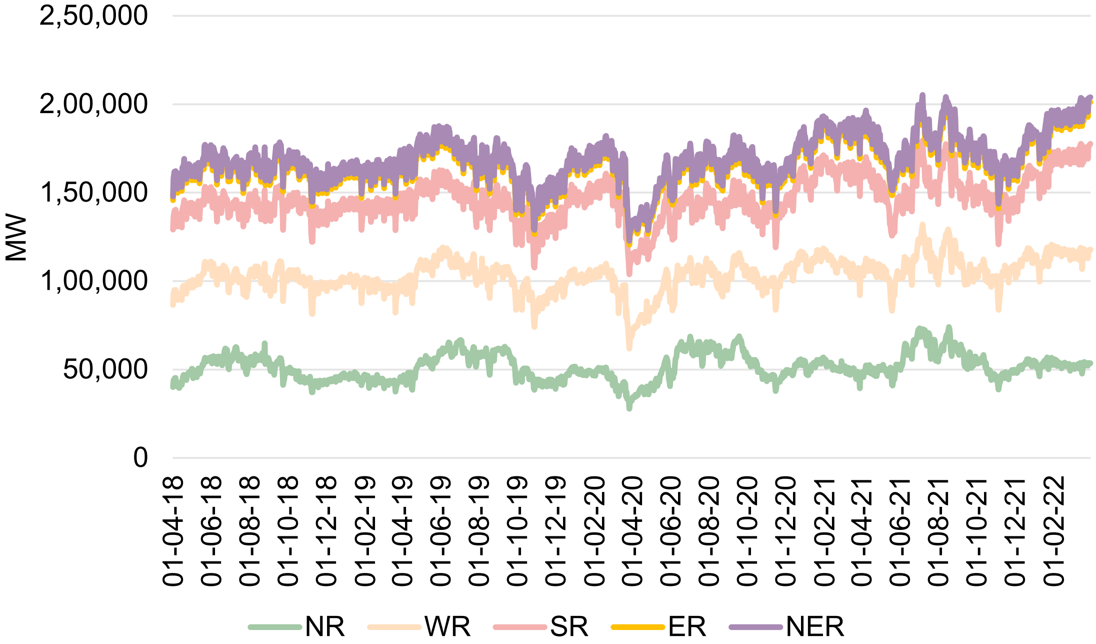
Figure 4.7: Actual load curve and its composition: Monthly maximum demand met day for March 2022 (March 31, 2022)



Source: https://meritindia.in/

Figure 4.8 provides the maximum daily demand met data from 2018–19 to 2021–22 across various regions. The data is used for forecasting maximum demand for 2029–30.

Figure 4.8: Daily data: Maximum demand met—Stacked line chart for 2018–2022



Note: NR, Northern region; WR, Western region; SR, Southern region; ER, Eastern region; NER, Northeastern region.

The model was initially run in an unconstrained condition to generate a scenario that, though unrealistic, provided an insight into the supply side over time. Relaxations were made for the hydro load to go down to zero for peak supplies. This had arrested sharp coal backdowns, and individual backdown limits were adhered to. Figures 4.9–4.15 show the load curves across various scenarios. The peak demand considered for each scenario in 2030 is in figures 4.9, 4.10 and 4.11. The energy model does not consider hourly demands; it calculates the total annual energy demand with a share of electricity in it. As mentioned, the energy and electricity demand for each scenario is driven by assumptions for income, sectoral GVAs, population growth along with end use technology efficiencies and costs. This electricity demand is then used to estimate the capacity mix based on generation technology characteristics, investment and fuel costs.

Figure 4.9: Load curve under the NDCL scenario in 2030

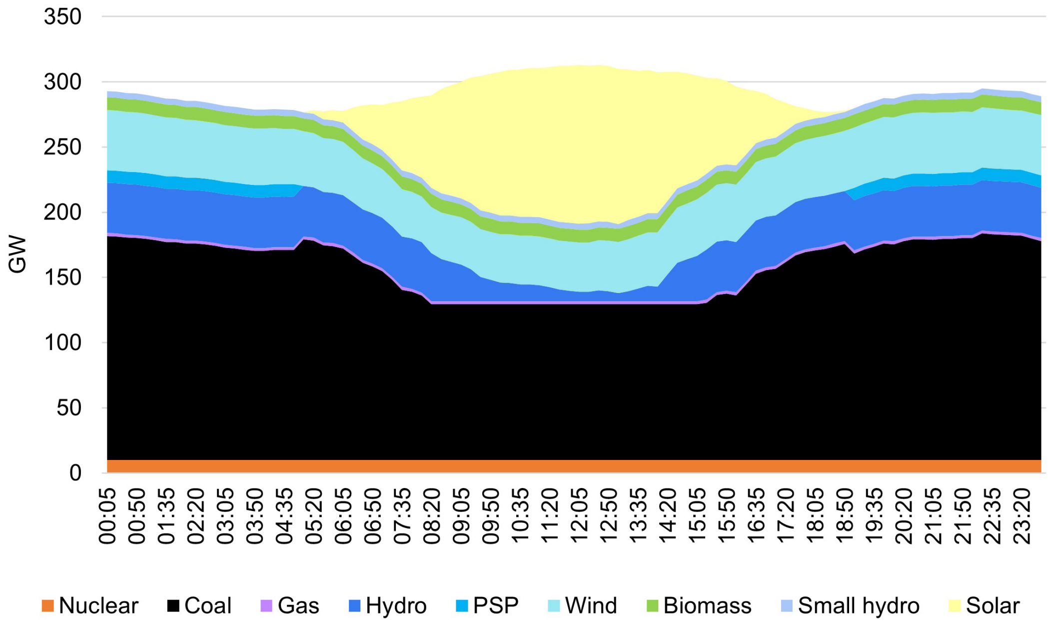


Figure 4.10: Load curve under the NDCM scenario in 2030

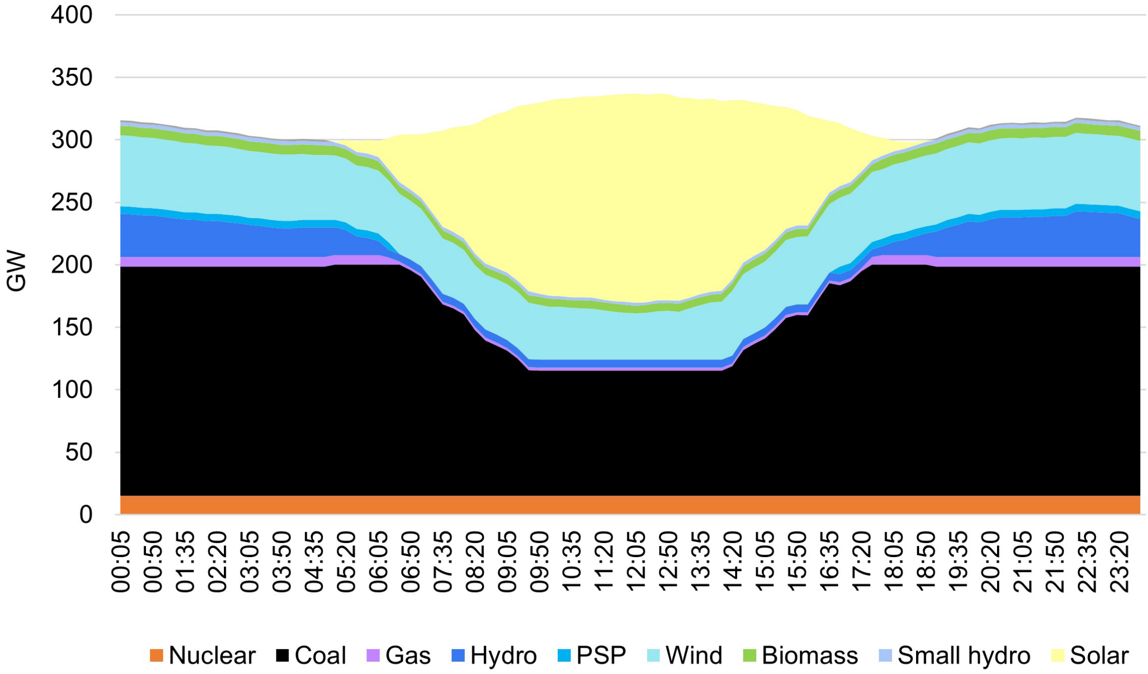


Figure 4.11: Load curve under the NDCH scenario in 2030

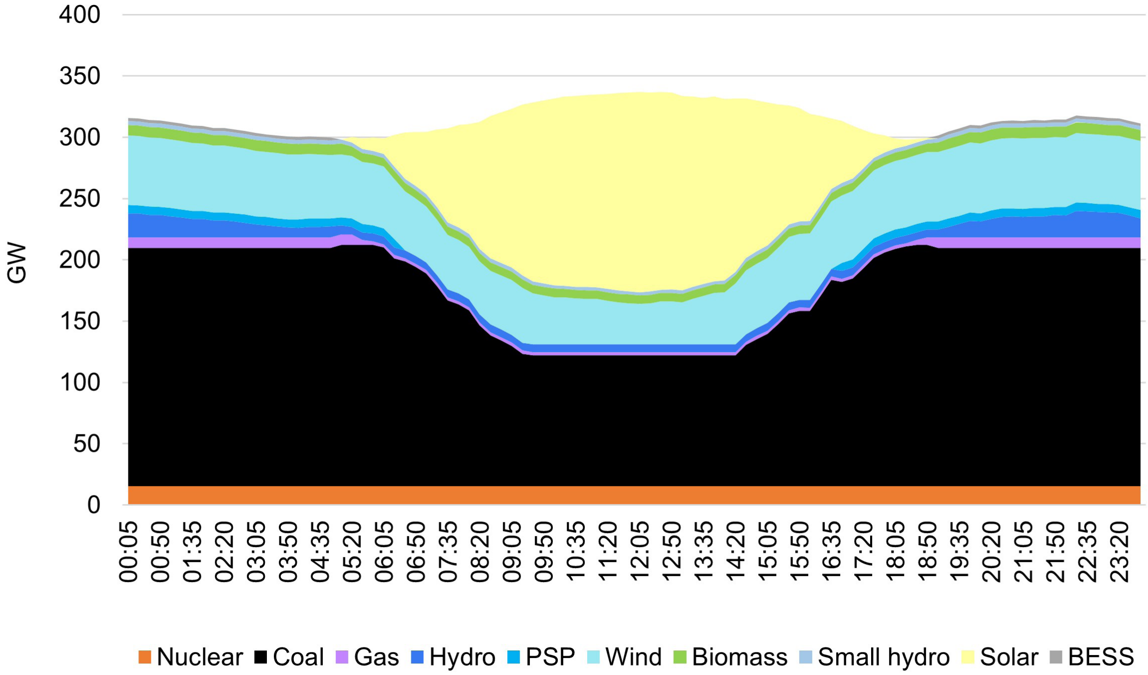


Figure 4.12: Load curve under the NZ1 scenario in 2030

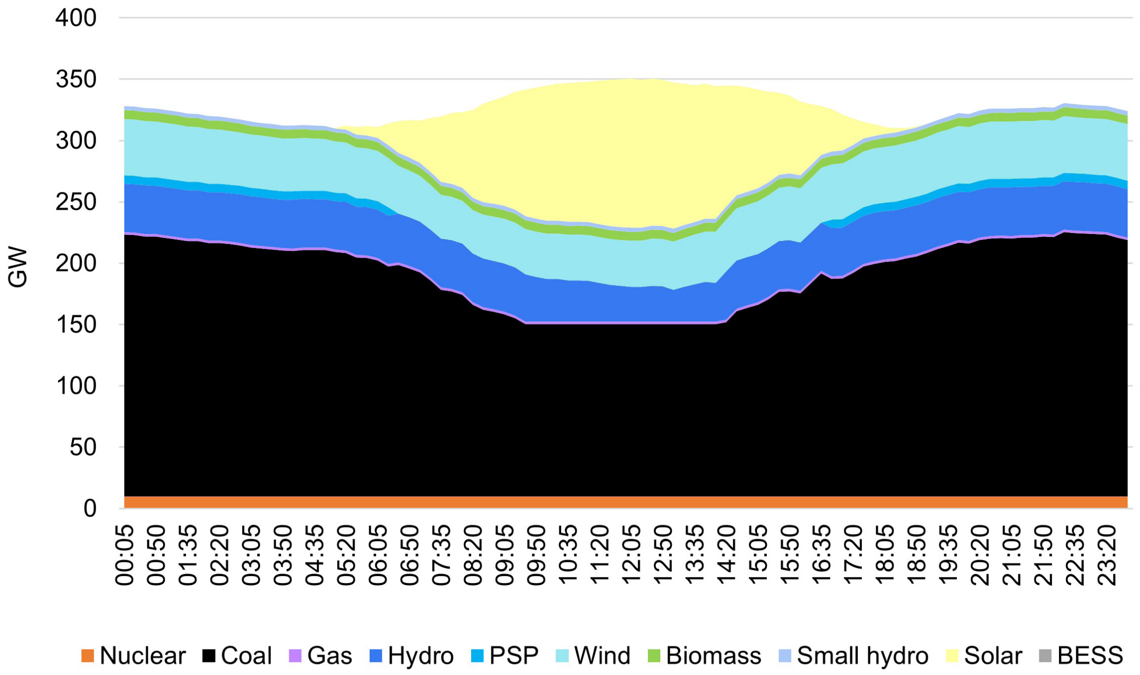


Figure 4.13: Load curve under the NZ2 scenario in 2030

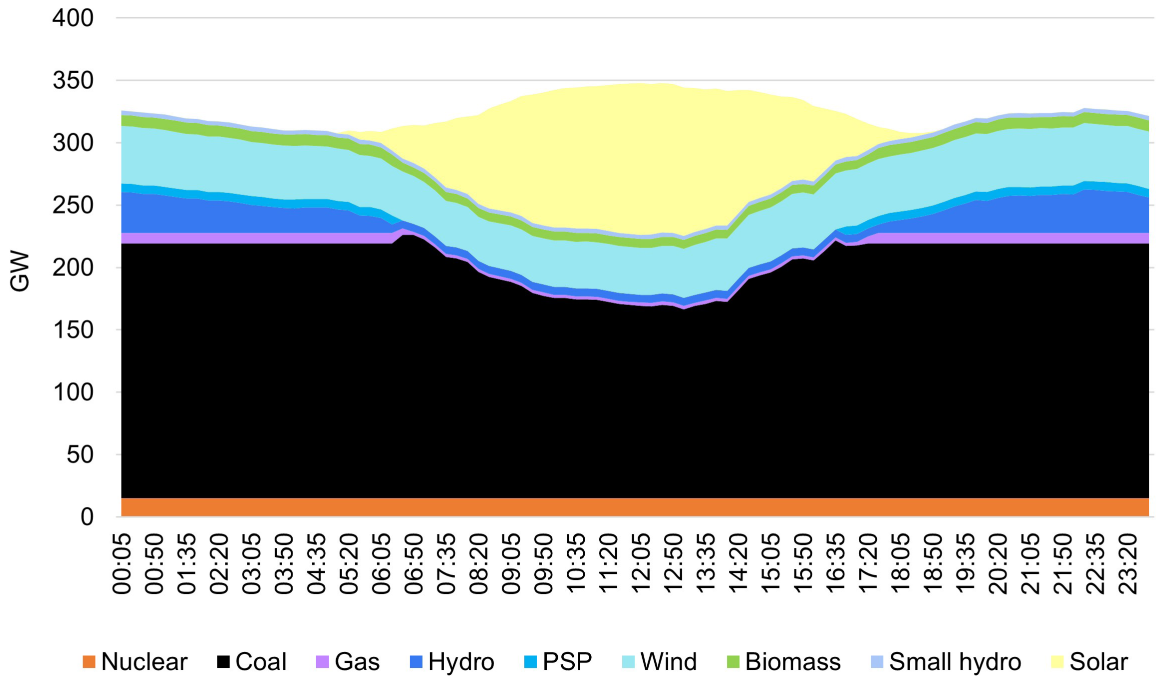


Figure 4.14: Load curve under the NZ3 scenario in 2030

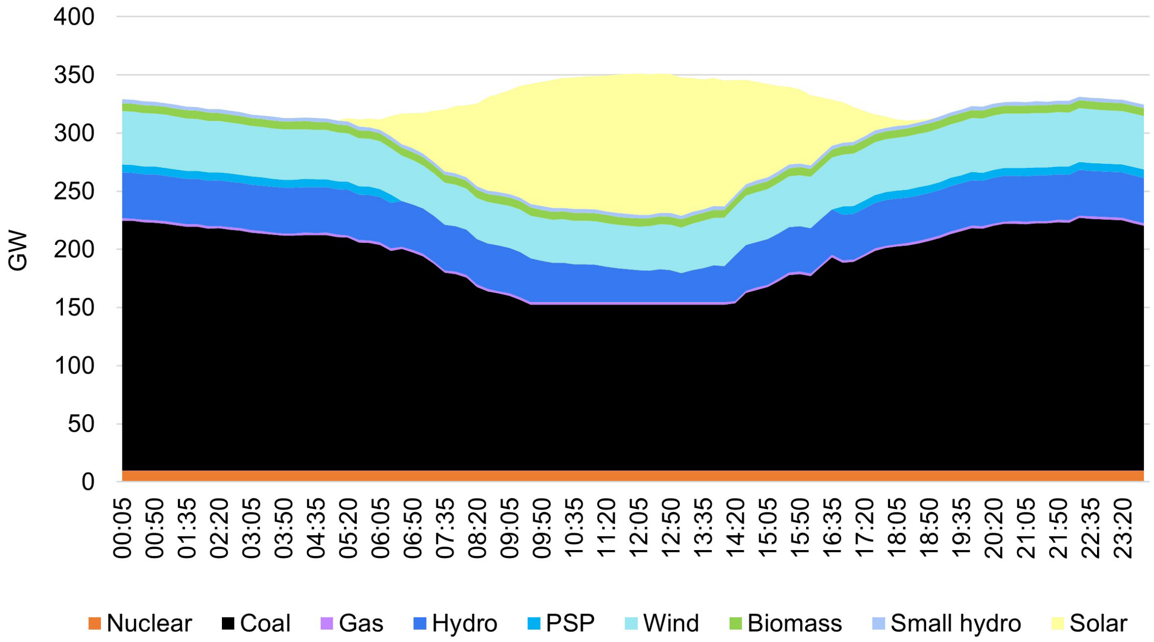
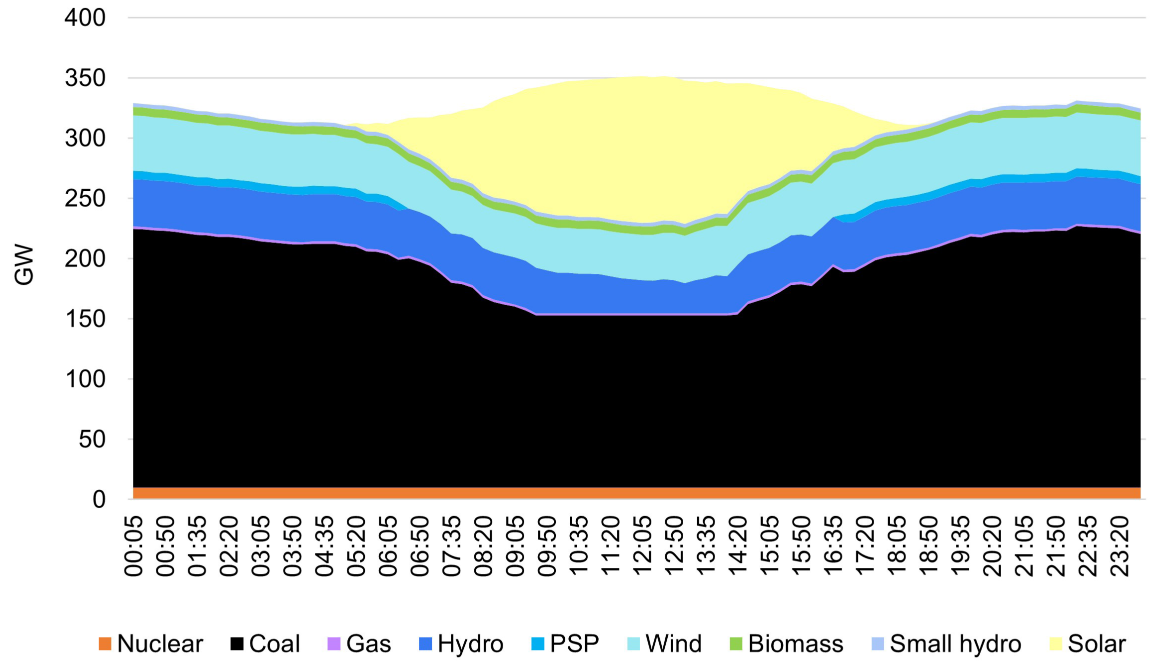


Figure 4.15: Load curve under the NZ4 scenario in 2030



4.5.1 Increase in electricity as a percentage of energy demand

According to studies conducted by the NiTi Aayog, India may be witnessing a steady growth in the share of electricity in its energy demand, which is expected to reach 25% by 2047. The share of electricity in energy demand is estimated to be 20.6% by 2030, which was estimated at 18.3% in 2021. A larger share of electricity in the energy mix is likely to increase the electricity demand (Table 4.4). It should be noted here that the assessments undertaken for 2047 have to be reviewed in light of the NZ 2070 commitments, where the expected share of electricity in the total energy demand is expected to rise to around 47-52% by 2070. The share of electricity would rise to 29–32% by 2070 under the NDC scenarios.

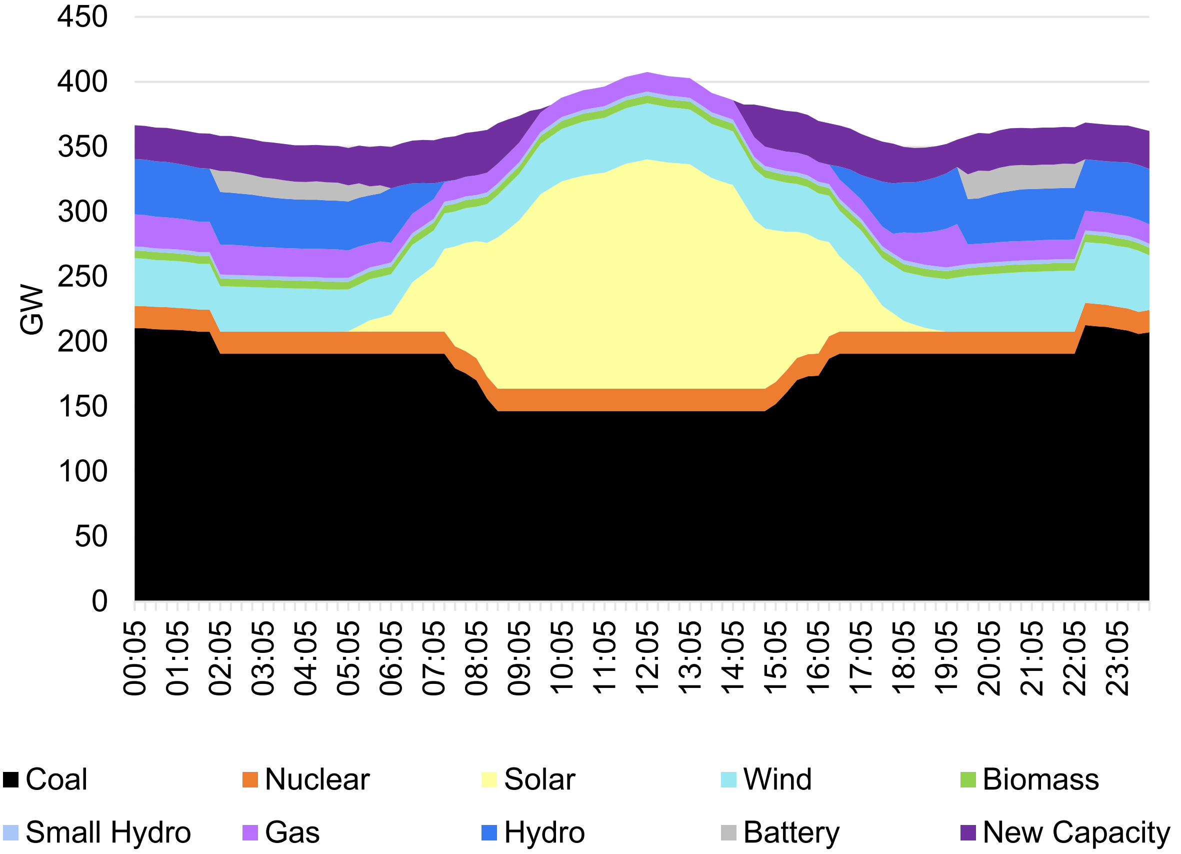
India's total energy consumption in 2021 was 939.507 Mtoe, and it is estimated to reach 1,500 Mtoe (estimated in the Integrated Energy Policy Report) by 2030, as envisaged by the Ministry of Power, GoI. A 2.3% increased share of electricity would translate to 34.5 Mtoe, equivalent to 401.235 million MWh, which can be estimated as 61.07 GW of demand using a PLF of 0.75. However, this assumption of uniform demand imposition needs to be replaced with an estimated demand shape for accurate results (Figure 4.16).

Table 4.4: Share of electricity in energy demand in India

Parameter	2012	2022	2047	
			BAU	Ambitious
Share of electricity in energy demand	16%	17.6%	25%	29%

Source: NITI Aayog and IEEJ, Energizing India, June 2017

Figure 4.16: Load curve in 2029–30—A higher share of electricity in energy use

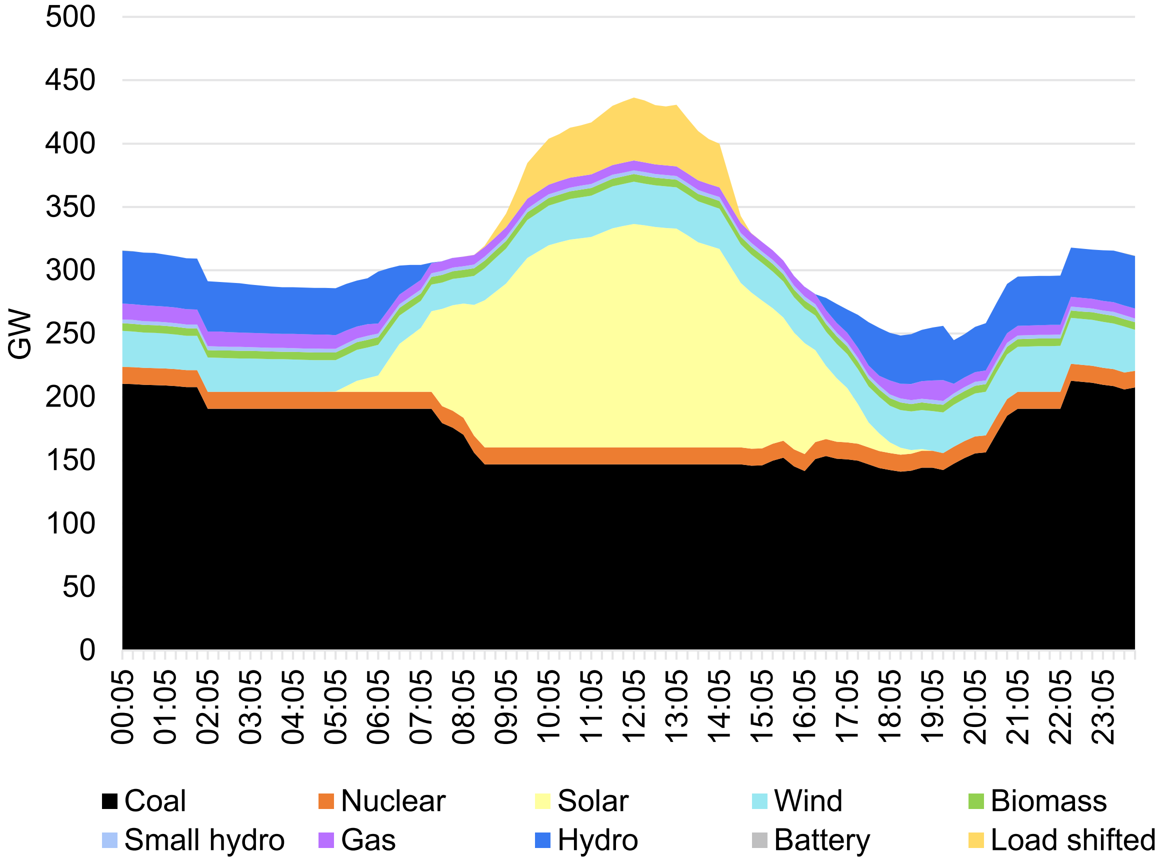


4.5.2 *Load shifting due to demand-side management*

All utilities have undertaken demand-side management initiatives, with a basic focus on efficiency improvement rather than temporal shifts. Time-of-day tariffs are available for a few categories of customers, which could lead to temporal shifts. However, implementing these tariffs would require shifts in the metering infrastructure in addition to tariff regimes.

Among the studies surveyed, only Abhyankar's study mentions the possibility of shifting 50 GW of agricultural load and 10 GW of industrial load from evening to solar hours (Abhyankar et al., 2021). Our study finds the possibility of shifting approximately 50 GW of load from evening hours to solar hours and avoiding the curtailment of RE (Figure 4.17).

Figure 4.17: Load curve in 2029–30—Load shifting

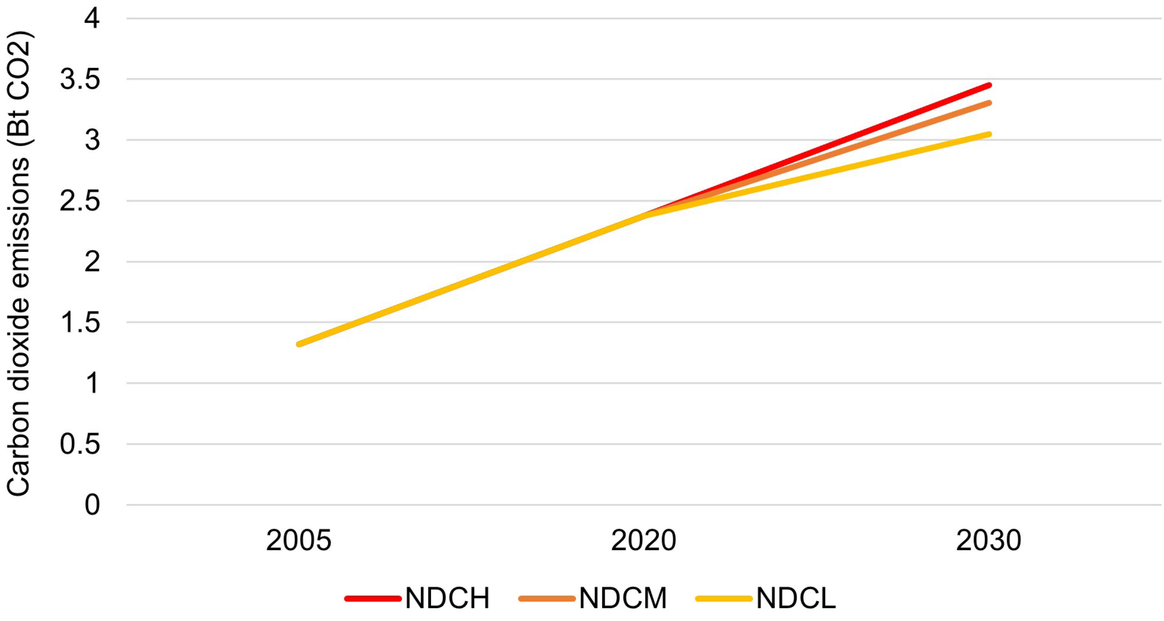


The state of demand-side management and the effectiveness of demand-side management policies, which depends on the development of people in a country as well, may also impact future load profiles. One such measure is the HDI, which is available for 2021 in the UNDP's Human Development Report (UNDP, 2022). Our study tracks load profiles of countries having very high HDI and those of tropical countries (Section 5.1 in Annexure 5).

4.6 GHG emissions

India's per-capita emissions are considerably smaller than those of China and other developed countries. However, it is among the most vulnerable countries to be hit by the impact of climate change in the form of unpredictable weather conditions and increasing water scarcity. Over the past decade, policy interventions through regulatory instruments such as emission standards, economic instruments such as subsidies, taxes, and tariffs, and information-related instruments such as labeling have been implemented. Additionally, changes in economic structure and the electricity regulatory framework have been made through a combination of ongoing policies. Overall, CO_2 emissions are observed to increase in NDCH, NDCM, and NDCL growth scenarios to 3.45, 3.3, and 2.75 btCO_2, respectively, in 2030 (Figure 4.18).

Figure 4.18: CO_2 emissions under NDCH, NDCM, and NDCL growth scenarios by 2030



4.7 Performance on meeting NDC targets

India has committed to reducing the GHG intensity of its economy by 33–35% between 2005 and 2030 under its first NDC as per the Paris Agreement. The target has been increased up to 45% under its updated NDC targets. India's GHG/GDP intensity reduced by 24% (excluding agriculture) during 2005–2016 (MoEFCC, 2021). Our initial estimates suggest that the GHG intensity has been further reduced by 33% between 2005 and 2019. Our estimates indicate that the intensity has touched 36% during 2005–2021, which puts India well on track to meet its enhanced NDC target. This has been possible through the implementation of multiple policies and measures totaling around 450. These policies have been implemented by both central and state governments, either directly or indirectly. Approximately 70% of these policies have been implemented over the past eight years.

India's other major NDC is to have 40% of its electricity generation capacity come from non-fossil sources by 2030. India has further enhanced this target to 50% by 2030, and as of December 2022, 41% has been achieved. As of July 31, 2023, India had already achieved 43.7%(CEA, 2023b).

Figure 4.19 shows the assessment on India's projected performance against its NDC target on reducing the GHG intensity of GDP between 2005 and 2030 under all the scenarios considered under this study. The GDP growth under the low, medium and high scenarios are considered at a CAGR of 5.8%, 6.5% and 7% between 2005 and 2030. It can be noted that except for a slow growth scenario and the scenario with thrust on fossil fuels with CCUS (NZ2), the targeted decoupling of GHG and GDP is achievable. If GDP growth is strong, decoupling would be also strong since GHG emissions grow by almost same percentage year on year. If GDP growth is lower, decoupling will also be weaker as GHG emissions have a minimum level since minimum economic activities have to be continued in any country. Again, higher GDP growth may not necessarily result in proportionately higher GHG emissions. Emission growth may also be subdued by government policies and measures such as for energy efficiency, renewable, bioenergy and ethanol blending, etc. Table 4.5 presents the assessment on share of non-fossil sources in electricity generation. While NZ scenario are targeted towards 2070, the trajectories by 2030 show the achievement of NDC target of 50%. Thus, indicating that India may push for higher economic growth supported by higher share of non-fossil sources of electricity in order to achieve its NDC targets by 2030.

Figure 4.19: India's performance on GHG intensity of GDP under various scenarios

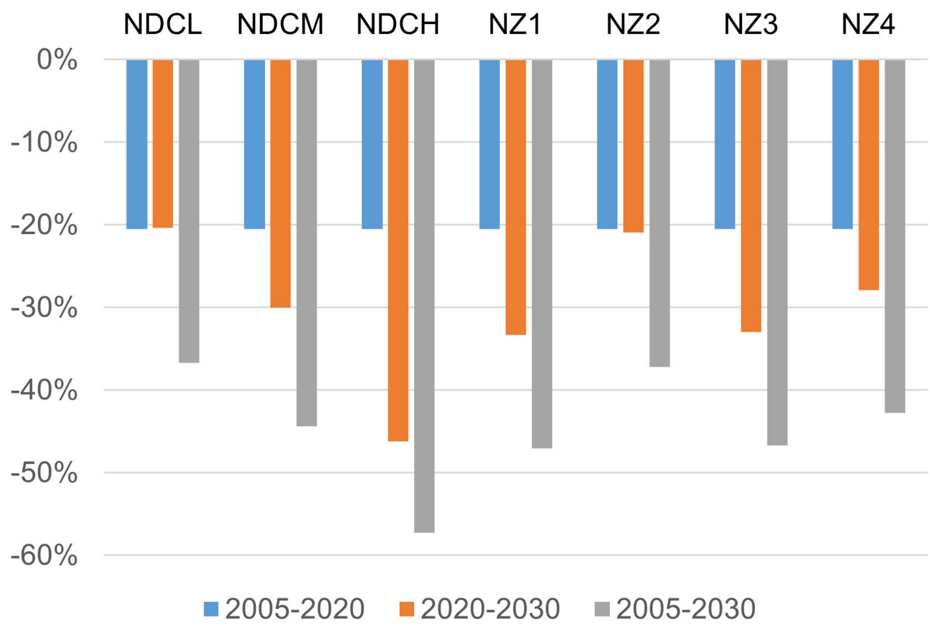


Table 4 5: India's performance on share of non-fossil sources in electricity generation under various scenarios

	Share of non-fossil sources in electricity generation (%)						
Year	NDCL	NDCM	NDCH	NZ1	NZ2	NZ3	NZ4
2005	35%	35%	35%	35%	35%	35%	35%
2020	38%	38%	38%	38%	38%	38%	38%
2030	56%	46%	43%	70%	54%	71%	65%

4.8 Biofuel

Bioenergy is also one of the sources that the Government of India has been pushing to move towards cleaner energy systems. In this modelling exercise, the bioenergy manifests in different forms. The solid fuel or biomass is reflected and modelled under the electricity sector (biomass to power route). Further, the BECCS assessments also include biomass to energy flows. The biogas is reflected in the residential sector of the model in terms of PNG and CNG blending. This section focuses on the liquid bioenergy- biofuel use in the transportation sector.

As discussed in this report earlier, biochar is being actively considered by the steel sector. Power projects on biomass to power and heat are under operations and receiving incentives under various government policies. The Ministry of New and Renewable Energy has notified a National Bioenergy Programme in November 2022. The first phase of this programme includes the Biogas Programme to support setting up of small and medium sized biogas plants. Further, in November 2023, the National Biofuels Coordination Committee has approved policy on mandatory blending of compressed biogas (CBG) in the transportation and domestic segments of the city gas distribution (CGD) sector in a phased manner – 1% of total CNG and domestic PNG consumption for FY26, 3% for FY27, and 4% for FY28.

During the G20 summit held in September 2023 under India's presidency where the Global Biofuel Alliance was launched. It aims to support use of sustainable biofuels, advances in biofuel technologies, shaping "robust standard setting and certification.

Ethanol-blended petrol was first introduced in India in 2003. By 2006, the Ministry of Petroleum and Natural Gas directed the public oil marketing companies (OMCs) to blend 5% ethanol in petrol. However, the program faced several challenges during the initial years of implementation, including procurement and infrastructural challenges, high taxation, limited availability of feedstock due to the non-inclusion of grain-based ethanol, and pricing concerns. Although efforts were made to increase the effectiveness of the program from December 2014, the big push for fuel came in 2018 through the National Biofuel Policy.

The interest subvention scheme and reduction of the GST taxation on ethanol from 18% to 5% encouraged ethanol production in India. The policy also allowed for the conversion of B-heavy molasses, sugarcane juice, and waste food grain into ethanol. Until 2018–19, C-heavy molasses was the main feedstock for ethanol production. In 2020, the use of maize for ethanol production was also approved. Thus, it is only in the past few years that the ethanol blending program has received a significant push. India achieved its 10% blending target by June 2022. The amended National Biofuel Policy 2018 has set a target of 20% blending by 2025–26, advanced by 5 years from the initial 2030 target. In February 2023, India rolled out 20% blending at select petrol pumps in 11 states and UTs.

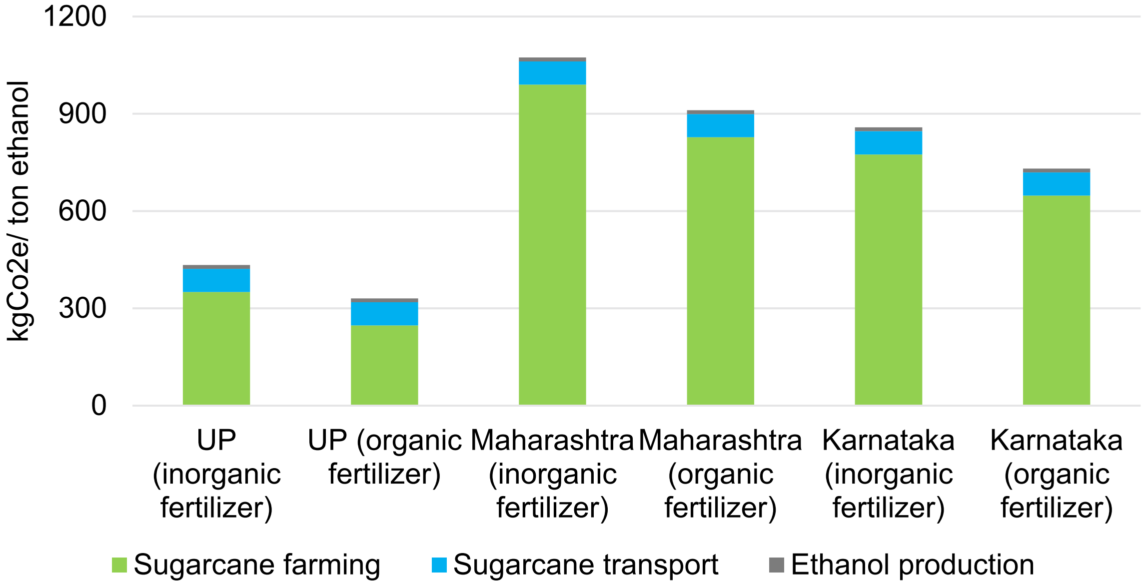
Achieving the GoI's ethanol blending target needs a paradigm shift in the production and distribution of ethanol. The current ethanol production capacity stands at 426 crore liters from molasses-based distillation and 258 crore liters from grain-based distillation (NITI Aayog, 2021). With ethanol demand for blending purposes expected to reach 722–921 crore liters by 2025 at a 20% blending rate, there will be a huge capacity gap that needs to be filled. Thus, sugarcane-based ethanol cannot be the only source of ethanol in transport.

Moreover, focusing heavily on sugarcane-based ethanol production has environmental impacts. A quick estimate indicates that if ethanol producers continue to use molasses as the bioethanol feedstock to meet the blending requirements, it would require additional water and land resources and lead to higher sugarcane production. However, using sugarcane juice can allow for the target to be met without demanding water and land beyond current levels. In addition, as previously discussed, sugarcane molasses alone will not suffice to meet India's increasing ethanol requirements. Therefore, using surplus sugarcane juice can be an excellent upcoming option for ethanol production, which can also help India meet its nutrition requirements and make resources such as land and water more sustainable. Furthermore, there are possibilities of energy plantation for non-food crops like Bamboo, Jatropha, Karanja, Linseed, etc to be cultivated in relatively infertile wastelands in India that comprise up to almost 48 million hectares. However, this is a work in progress that needs further exploration.

However, the comparative benefits and positive impacts of the biofuel economy are also dependent on the net emissions during its life cycle—right from production to transport, distribution, and use. Hence, it was necessary to undertake an LCA to assess the benefits of bioethanol blending vis-à-vis fossil gasoline. The main objective of an LCA exercise is to provide as complete a portrait as possible of resource consumption, environmental viability, and their rebound effects, hence enabling effective planning for a sustainable society. Thus, we have conducted an assessment of life-cycle emissions from ethanol production through the sugarcane-juice-to-bioethanol route. Uttar Pradesh in the north, Maharashtra in the west, and Karnataka in the south are the top three sugarcane-producing states; therefore, the assessment has been undertaken for these three regions. See Annexure 6 for details on the data and methodology employed.

The results suggest that emissions from sugarcane farming are the highest, followed by transport, while the least emissions come from ethanol production (not considering the biogenic CO_2 emissions). The emission footprint of sugarcane-based ethanol production in these states is 0.34, 0.85, and 0.68 $kgCO_2e$/liter ethanol, respectively. Figure 4.20 shows the emission profile for sugarcane-based ethanol production in Uttar Pradesh, Maharashtra, and Karnataka. The variation in the emissions across states can mainly be attributed to the energy requirements for irrigation purposes. We have also estimated two scenarios here to understand the impact of fertilizer use—inorganic fertilizer and organic fertilizer use—on emissions during sugarcane farming.

Figure 4.20: Life-cycle emissions from sugarcane-based ethanol production in Uttar Pradesh, Maharashtra, and Karnataka



Additionally, the geographical concentration of ethanol production translates to high transportation costs to states that do not produce ethanol, which further adds to transport-related emissions. Therefore, the government is promoting the augmentation of grain-based ethanol production capacity. According to NITI Aayog's report on ethanol blending in India, the expansion in ethanol production capacity in India is expected to reach 760 crore liters and 740 crore liters from molasses and grain, respectively, by 2025. With enhanced grain-based ethanol production capacity, the production of ethanol is expected to become relatively more distributed across the country. This would lead to reduced transport and distribution logistic requirements and fewer delays in meeting the blending targets.

To achieve this, the government has allowed the use of surplus stocks of maize and rice available with the FCI for ethanol production. To incentivize grain-based ethanol production, the government allocated 78,000 tons of rice to distilleries during the ethanol supply year (ESY) 2020–21. The procurement price has been fixed at INR 2,000 per quintal under the open market sale scheme (domestic) of the Department of Food and Public Distribution. The purpose is to use surplus grain or waste/damaged grains to produce ethanol required for blending purposes, thereby not impacting the food availability in the country.

However, several concerns need to be addressed to ensure that the 20% blending targets are met. Currently, the government follows a dual pricing system for ethanol from sugarcane vs. grain-based ethanol. The government has currently fixed three different price bands for ethanol generated using C-heavy molasses, B-heavy molasses, and sugarcane juice/sugar/sugar syrup. For grain-based ethanol, OMCs fix a single price across feedstock. In 2020–21, the Indian government fixed different prices for ethanol from maize and rice feedstock from FCI. Again, these prices are fixed for each ESY. Moreover, under the "Ethanol procurement policy on a long-term basis under ethanol blended petrol (EBP) program," long-term (5 years) purchase contracts are being envisaged. This would bring in price predictability and ease out investment decisions for ethanol producers.

Transportation and interstate movement of ethanol also need to be made easier to achieve uniform blending rates across the country. The amendment of the Industries (Development & Regulation) Act, 1951 allows state governments to legislate, control, and levy taxes and duties on liquor meant only for human consumption. Denatured ethanol (used for blending) will be controlled only by the central government. However, some states have not implemented these amended provisions, leading to movement restrictions and differential levies/taxes on ethanol used for petroleum blending.

The geographic concentration of sugarcane-based ethanol production leads to high transport needs. The costs of logistics and transportation is another obstacle that determines the final price of the supply of ethanol to the OMCs. Currently, the primary mode of transport is by road, with railways being recently involved. However, the government is also planning to shift to pipelines for the transportation of ethanol. All these initiatives may ease the logistics concerns.

India also needs a longer-term vision of what comes after the 20% target is achieved. The scenarios could be many and varied. One of the options is to allow higher blending rates in states that produce higher quantities of ethanol, thus reducing transportation needs and related emissions. However, an increased blending mandate would require a switch in automobile technology (upgrading certain vehicle components) and bringing in flex-fuel vehicles. Investing in 2G ethanol is another viable option. The Indian Oil Corporation recently launched a 2G ethanol plant at its Panipat refinery, which is expected to produce 3 crore liters of ethanol annually using 2 lakh tons of agricultural waste. Policies such as sub-mandates for 2G ethanol, such as 10% of total blending to come from 2G ethanol, may be used to build demand for 2G ethanol.

Chapter 5:
LONG-TERM RESULTS UNDER ALTERNATE GROWTH TRAJECTORIES

5. Long-Term Results Under Alternate Growth Trajectories

This chapter presents an outlook of the total primary energy demand, required power supply, FEC in end-use sectors, and subsequent CO_2 emissions in this decade under low-, medium-, and high-economic-growth scenarios until 2070. It also explores the role of fossil fuels and RE under these scenarios. We further discuss the Kaya identity and affordability of the energy here.

5.1 Total primary energy demand (TPED)

Figure 5.1 presents the total primary energy demand by fuel. Primary energy growth is set to increase at an annual growth rate of 2.9% in the high-economic-growth scenario, 2.3% in the medium-economic-growth scenario, and 2.1% in the low-economic-growth scenario between 2030 and 2050. There is an increase in energy demand when compared with 2020 and 2030 projection in the respective pathways. The high-growth scenario focuses on increasing demand, which is met by the coal-intensive power sector. In the low growth scenario, although the coal capacity is seen to decrease (Figure 5.2), generation capacity of solar, wind, gas, nuclear, hydro and other sources increase by 2070. Energy demand decreases at an annual rate of 0.4% in the high-economic-growth scenario, 0.6% in the medium-economic-growth scenario, and 1% in the low-economic-growth scenario between 2050 and 2070. In all the three scenarios, reduction of energy demand between 2050-2070 is observed despite the positive economic growth assumed in this period. The curve of energy demand is dependent unidirectionally on GDP growth, and it also follows the Environment Kuznet Curve (EKC) hypothesis (Kamarova et al. 2022; Bekun et al. 2019; Waheed et al. 2019). Low growth energy demand in NDCL in 2070 due to a combination of a) energy efficiency and technical efficiency in both the electricity supply as well each of the sectoral systems and b) low service demand (implementation of LiFE mission). As the economy is growing (despite low growth rate), energy efficiency and conservation are some of the measures that will help meet and sustain the overall energy requirement of the population going. Additionally, decoupling and sustainable consumption becomes more efficient to ensure sustenance of economy. Net Zero is not perceived in our modelling as an end-of-the-pipe solution wherein energy systems are normally allowed to continue to release unbridled emissions that must then be brought to net zero. Our modelling incorporates India's LiFE mission towards a "Mindful and Deliberate Utilization, instead of Mindless and Destructive Consumption" and it is projected to reduce material and service demands across economy towards a Net Zero movement under all scenarios. NDCL puts further economic constraints on investment possibilities, therefore energy does not rise as perceived by some, but the model remains feasible.

The primary energy sources are consumed in the demand sectors (agriculture, industry, transportation, and buildings) either directly or after conversion into electricity. In 2050, across the three scenarios, around 58% of the energy is consumed in the industry sector, followed by buildings (25-28%), transport (9-12%) and agriculture (5%) sectors. However, by 2070, the share of industry sector across the three scenarios rises to 73% at the cost of the buildings sector whose share reduces to 12%. The share of transport and agriculture sectors in 2070 remains similar to their corresponding shares in 2050.

Figure 5.1: Total primary energy demand by fuel under NDCH, NDCM, and NDCL growth scenarios in the long term

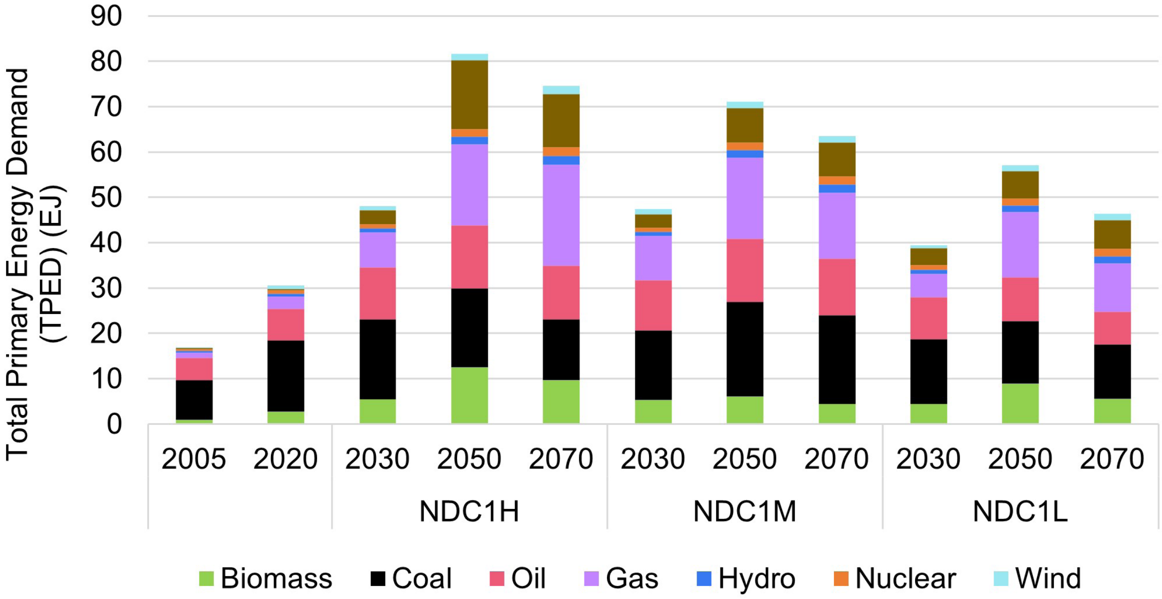


Figure 5.2 and Table 5.1 present power generation capacity under high-, medium-, and low-growth scenarios until 2070. The capacity reaches 710 GW in 2030, 1075 GW, and 1,348 GW in 2070 in the NDCH growth scenario. It is observed to reach 650 GW in 2030, 1004 GW, and 1,150 GW in 2070 in the NDCM growth scenario and 552 GW in 2030, 675 GW and 625 GW in 2070 in the NDCL growth scenario. The annual growth rate in generation capacity is estimated to increase by 2.7% in the high-economic-growth scenario, 2.5% in the medium-economic-growth scenario, and 0.8% in the low-economic-growth scenario between 2030 and 2050. Between 2050 and 2070, the annual growth rate in generation is estimated to increase by 1.1% in the high-economic-growth scenario, increase by 0.7% in the medium-economic-growth scenario, and decrease by 0.5% in the low-economic-growth scenario. The fossil fuel (coal and gas) generation capacity share decreases from 69% in 2005 to 50-52% in 2030 and 29–35% in 2070. The renewable (excluding hydro) share increases to 31–35% in 2030 and 47–56% in 2070. The hydropower share decreases from 19% in 2005 to 8–10% in 2030 and 5–11% in 2070, while the nuclear power share increases to 2–3% in 2030 and around 7% in 2070 under the NDC growth scenarios.

Table 5.1: Electricity generation capacity (in GW) under NDCH, NDCM, and NDCL growth scenarios in the long term

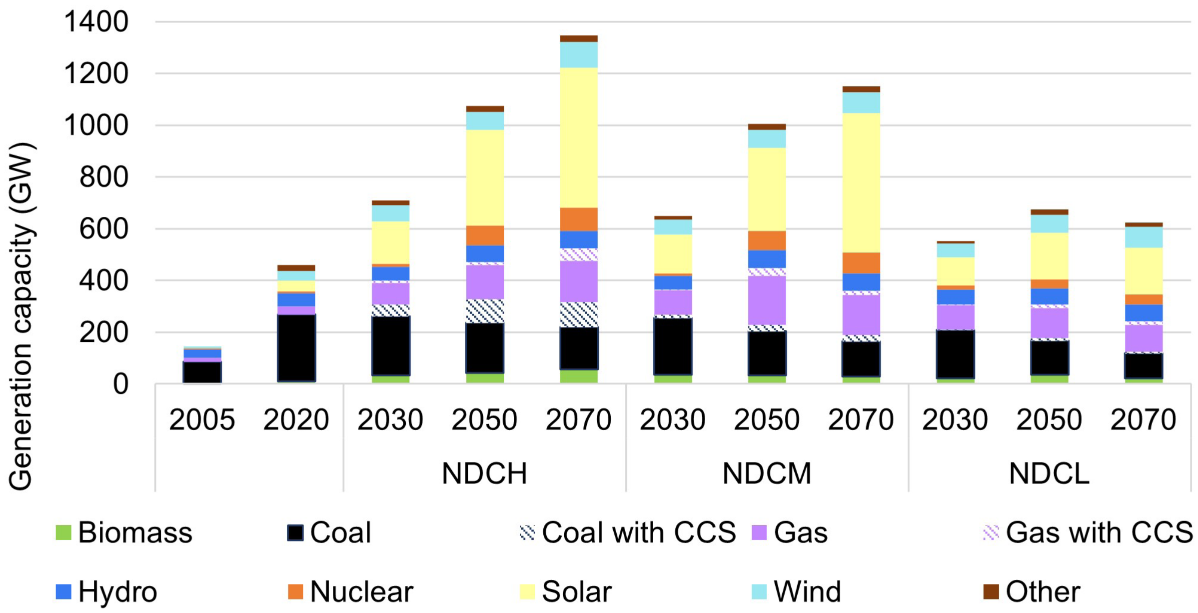
Scenario	Year	Biomass	Coal	Coal with CCUS	Gas	Gas with CCUS	Hydro	Nuclear	Solar	Wind	Other	Total
	2005*	1.1	71	0	16	0	32	3.36	0.5	7	0	131
	2020**	10	206	0	25	0	51	6.7	37	39	1	375
NDCH	2030	34	227	47	82	10	53	11	166	63	19	712
	2050	42	194	92	132	11	65	75	370	70	24	1075
	2070	57	163	98	157	49	69	90	540	100	25	1348
NDCM	2030	35	220	13	95	3	53	11	149	58	16	653
	2050	33	170	25	189	32	67	75	320	70	23	1004
	2070	30	135	25	155	16	67	80	540	80	22	1150

Scenario	Year	Biomass	Coal	Coal with CCUS	Gas	Gas with CCUS	Hydro	Nuclear	Solar	Wind	Other	Total
NDCL	2030	22	186	2	95	2	57	18	108	53	10	553
	2050	35	132	12	115	13	63	35	180	70	20	675
	2070	23	96	6	105	14	64	40	180	80	17	625

Note: ** Numbers are based on the Energy Statistics 2007 for financial year 2005-06 and Growth of Electricity sector in India, CEA, 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at around 14 GW.*

*** Numbers are based on CEA's General Review 2022 and installed capacity reports upto December 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at 47.8 GW.*

Figure 5.2: Electricity generation capacity under NDCH, NDCM, and NDCL growth scenarios in the long term



The energy model does not consider hourly demands; it calculates the total annual energy demand with a share of electricity in it. As mentioned, the energy and electricity demand for each scenario is driven by assumptions for income, sectoral GVAs, population growth along with end use technology efficiencies and costs. This electricity demand is then used to estimate the capacity mix based on generation technology characteristics, investment and fuel costs.

The decrease in coal capacity in the NDCL scenario is a result of multiple factors at both supply and demand side. Due to the low-growth rate after 2040, the sectoral demands may decrease. Due to the decrease in demand, the overall electricity demand may decrease. The retirement of 50-60 GW of coal power plants between 2040 and 2070 after the completion of plant life, in addition to the cancellation of a few planned capacity, and stranded capacity due to low economic growth rate, the study estimates a coal capacity of 188-198 GW in 2030 in the NDCL scenario. This is based on the ongoing, under construction and planned coal plants capacity in 2020 according to the Global Energy Monitor's Coal Plant Tracker database[10]

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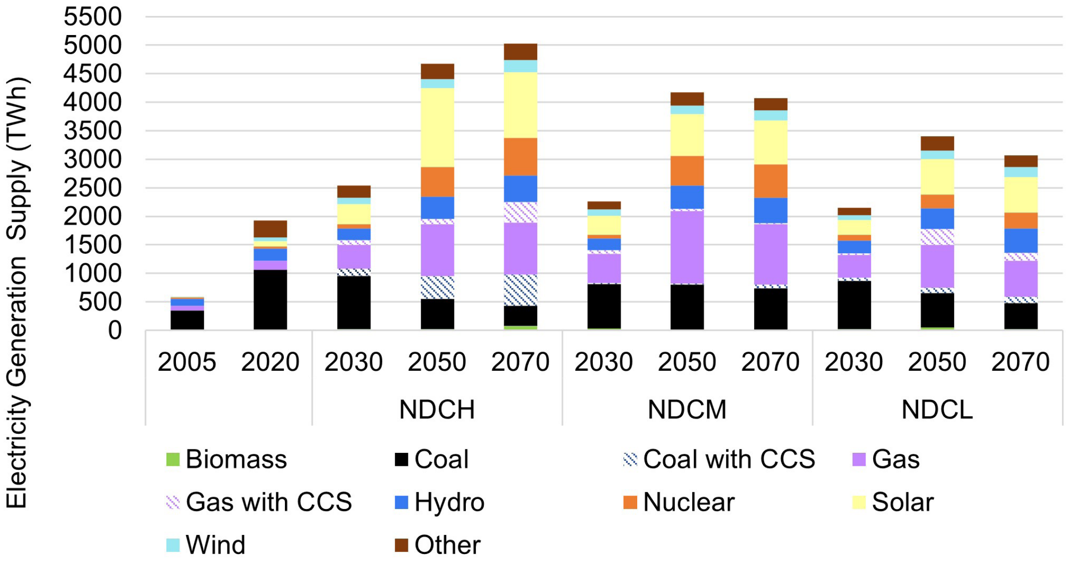
[10] https://globalenergymonitor.org/projects/global-coal-plant-tracker/

5.2 Electricity generation (TWh)

Figure 5.3 shows the trend and share of electricity generation from different sources until 2070. The total electricity generation goes from 2,542 TWh in 2030 to 4, 678 TWh in 2050 and 5,026 TWh in 2070 in the NDCH growth scenario, from 2,259 TWh in 2030 to 4,176 TWh in 2050 and 4,070 TWh in 2070 in the NDCM growth scenario, and from 2,146 TWh in 2030 to 3,406 TWh in 2050 3,070 TWh in 2070 in the NDCL growth scenario. The annual growth rate in generation is estimated to increase by 3.1% in the high- and medium-economic-growth scenarios, and 2.2% in the low-economic-growth scenario between 2030 and 2050. Between 2050 and 2070, the annual growth rate in generation is estimated to increase by 0.4% in the high-economic-growth scenario, decrease by 0.1% in the medium-economic-growth scenario, and decrease by 0.6% in the low-economic-growth scenario. The decrease in generation in the medium-economic-growth scenario is attributed to the demand of electricity from enduse sectors. The sectoral demand is dependent on the economic growth rate. Compared to high growth rate, the electricity generation decreases in the medium growth rate scenario between 2050 and 2070 due to a combination of improved energy efficiency, and decrease in sectoral demand due to a combination of sustainable lifestyle changes. The coal share decreases to 14–17% in 2070, while the renewable (excluding hydropower) share increases to 28–32% in 2070 in high-, medium-, and low-growth scenarios.

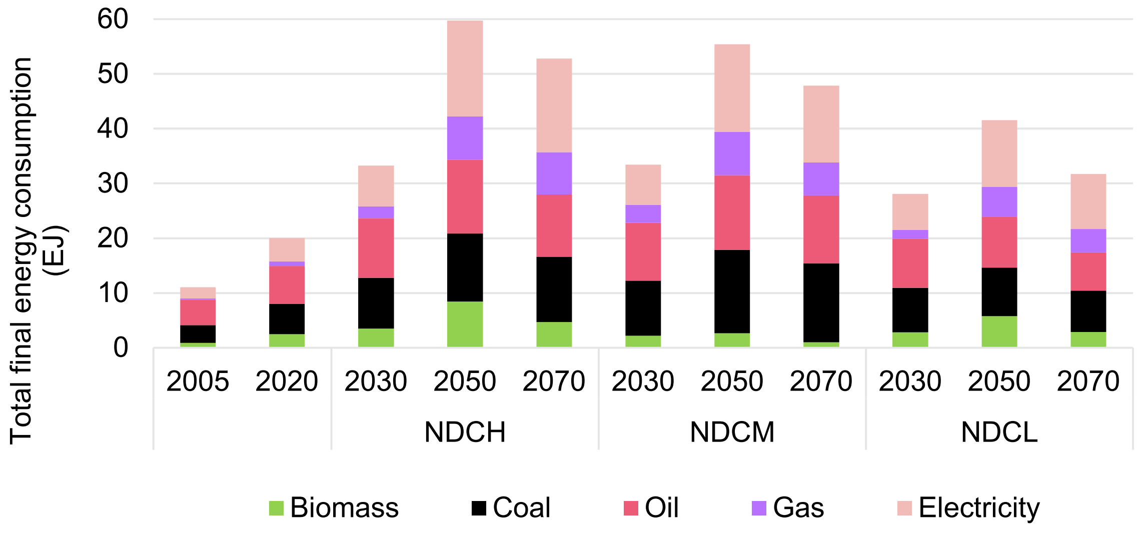
Figure 5.3: Electricity generation supply under NDCH, NDCM, and NDCL growth scenarios in the long term



5.3 Total Final Energy Consumtion (FEC)

The economy-wide FEC increases from 11 EJ in 2005 to 32–53 EJ in 2070 under different growth scenarios. Figure 5.4 shows the total FEC under NDCH, NDCM, and NDCL growth scenarios. Most of the coal is used in the industry sector for energy and industrial processes. Oil is majorly used in the transport and industry sectors, followed by the building and agriculture sectors. Natural gas is consumed by the industry sector, followed by the transport and building sectors. Electricity is mainly used by the building sector in 2070, followed by the industry, transport, and agriculture sectors. Electricity demand increases to 29–32% of the FEC in the NDC scenarios in 2070. Agriculture, industry, transport, and building sectoral shares were observed to be around 6–7%, 67–73%, 8–15%, and 11-12%, respectively, under NDC growth scenarios in 2070.

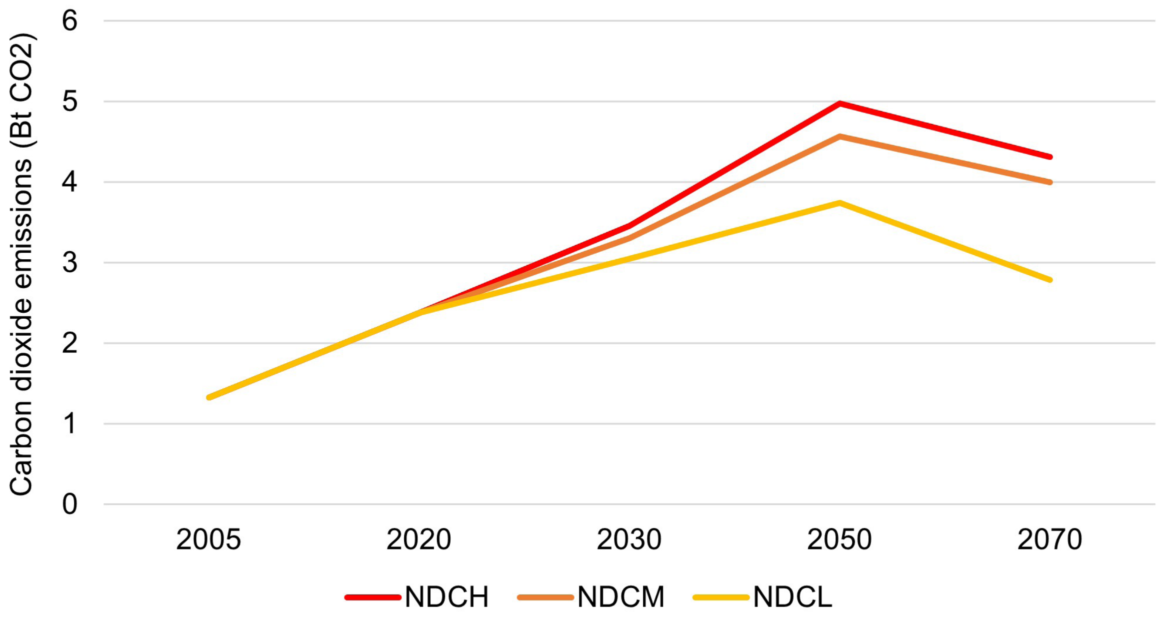
Figure 5.4: FEC in the industry sector under NDCH, NDCM, and NDCL growth scenarios in the long term



5.4 GHG emissions

Carbon emissions increase to 5, 4.6, and 3.7 btCO_2, peaking in 2050, to decrease to 4.3, 4, and 3 btCO_2 in 2070 under NDCH, NDCM, and NDCL growth scenarios, respectively (Figure 5.5). The cumulative budget between 2020 and 2050 is estimated to be 200 btCO_2 in the NDCH growth scenario, 190 btCO_2 in the NDCM growth scenario, and 148 btCO_2 in the NDCL growth scenario. Compared to 2020 emission estimates, the 2070 emission estimates are 75% higher in the NDCH growth scenario, 68% higher in the NDCM growth scenario, and 15% higher in the NDCL growth scenario. Decarbonization of the power sector is responsible for the major decrease in overall emissions. Transport is the second major sector responsible for a reduction in emissions because of an increase in electrification.

Figure 5.5: CO_2 emissions under NDCH, NDCM, and NDCL growth scenarios by 2070



5.5 Role of fossil fuels

In 2005, coal was the main source of energy for the power, industry, and building sectors. In 2022, India produced approximately 778.21 Mt of coal and imported about 200 Mt. India is the second largest producer of coal after China. The power sector (including captive power plants in the industry sector) used around 700 Mt of coal, and the industry sector (industry processes) used the rest. Coal remains the bedrock of India's energy economy until 2030 under NDC growth scenarios. The coal share in the total primary energy demand decreases from 28–31% in 2030 to 14–25% in 2070. Until 2030, coal demand aligns with economic growth; however, the demand gets detached after 2030 because of the implementation of revised energy and climate policies.

In 2005, oil remained the major fuel in the transport, building, and agriculture sectors. India imports over 80% of its oil from the Middle East, Africa, and Latin America. It is the second largest importer of oil after China. The subsidies for transport fuel (petrol and diesel) prices were removed in 2015–2016. LPG and kerosene are currently sold at a subsidy to low-income households. The oil share in the total primary energy demand remains around 20–21% in 2030 and reduces to 12–16% in 2070. It reduces in the transport sector with an increase in EVs by 2030 because of the pro-climate policies (blending policies, improvement in the technical efficiency of engines, a shift toward two-wheeler, three-wheeler, and four-wheeler EVs by 2030).

India's natural gas demand has outpaced its domestic production. About 50% of natural gas consumed in India is imported, and the share of natural gas has remained around 6–7% in the primary energy mix. The city gas distribution catering to residential and commercial households has been installed in 18 states. The demand for natural gas as fuel in the power and industry sectors has increased more than 10-fold. Most of the natural gas (over 50%) is used by the power sector, followed by the industry sector. The use of natural gas in the industry increases two to threefold by 2070. The use increases in the building sector until 2050; however, it will be phased out because of the electrification of cooking and other services by 2070. Natural gas shares in the total primary energy demand increase from 13–18% in 2030 to 18–24% in 2070.

5.6 Role of renewables

The NAPCC had a renewable target of 100 GW in 2010 (to be achieved by 2020), which was raised to 175 GW in 2015 (to be achieved by 2022), as mentioned in India's first NDC. In 2019, the non-fossil power capacity share was further ratcheted up to 450 GW (to be achieved by 2030), which was finally enhanced to 500 GW at COP26 in Glasgow (in 2021). In addition to gradually raising its own renewable targets, the Indian government has also shown leadership by co-initiating the International Solar Alliance (ISA) with France, which has 81 countries as its members. The solar target of 100 GW under the NDC has been increased to 280 GW, while the wind target of 60 GW has been increased to 140 GW under the revised second NDC to be achieved by 2030.

India has implemented several policy initiatives to support the expansion of RE. Installation of renewables, in addition to rooftop solar, has been observed mainly in the power sector. The industry, transport, and building sectors prefer to increase the renewables in the electricity share and use off-grid solar (buildings, agriculture). An increase in renewables to 600–700 GW in 2070 will require the flexibility of the current grid infrastructure in a phased manner. About 1 MW of solar photovoltaic (PV) may require around 1–1.5 hectares (ha) of land, so 60 GW of solar power would require about 600–900 km2 of land area at an all-India level. However, site location for solar PV plants may require land acquisition in quasi-habituated areas for shorter grid evacuation infrastructure, which could pose a challenge. Moreover, installing 40 GW of solar rooftops is also a challenge, mainly because of diminishing financial returns—as solar prices are falling rapidly, which reduces the high-end customer base—and increased supplier competition. Therefore, solar PV needs to be integrated with other value-added services and initiatives such as smart microgrids, battery storage, and charging of EVs. Battery storage technologies (grid connected as well as mobile) will become essential to maintain grid balance. In the medium- and long-term scenarios, the production and supply of critical minerals will become increasingly important.

5.7 Role of critical minerals

Minerals and metals will play a pivotal role in the transition to a much lower carbon future, and the minerals and metals sector may experience considerable changes. Metals are essential for the generation and use of energy. The transition to a low-carbon economy, which will be focused on low-carbon power generation and energy-efficient technologies, has the potential to profoundly alter the magnitude and composition of mineral and metal demand. (The World Bank, 2017). Ali et al. (2017) explained that huge amounts of metals and minerals are needed for an adequate supply of raw materials to manufacture clean technologies to tackle climate change. In this study, we estimate the future demand for raw materials focusing on clean technologies such as solar, wind, battery storage, and nuclear energy in various future scenarios for clean energy. See Annexure 7 for the methodology adopted for this study.

The shift to "clean" energy emphasis more on mineral-intensive than fossil-based electricity generation. Table 5.2 shows the overview of minerals used with relevant low-carbon technologies. Copper, aluminum, manganese, chromium, nickel, and molybdenum are the critical minerals for a range of low-carbon technologies.

Our study illustrates the future availability of some raw materials considering all clean technologies. All structural materials such as concrete, steel, plastic, glass, aluminum, chromium, copper, iron, manganese, molybdenum, nickel, and zinc, as well as technology-specific materials such as rare-earth elements and minor metals, are expected to see a significant rise in demand. India lacks domestic endowments for some of the raw materials imported from different countries. Any mineral shortfall will have to be imported. There are supply concerns such as the environmental and energy-use impacts of increased extraction of mineral resources and the relative vulnerability of developed countries to the supply of critical elements required for the shift to clean energy.

Table 5.2: Minerals used in different low-carbon technologies

S. No.	Mineral	Wind	Solar PV	Energy Storage (Li-ion)	Nuclear
1	Aluminum	▨	▨	▨	▨
2	Chromium	▨		▨	▨
3	Cobalt			▨	
4	Copper	▨	▨	▨	▨
5	Graphite			▨	
6	Indium		▨		▨
7	Iron	▨		▨	▨
8	Lead	▨	▨	▨	▨

S. No.	Mineral	Wind	Solar PV	Energy Storage (Li-ion)	Nuclear
9	Lithium			▨	
10	Manganese	▨		▨	▨
11	Molybdenum	▨	▨		▨
12	Neodymium (proxy for rare earths)	▨			
13	Nickel	▨	▨	▨	▨
14	Silver		▨		
15	Titanium				▨
16	Vanadium			▨	
17	Zinc	▨	▨	▨	
18	Uranium				▨

Source: Hund et al. (2020), IEA (2022) ; IEA (2021)

Note: The original table by Hund et al. concentrated on select 18 minerals and didn't include uranium. This has been added by the authors. Also, Hund et al. included iron only with reference to its use in the generator core, etc. However, iron is used in nuclear reactors in the form of steel and this is indicated in the above table.

See Annexure 7 for the detailed results of mineral needs assessments.

Recently, the Geological Survey of India discovered lithium reserves of an estimated 5.9 million tons in Jammu and Kashmir. Although this is still at the exploratory stage, and the viability of extraction and quality is yet to be verified, this discovery poses a silver lining for India in achieving its NZ 2070 targets. Lithium is especially critical for clean transitions because of its use in aluminum manufacturing and battery applications, which impact wind, solar, energy storage, and electric-mobility-related transitions.

With the increasing demand for minerals for clean transitions, technological development on the reuse, recovery, and recycling of critical minerals would also become important. Refurbishing, recycling, and mineral recovery would play a vital role in limiting and meeting future mineral demands. However, the recycling of minerals comes with its own energy penalty – for example a study found that recovery of lithium from lithium batteries leads to 38-45% higher energy consumption compared to its primary production (Golroudbary et al., 2019).

5.8 Kaya identity

To further understand the underlying drivers of CO_2 emissions in the NDC scenarios, we use the Income, Population, Affluence, and Technology (IPAT) model, also known as the Kaya identity (IPCC, 2000; Kaya, 1990). See Equation 1 for the Kaya identity used for this analysis.

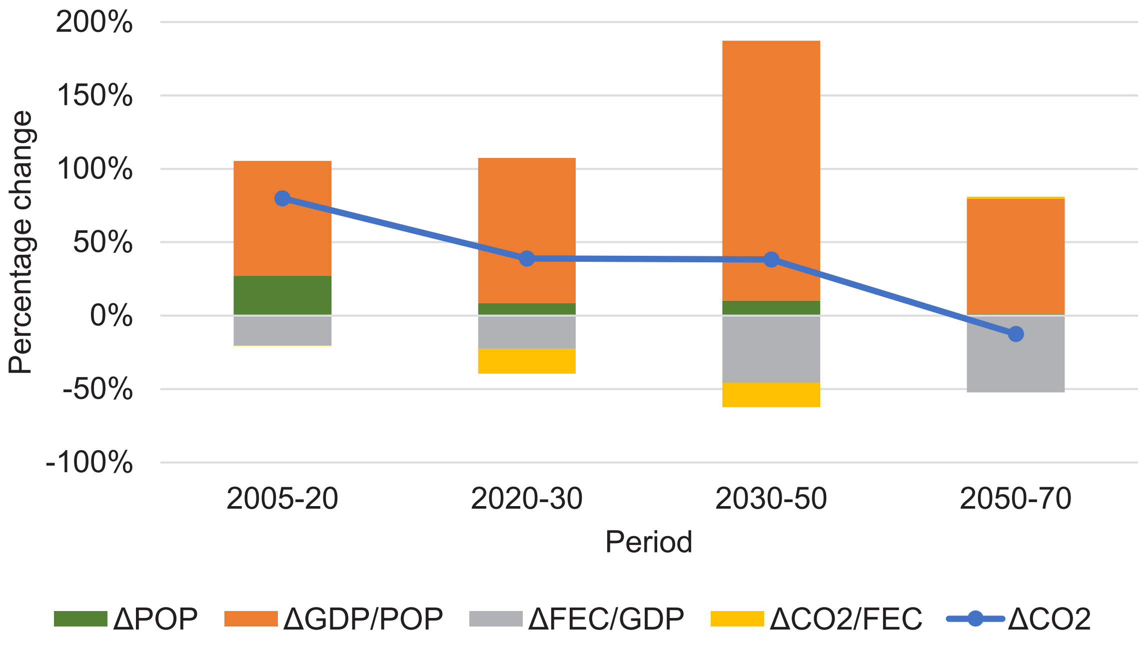
$$CO_2 = POP * \frac{GDP}{POP} * \frac{FEC}{GDP} * \frac{CO_2}{FEC} \qquad \text{--(1)}$$

Here, CO_2 = CO_2 emissions, POP = population of the country, FEC = final energy consumption in the economy, and GDP = gross domestic product for the year.

The Kaya identity was used to benchmark the effect of different emission drivers in the current energy system and was further employed to evaluate the role of these drivers in energy transitions under the NDC scenarios. See Figure 5.6 for an illustration of the NDCM growth scenario. Our scenario results suggest that the emission intensity of GDP decreases by over 80% between 2005 and 2070, but the overall CO_2 emissions do not reach zero by 2070. After diving deeper into these results, we find that the growth rate of CO_2 emissions sees a downward trend after

2020 because of the NDCs and other policy measures undertaken during this period. Moreover, we anticipate the continuation of the climate policies from 2030 to 2070, which will further reduce the rate of growth of CO_2 emissions. The energy intensity of GDP was already negative in the reference period owing to technological advancements and policies such as the National Mission on Enhanced Energy Efficiency (NMEEE), which includes schemes such as Perform, Achieve and Trade (PAT) for large industries, CAFÉ standards for the transport sector, and the Energy Conservation Building Code (ECBC) for the buildings sector. In addition, drastic improvements in end-use technologies (for example, LED lights), electrification, and modal shift in the transport sector and other conservation measures would lead to the rate of energy intensity of GDP reducing further between 2015 and 2070. However, these measures cannot counterbalance the rate of growth in per-capita income, which becomes the major driver for CO_2 emissions in the NDC scenarios. Hence, despite the low-carbon transitions, India's total CO_2 emissions will remain around 4 billion tons in 2070 under the NDCM growth scenario.

Figure 5.6: Drivers of CO_2 emissions under the NDCM growth scenario



Notes: ΔPOP, population growth; ΔGDP/POP, growth in per-capita income; ΔFEC/GDP, change in the energy intensity of GDP; and ΔCO_2/FEC, change in the CO_2 emissions intensity of energy consumption.

5.9 Affordability vs. emission intensity of electricity

A concern regarding decarbonization policies is that they could raise the cost of energy. As the share of electricity in end-use services rises, the cost and affordability of electricity would become a concern in an emerging economy such as India. Similarly, switching to VRE technologies, such as solar and wind, which require storage and flexible grid operations, may be expensive and require further evaluation. The LCOE, despite its limitations, is a useful metric and is widely used to compare the cost of electricity across different technologies (IEA, 2020b). It is pertinent to mention here that since LCOE assessments do not include any parameter related to intermittency, they tend to overestimate the economic efficiency of RE and the extent of overestimation goes up with an increase in the penetration of renewable technologies (Ueckerdt et al., 2013). Therefore, metrics such as value-adjusted LCOE (VALCOE) have been proposed. For one case (stated policy scenarios for India in 2050), the results of VALCOE have been reported as follows. For nuclear, LCOE and VALCOE remain the same at 65 USD/MWh,[11] but for solar, LCOE is 15, while VALCOE is 55 USD/MWh. With the increasing penetration of variable renewables, there is a growing realization that while renewable sources are needed for decarbonization, firm dispatchable sources such as nuclear and fossil with carbon capture and storage (or use) have to be a significant part of the energy mix. Electricity must be generated and provided to consumers wherever they are located and whenever they need it. This results in high integration costs for renewables because of their variability and non-dispatchability. The current practice of socializing the integration cost of renewables is a hidden subsidy. Nevertheless, on the basis of LCOE, estimates of energy, capacity, and flexibility are incorporated to provide a more complete metric of competitiveness for power generation technologies (IEA, 2022b).

See Annexure 8 for the detailed calculation methodology.

Figure 5.7: LCOE vs. emission intensity of electricity in the NDCM growth scenario

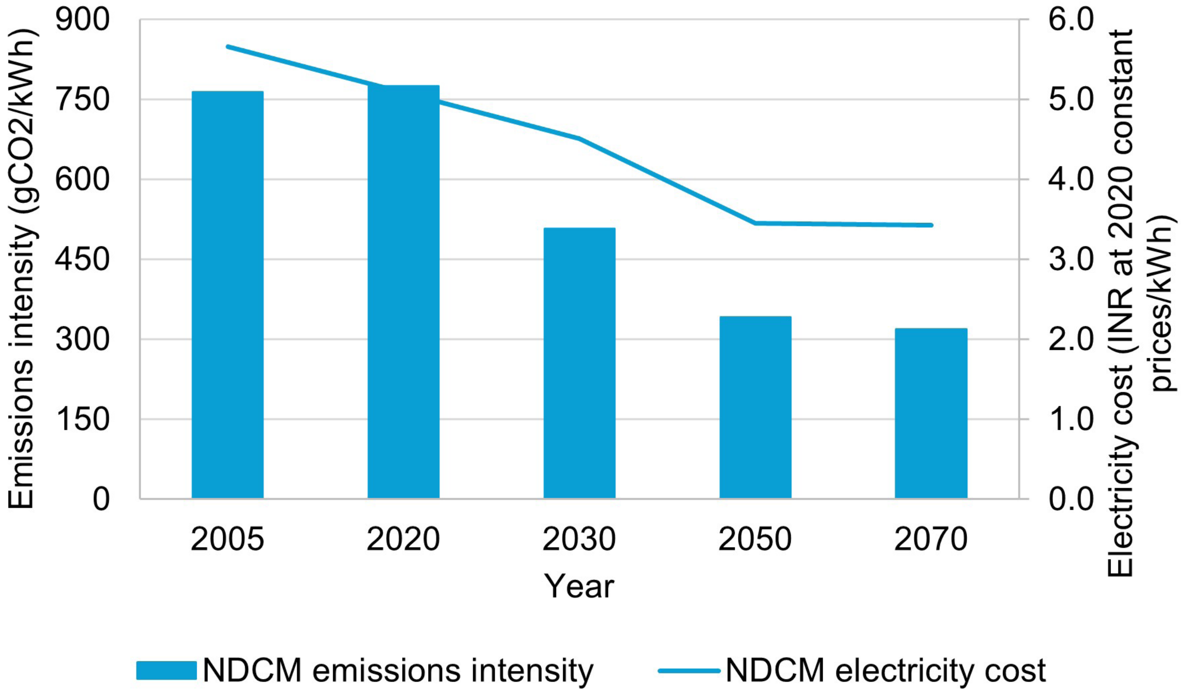


Figure 5.7 illustrates the LCOE vs. emission intensity under the NDCM growth scenario. The cost of electricity is reported after accounting for transmission and distribution losses, which are assumed to reduce from over 25% in 2005 to less than 10% in 2050, in line with the current policies for the electricity sector. The investment and installation costs of nuclear power plants are high in the current policy scenario. For this analysis, the investment costs of nuclear were assumed to be approximately INR 15 crores per MW in 2020. Additionally, the cost of new coal plants remains stable around the 2020 numbers, in line with the CEA projections. The rising share of solar energy, whose prices are assumed to further reduce in coming years, contributes to the lowering of electricity costs in the current policy scenario. Because of the rising share of cleaner and cheaper electricity generation technologies, the emission intensity in the NDCM growth scenario will be reduced by approximately 60% between 2020 and 2070. This high share, coupled with the falling costs of solar, wind and battery storage reduce the cost of electricity in future net-zero scenarios. In addition, we assume a reduction in cost of capital (WACC is assumed to go down from 9.5% today to approximately 5% in 2070) which further bring down the LCOE in future scenarios.

Chapter 6:
NET ZERO 2070 SCENARIOS

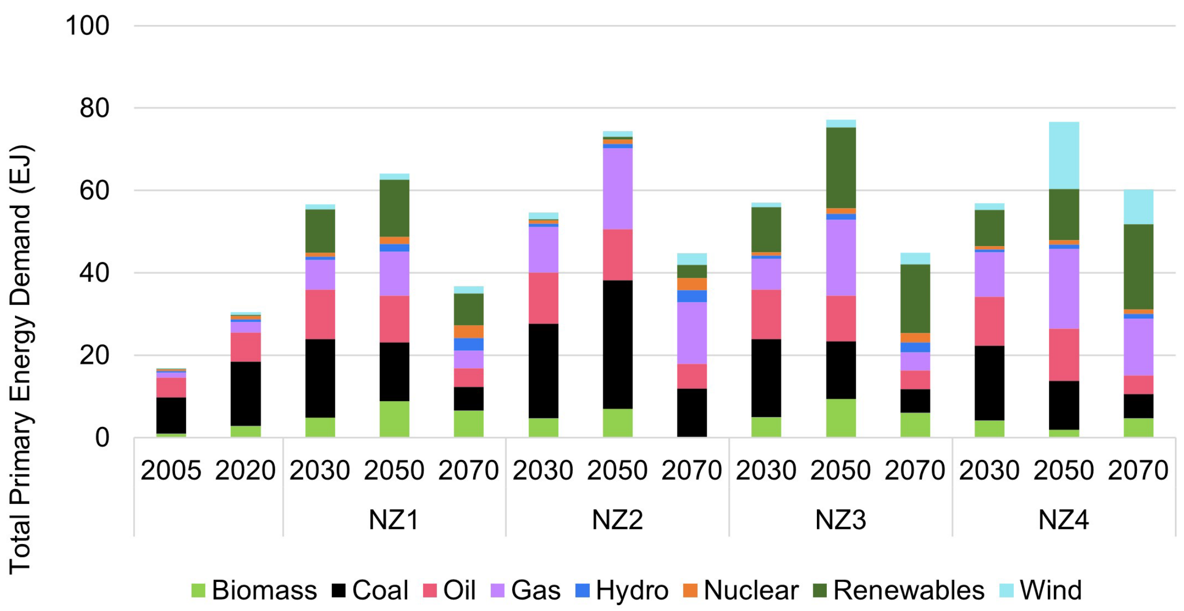
6. Net Zero 2070 Scenarios

This chapter presents an overview of the total primary energy demand, required power supply, electricity projections, FEC in end-use sectors, and subsequent CO_2 emissions under NZ pathways until 2070. We have further discussed the LCOE, carbon intensity, and related investment needs.

6.1 Total primary energy demand (TPED)

Figure 6.1 shows the total primary energy demand by fuel, until 2070. The primary energy growth in the NZ scenarios is set to increase at an annual rate of 5.6–6.0% by 2030, followed by an increase at an annual rate of 1.1–2% between 2030 and 2050 and a decrease at an annual rate of 0.6–1.7% between 2050 and 2070. The share of coal ranges from 28% to 35% in 2030 and further from 7% to 17% by 2070. The oil share decreases to about 18–19% in 2030 and further to 5–9% by 2070. The natural gas share increases to about 11–17% in 2030 and 6–22% in 2070. We have used medium economic growth projections for all NZ scenarios.

Figure 6.1: Total primary energy demand by fuel under NZ scenarios in the long term



Note: Under NZ2 for 2070, the biomass value stands at 0.6 EJ, hence may not be clearly visible in the figure above.

The model estimates electricity and energy demand from end use sectors, and then selects technologies from energy supply that should meet the estimated demand from enduse sectors. Between 2050 and 2070, across the four NZ scenarios, the industry sector accounts for a share of 58-65 per cent, the building sector for 16–26%, the transport sector for 11–16%, and the agriculture sector for 4–8%. The demand reduction post 2050 can be attributed to demand moderation and uptake of energy efficiency measures and as per India's commitment to LiFE (Lifestyle for Environment) to promote sustainable lifestyles.

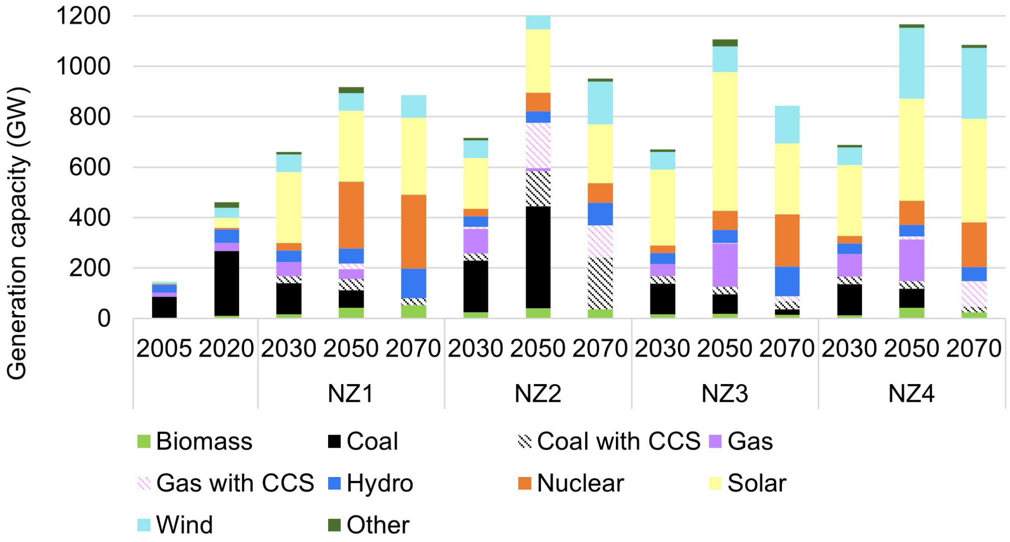
6.2 Electricity projections

Figure 6.2 and Table 6.1 display electricity generation capacity under NZ scenarios in the long term until 2070. Between 2020 and 2070, the electricity generation capacity increases at a

CAGR of 1.87% in the NZ1 scenario, reaching 953 GW, while it increases at a CAGR of 1.86% in the NZ2 scenario, reaching 951 GW. It increases at a CAGR of 2.25% in the NZ3 scenario, reaching 1149 GW, and at a CAGR of 2.14% in the NZ4 scenario, reaching 1,088 GW. The share of fossil fuel capacity decreases from 70% to 5% in the NZ1 scenario, to 35% in the NZ2 scenario, and to 12% in the NZ4 scenario in 2070. In contrast, the share of renewables (including hydropower) increases to 75% in the NZ3 scenario and to 71% in the NZ4 scenario in 2070. The share of nuclear capacity increases to 35% in the NZ1 scenario, to 8% in the NZ2 scenario, to 18% in the NZ3 scenario, and to 16% in the NZ4 scenario in 2070.

Figure 6.3 presents the trend and share of electricity generation under various NZ scenarios. The generation supply increases at a CAGR of 2.1% in the NZ1 scenario, reaching 4399 TWh between 2020 and 2070. Similarly, in the NZ2 scenario, it increases at a CAGR of 2.2% and reaches 4,578 TWh, while in the NZ3 scenario, it increases at a CAGR of 2% and reaches 4271 TWh. In the NZ4 scenario, it increases at a CAGR of 2.3% and reaches 4,958 TWh. The share of fossil fuel generation decreases to 2% in the NZ1 scenario, to 44% in the NZ2 scenario, to 27% in the NZ3 scenario, and to 13% in the NZ4 scenario in 2070. The share of renewable (including hydropower) generation increases to 49% in the NZ1 scenario, to 42% in the NZ2 scenario, to 62% in the NZ3 scenario, and to 60% in the NZ4 scenario in 2070. The share of nuclear generation increases to 49% in the NZ1 scenario, to 12% in the NZ2 scenario, to 35% in the NZ3 scenario, and to 26% in the NZ4 scenario in 2070. The steep decline in 2070 is a combination of a) improved technical efficiency of technologies that results in overall energy efficiency, b) material efficiency, c) demand reduction across all sectors, d) decrease in transmission and distribution losses. Further, one of the insights from the study is the increase of fossil fuel stranded assets in 2070 based on the energy demand. We recommend further assessment on the feasibility of the options to recommend an action plan on overall cumulative reduction in stranded fossil fuel assets.

Figure 6.2: Electricity generation capacity under NZ scenarios in the long term



The economy-wide FEC increases from 11 EJ in 2005 to 30–32 EJ in 2070 under different NZ scenarios. The electricity share in the FEC under the NZ1 scenario is approximately 20% in 2030 and 50% in 2070. Similarly, the electricity share in the FEC under the NZ2 scenario is approximately 26% in 2030 and 52% in 2070. In the NZ3 scenario, it is approximately 21% in 2030 and 48% in 2070, while in the NZ4 scenario, it is approximately 22% in 2030 and 47% in 2070. Electricity generation ranges between 4270 – 5000 TWh across NZ scenarios in 2070. The electricity share is a percentage of final energy consumption. This is because the electricity required for carbon capture, utilization and storage, hydrogen production and auxiliary consumption have been accounted for in these estimates.

There is substantial variability in hydrogen uptake in prospective net-zero scenarios (please refer section 6.3).

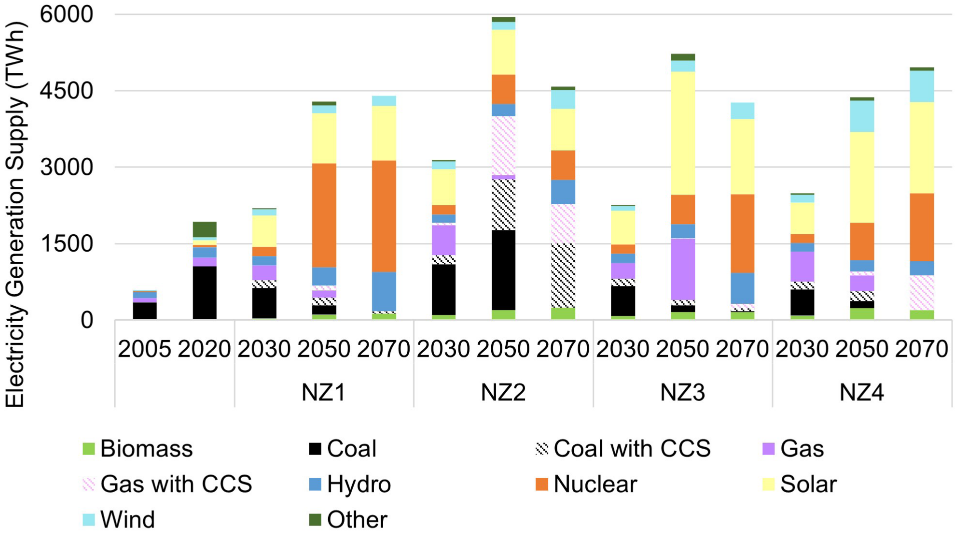
Table 6.1: Electricity generation capacity (in GW) under all scenarios in the long term

Scenario	Year	Bio-mass	Coal (includes lignite)	Coal with CCUS	Gas	Gas with CUCS	Hydro (includes pumped storage)	Nuclear	Solar	Wind	Other	Total
	2005*	1.1	71	0	16	0	32	3.36	0.5	7	0	131
	2020**	10	206	0	25	0	51	6.7	37	39	1	375
NDCH	2030	34	227	47	82	10	53	11	166	63	19	712
	2050	42	194	92	132	11	65	75	370	70	24	1075
	2070	57	163	98	157	49	69	90	540	100	25	1348
NDCM	2030	35	220	13	95	3	53	11	149	58	16	653
	2050	33	170	25	189	32	67	75	320	70	23	1004
	2070	30	135	25	155	16	67	80	540	80	22	1150
NDCL	2030	22	186	2	95	2	57	18	108	53	10	553
	2050	35	132	12	115	13	63	35	180	70	20	675
	2070	23	96	6	105	14	64	40	180	80	17	625
NZ1	2030	16	123	29	55	0	46	30	281	70	9	659
	2050	43	69	44	40	21	61	265	281	70	23	917
	2070	51	0	29	0	21	117	331	304	100	0	953
NZ2	2030	24	204	29	97	7	43	30	201	70	11	716
	2050	39	404	140	13	178	45	75	251	70	20	1235
	2070	35	0	207	0	126	91	78	233	169	12	951
NZ3	2030	16	122	29	47	0	45	30	301	70	10	670
	2050	18	77	29	172	2	53	75	551	200	28	1205
	2070	13	0	26	0	50	117	207	486	250	0	1149
NZ4	2030	13	123	29	90	0	42	29	281	71	10	688
	2050	41	77	29	166	12	45	95	405	281	15	1166
	2070	23	0	26	0	101	56	178	410	282	12	1088

Note: ** Numbers are based on the Energy Statistics 2007 for financial year 2005-06 and Growth of Electricit sector in India, CEA, 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at around 14 GW.*

*** Numbers are based on CEA's General Review 2022 and installed capacity reports upto December 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at 47.8 GW.*

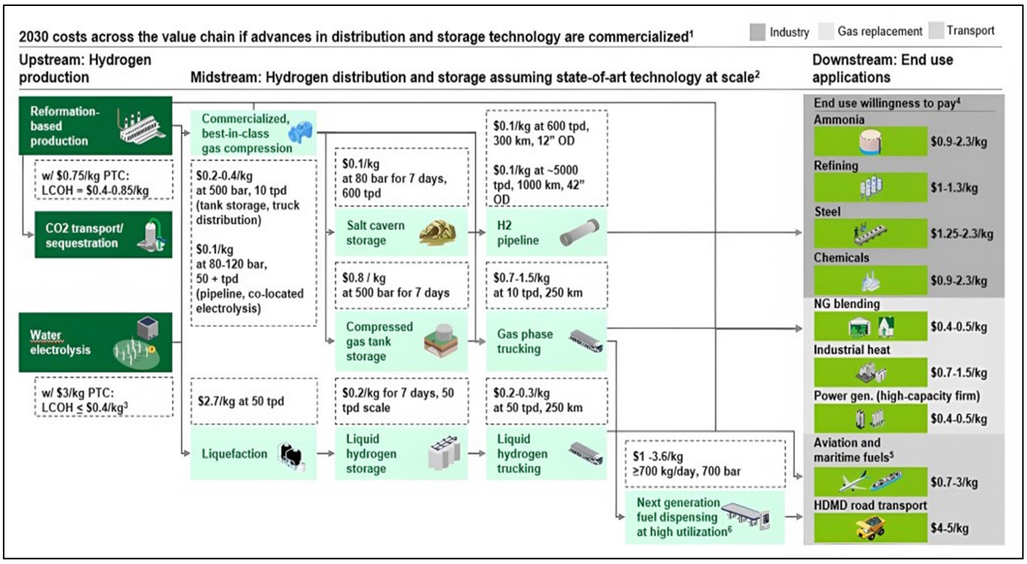
Figure 6.3: Electricity generation supply under NZ scenarios in the long term



6.3 Hydrogen for clean energy transitions

Hydrogen may be termed by different names depending upon the production processes and fuels used. For instance, green hydrogen is produced using renewable power as the energy source to electrolyze water. Blue hydrogen is produced mainly from natural gas, using a process called steam reforming, with hydrogen and CO_2 as outputs wherein CO_2 must be captured using CCUS. If CO_2 is not captured, it becomes grey hydrogen. If coal or lignite are used instead of gas, it is termed black or brown hydrogen. Similarly, nuclear-derived hydrogen may be called purple hydrogen and naturally occurring hydrogen as white or gold hydrogen. Irrespective of the nomenclature, the critical metric is the greenhouse gas intensity of hydrogen which must be reflected in the entire value chain. Figure 6.4 describes the hydrogen value chain.

Figure 6.4: Hydrogen value chain



Sources: HDSAM, Argonne National Laboratory; DOE National Hydrogen Strategy and Roadmap, Hydrogen Council
HDMD- heavy duty and medium duty

1. *Data based on cost-downs shared from leading-edge companies who have deployed at demonstration scale (or larger)*
2. *Range based on varying renewables costa and electrolyzer sizes/technologies.*
3. *Defined as the price an off-taker will pay for clean hydrogen*
4. *Represents delivery of hydrogen to aviation and maritime fuel productions facilities*
5. *Greater than or equal to 70% utilization, assumes line fill at high pressure.*

Low-carbon or renewable hydrogen is normally perceived to be the prominent energy carrier in future. Renewables, nuclear, CCS and hydrogen (among others) are projected to contribute towards NZ transitions under alternate scenarios based on technological developments and relative economics. Scaling-up hydrogen technologies would require several policy and technological interventions. The Ministry of New & Renewable Energy has released a document on Green Hydrogen as having a well-to-gate emissions (i.e., including water treatment, electrolysis, gas purification, drying and compression of hydrogen) of not more than 2 kg CO_2 equivalent / kg H_2, further, it also outlines that these emission thresholds must be met in order for hydrogen produced to be classified as 'Green', i.e., from renewable sources[12]. In view of the findings of this study, we recommend that all forms of low-carbon hydrogen below a GHG intensity of 2 $kgCO_2e/kgH_2$ could be incentivized, instead of just hydrogen obtained from renewables. The nature of these incentives could of course vary. For instance, Canada offers a different rate of tax credit for different ranges of GHG intensity from <0.75 $kgCO_2e/kgH_2$ to 4 $kgCO_2e/kgH_2$. Doing so could provide a level playing field to different energy sources used for hydrogen production.

There is substantial variability in hydrogen uptake in prospective net-zero scenarios. Overall, there is large uncertainty based on the costing assumptions of hydrogen production and use from various sources. Even so, the interquartile range for hydrogen's share in final energy is 1-6% overall and 2-8% in the industry sector as per the IPCC Sixth Assessment Report. If costs come down more drastically, some expert elicitations suggest that this share may increase as high as 40% (Bhattacharya et al, 2022). Hydrogen use may be considered as a spectrum – from unavoidable to uncompetitive, considering products such as methanol or hydrogenation of biodiesel. Low-carbon hydrogen production is imperative for these. This is also the case – in large part – for industrial processes such as DRI production and power-to-X as a form of energy storage. For other use cases, such as light-duty vehicles and domestic heating, electrification is much more amenable.

Steel sector deserves a specific mention here as a "difficult to abate" sector globally. Steelmaking process requires reduction of iron ore that is currently being done using coking coal or electricity. Green hydrogen based direct reduction of iron ore is projected to be an important technology for the steel sector in future. The Indian steel sector capacity is projected to grow to around 300 million ton by 2030 (around 150 million ton currently) and touch 500 million ton by 2050. The requirement of renewable energy (mainly solar and wind as per the current international thinking) to produce green hydrogen for so much steel would be daunting for India. Moreover, hydrogen production would require continuous electricity. Alternate input energy sources must be thought through. Biochar made from bamboo, rice stalks, cotton residues could also provide good options in India. The financial returns would mostly go to the farmers and could promote green energy ecosystems in rural areas. This would also create many green employment opportunities. For instance, to produce 100 million tons of steel, around 63-77 million ton of coal and coke are required. If we can replace even a fifth of coking coal with biochar by 2030, we may be reducing CO_2 emissions from steel industry by 20% as biochar is biogenic and is considered carbon neutral. We may need about one lakh (100,000) hectare of land to grow bamboo plantations for the Indian steel industry of today. Our initial results for GIS based optimization for energy plantations at all India district level indicate that about 121 Indian districts could be targeted for bamboo plantation as energy plantation. Biochar is about a third to 40% of dry bamboo crop. For instance, one ton of green bamboo after drying up may give 750-800 kg of dry bamboo, which in turn will give about 300-320 kg of biochar. Average crop

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[12] https://mnre.gov.in/img/documents/uploads/file_f-1673581748609.pdf

yield (including water) could be considered as 100 tons/hectare in India (up to 200 tons/ha in some parts of India's northeast with India having around 120 types of bamboo varieties). Bamboo plantation used as energy plantation could therefore employ considerable farm hands as well as in rural energy industry.

Hydrogen growth requires cost reductions via endogenous learning. As such, initial electrolyzer development can yield hydrogen that may be blended with natural gas. For doing this, it is necessary to match blending limits with end-uses. Most existing infrastructure (e.g., gas power plants) can tolerate only up to 5-6% hydrogen. NTPC has started blending at this level in the piped gas network in Surat. The maximum blending limit is 20%. It is recommended that blending guidelines are accordingly reframed in the Indian context (IRENA, 2020). Electrolyser units with small capacity (1-3 MW) could be beneficial to promote decentralized mode of green hydrogen production. Initially, it is essential to support the production of hydrogen from a variety of sources, including renewable energy, fossil fuels with carbon capture, utilization & sequestration (CCUS) technologies and nuclear energy, under the umbrella of clean hydrogen in order to speed up the availability of hydrogen in the market. This will ready the adoption of hydrogen as a carrier gradually in India and her energy basket. As demand picks up, the supply will also augment towards clean hydrogen (not more than 2 kg CO_2 equivalent / kg H_2) moving to green hydrogen. Thus, the government may not necessarily incentivize just green hydrogen from renewables, but any form of low-carbon hydrogen below a certain life cycle emission intensity. It could be termed "Clean Hydrogen". This is also the position adopted by some other governments, for instance by the United States in their 45V tax credits (Bergman, and Krupnick, 2022).

The current hydrogen intensity production from unabated fossil fuels is 10 to 14 kg-CO_2e/kg-H_2. With use of CCUS, this may reduce to nearly 2-3 kg-CO_2e/kg-H_2. This could itself represent a sizable reduction. Our results show that carbon intensity of 2 kg-CO_2e/kg-H_2 would be compatible with economywide net-zero emissions in 2070. The recently announced criteria by the National Mission of Green Hydrogen allocates Rs 17,490 crore under Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, which will be distributed through a Production-Linked Incentive (PLI) scheme for manufacturing of electrolysers and production of green hydrogen derived from renewables and pyrolysis. This is a welcome step indeed. It could be considered to expand it to be technology-agnostic and expand the scope to clean hydrogen production from nuclear energy sources, bioenergy (such as biochar production using bamboo, rice stalk etc) and also from fossil fuels with CCUS. This is important to develop India's capacity in high-temperature electrolysis and CO_2 capture from high-purity streams.

This allowable emissions intensity for hydrogen may be reduced in a phased manner over the next 2-3 decades. Emission intensity reduction gradually to around 4 kg-CO_2e/kg-H_2 in a decade and within 2 kg-CO_2e/kg-H_2 in long-term can be consistent with net-zero emissions. These should be considered in our revised NDCs and possible for use under Article 6 of the Paris Agreement. Of course, these would require some supplementation continuously through green hydrogen using renewable energy and/or nuclear power. Net zero would also anyway require support from GHG sequestration from the AFOLU sector. Regulatory changes also need to reflect hydrogen blending limits into natural gas networks. An analysis of the fugitive emissions from hydrogen transmission and distribution networks is also imperative because hydrogen could be more susceptible to leakages. Further, international co-operation to enable low carbon hydrogen reach appropriate markets at a feasible price would require some global standardization and certification related regulations. Similarly, hydrogen storage requires very low temperature (-252°C) and high pressure (350-700 bar). Alternatively, it can be converted to ammonia at 62 bar and reformed back to hydrogen during end-use, a process which leads to 7% energy loss relative to the hydrogen heating value (Singh and Dunn, 2022).

We caveat our modeling efforts by stating that most energy systems models arrive at their results via partial or global equilibrium. The extent to which they incorporate diffusion of breakthrough technologies may be limited in some cases. An example here is the thermochemical splitting of water via renewables or nuclear. These processes have been demonstrated and patented by Indian researchers at the ONGC Energy Centre. The energy consumption for these processes is low as they can occur at temperatures of 823-1173 K. Currently, these setups are in the process of scale-up to 10-12 MT-H2/year. Once commercialized, these systems may change the levelized cost of hydrogen production compared to the state-of-the-art shown in Figure 6.4.

6.4 Projected load curves in 2070

There are few long-term peak demand projections for India's electricity sector until 2070. The longest-term peak demand projections are from the CEA's 20th Electric Power Survey. Similar projections were also made in the 19th Electric Power Survey. On comparing the period from 2016–17 to 2021–22, we find the maximum difference in actuals and projections to be 10.81%. See Table 6.2 and Figure 6.5 for the peak demand projections of the 20th Electric Power Survey and for CAGR.

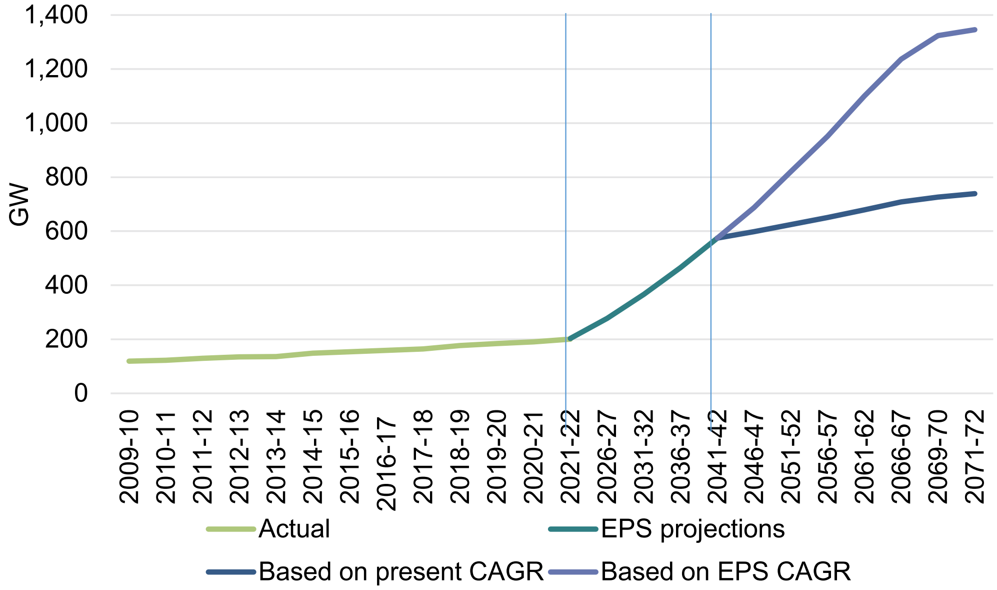
Table 6.2: Peak demand projections by the 20th Electric Power Survey

	Peak demand (GW)	CAGR (%)
2021–22	203.115	
2026–27	277.201	6.42
2031–32	366.393	5.74
2036–37	465.531	4.91
2041–42	574.689	4.30

Source: CEA, Report on 20th Electric Power Survey of India, Vol I

The load curves for 2070 have been projected using the capacities used in scenarios developed in accordance with the national energy model described in Chapter 3. The high peak demand scenario considers continuing with the EPS CAGR from 2042 till 2070, the low peak demand projections consider extending EPS projections after 2042 till 2070 using present CAGR till 2022 and the medium peak demand scenario considers CAGR reductions in projections as evidenced in table 6.2. Figures 6.6- 6.9 illustrate the load curve under the medium peak demand projections (dark blue line in Fig 6.5). However, if we use the present CAGR till 2022 with CAGR reductions factored to project loads in 2070 (following the yellow trajectory in Fig 6.5), we arrive at figures 6.10-6.13. These two sets have peak loads of 670 GW (Fig 6.6-6.9) and 946 GW for NZ1 and NZ2 and 964 GW for NZ3 and NZ4 in 2070 (Fig 6.10-6.13). These present two alternate assessments of total loads in 2070. Additional capacity indicated in Fig 6.10-6.13 across both peak loads could be appropriate fuel/technology depending upon scenario, its future policy thrust and the future demands achieved through the national modelling exercise. Energy modelling that tracks economy and energy transition towards net zero and evolution as well as penetration of technology is a complex problem with many potential inflections that could disrupt any model behavior. Subjective assumptions, constraints and policy evolution are inevitable and could lead to large variations in results. The actual realization of future could be somewhere in between 670 GW and 964 GW, or even something beyond. Our results are therefore policy indicative and not policy prescriptive.

Figure 6.5: Long-term peak demand projections



Source: 20th Electric Power Survey of India; Ministry of Power website; authors' own projections

Figure 6.6: Load curve under the NZ1 scenario in 2070 for peak load of 670 GW

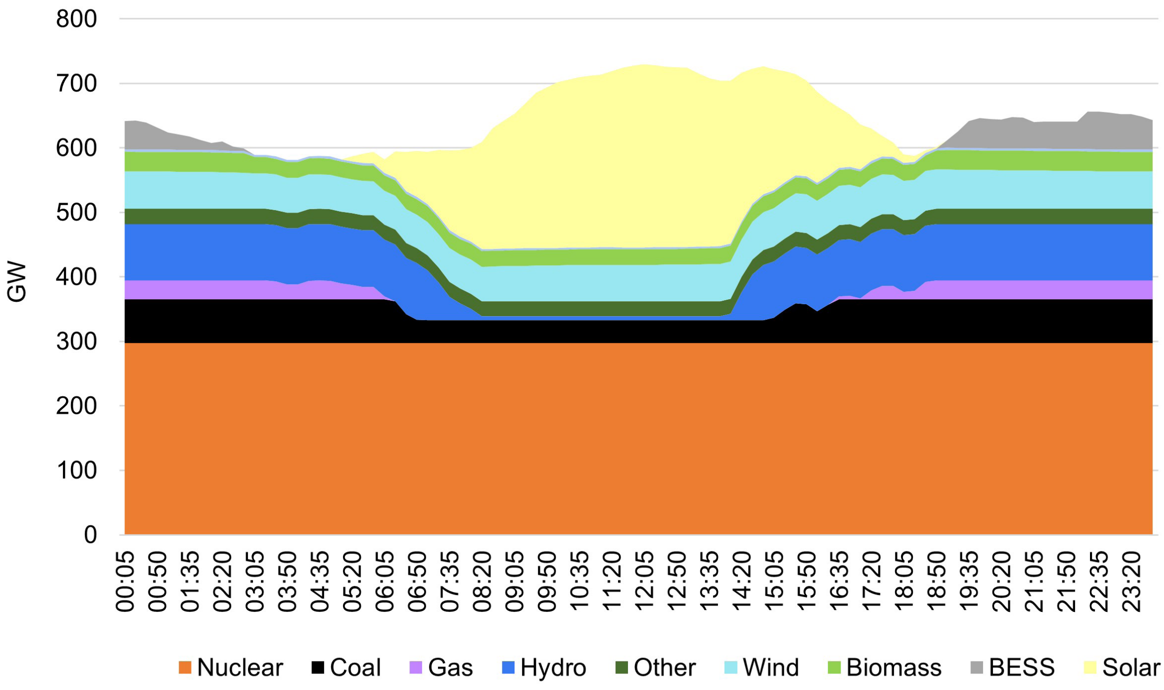


Figure 6.7: Load curve under the NZ2 scenario in 2070 for peak load of 670 GW

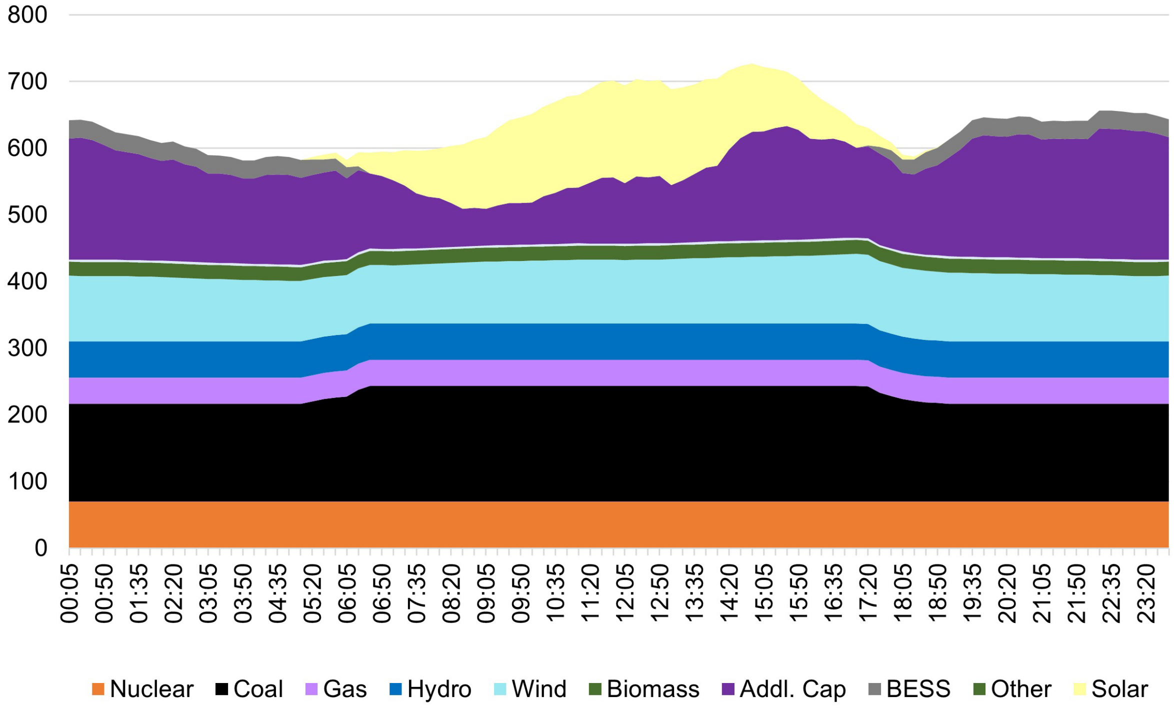


Figure 6.8: Load curve under the NZ3 scenario in 2070 for peak load of 670 GW

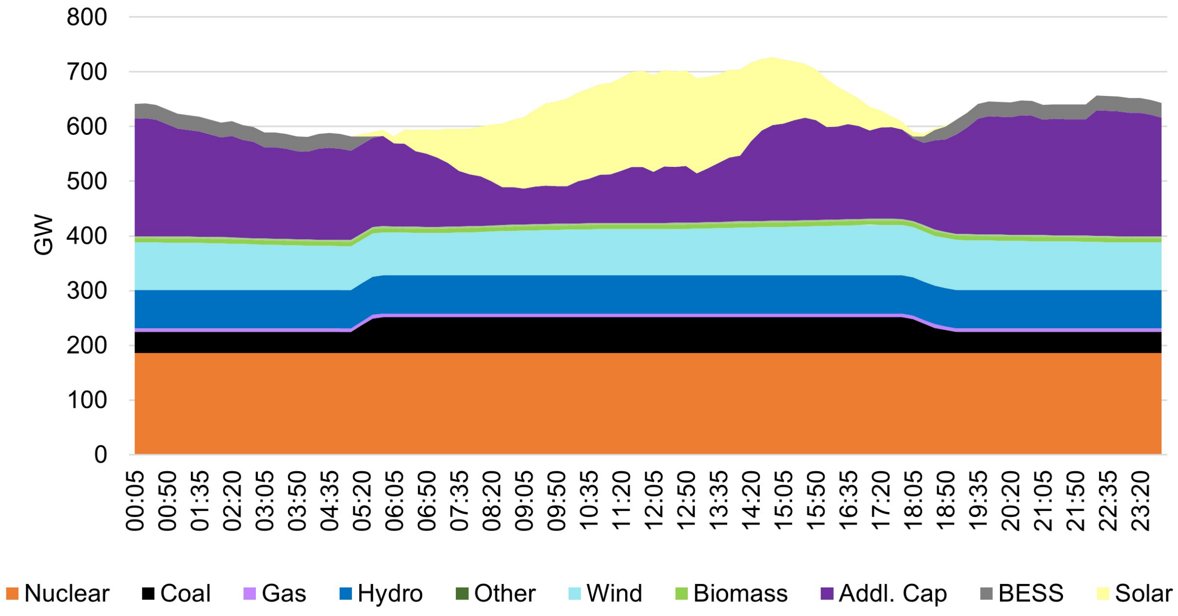
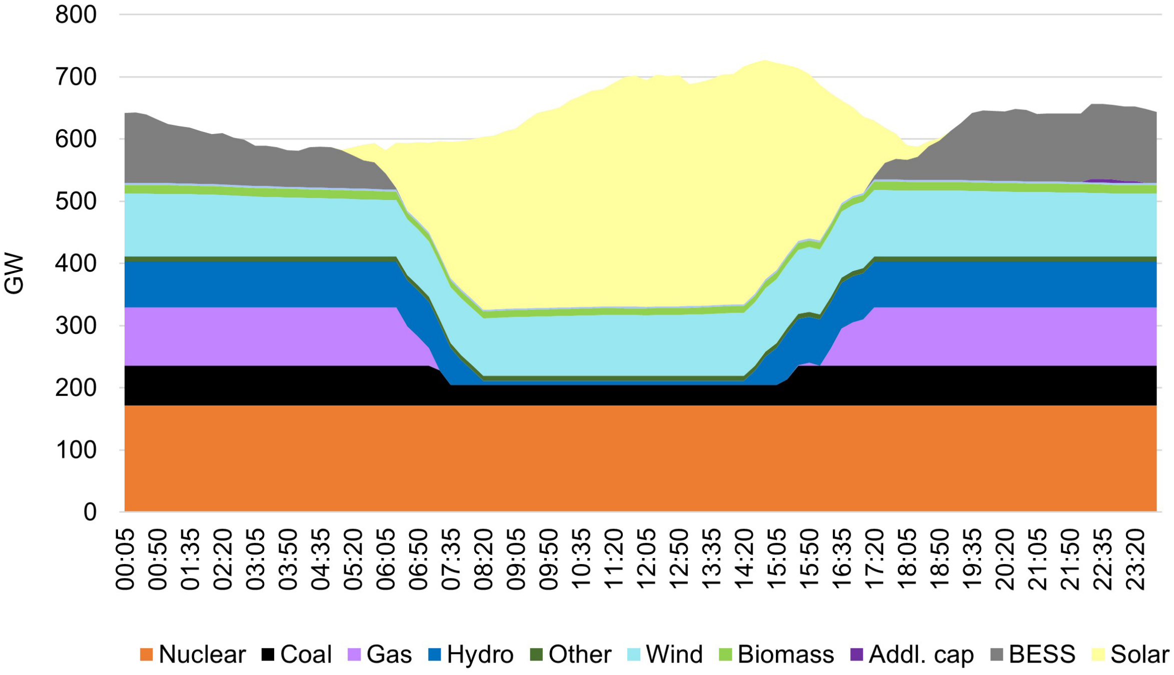


Figure 6.9: Load curve under the NZ4 scenario in 2070 for peak load of 670 GW



In addition to satisfying the conditions of grid integration, the above projections estimate the required battery capacities and their usage, as shown in Table 6.3.

Figure 6.10: Load curve under the NZ1 scenario in 2070 for peak load of 964 GW

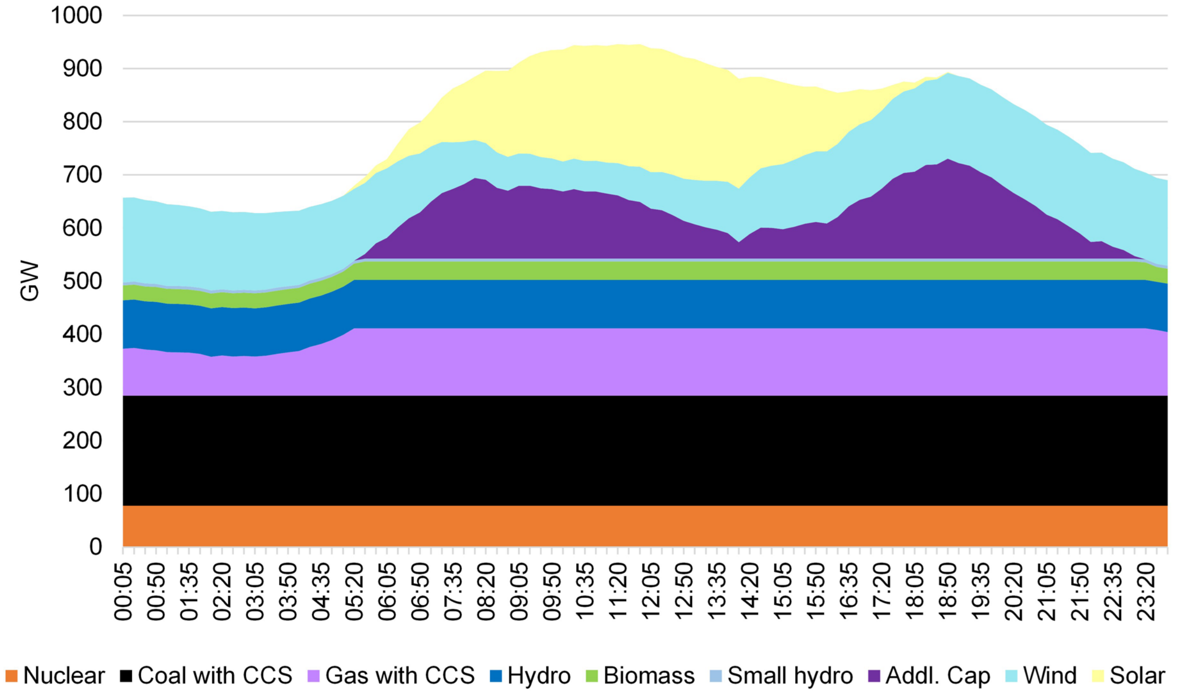


Figure 6.11: Load curve under the NZ2 scenario in 2070 for peak load of 946 GW

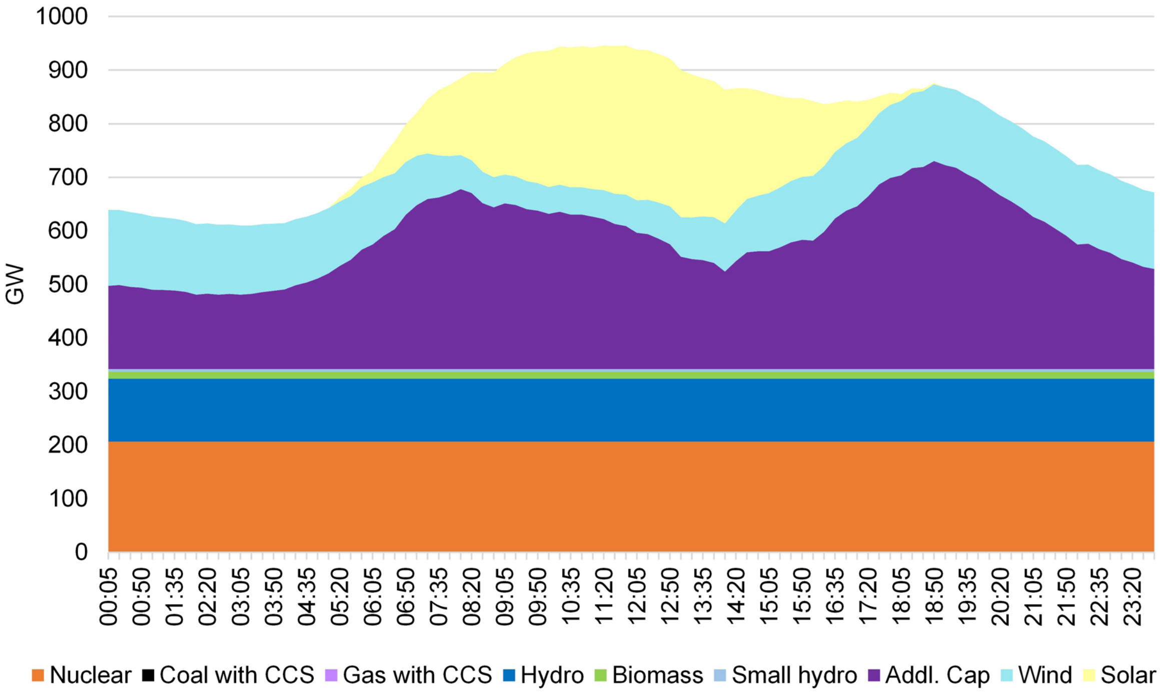


Figure 6.12: Load curve under the NZ3 scenario in 2070 for peak load of 964 GW

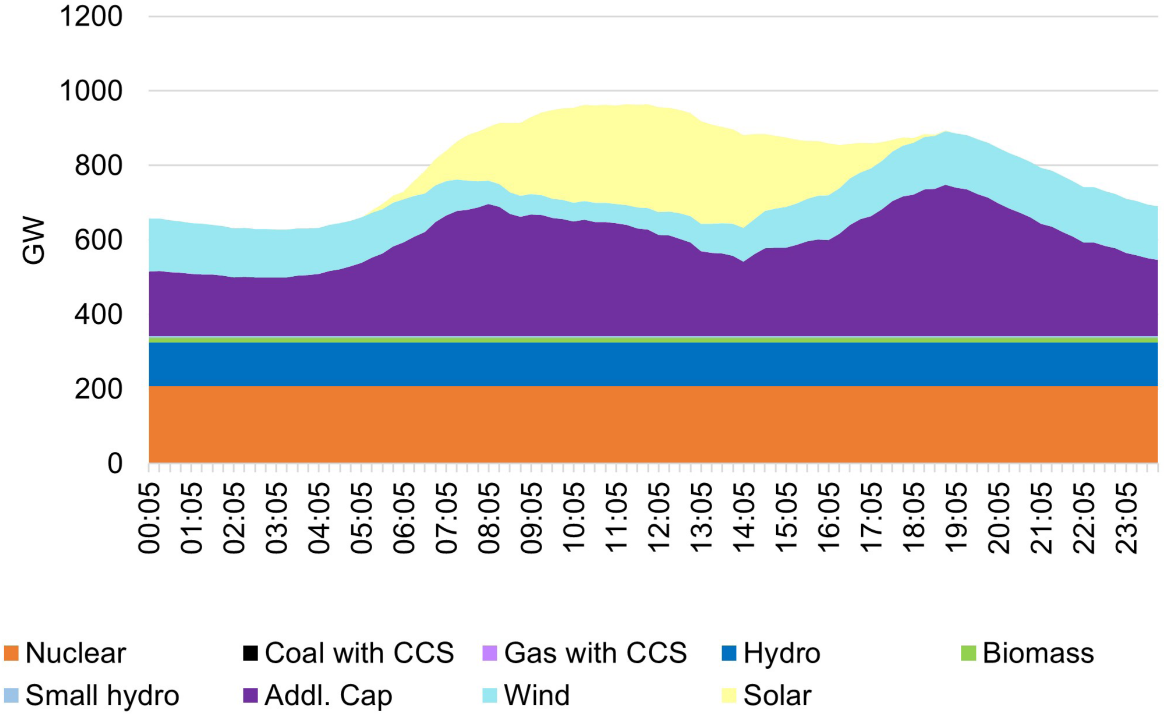
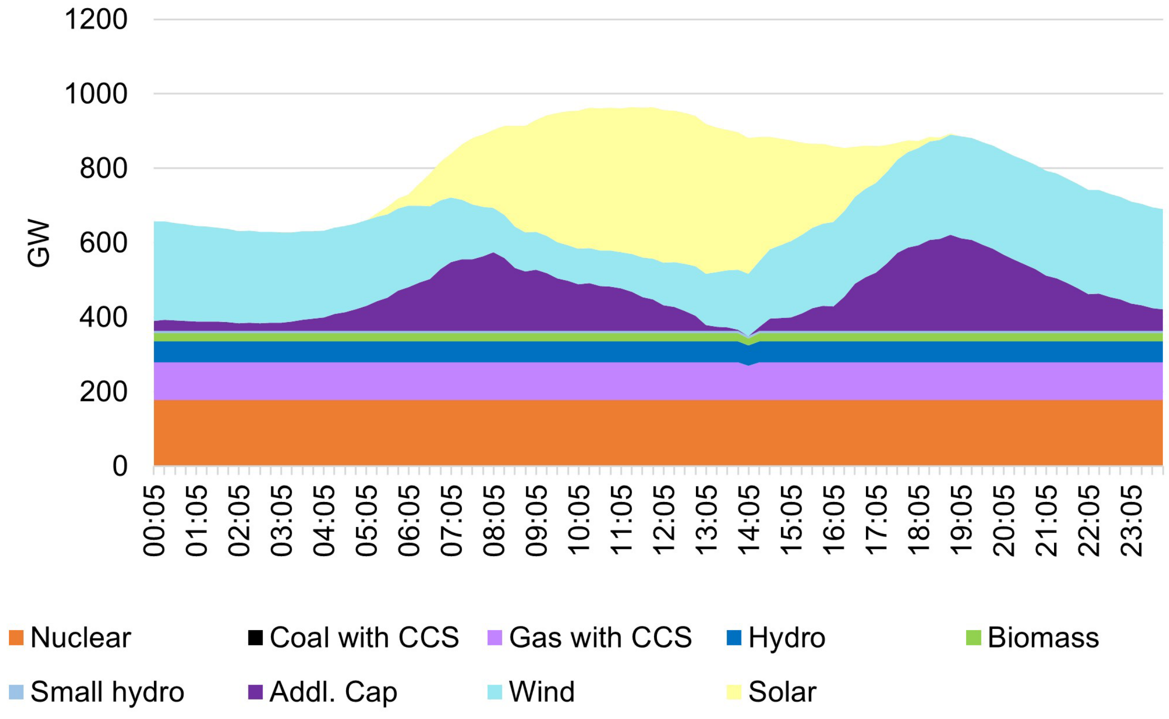


Figure 6.13: Load curve under the NZ4 scenario in 2070 for peak load of 964 GW



In addition to satisfying the conditions of grid integration, the above projections estimate the additional capacities required for a peak load of 946 for NZ1 and NZ2 and 964 for NZ3 and NZ4 as compared to 670 GW, as shown in Table 6.3.

Table 6.3: Projected additional capacities for NZ scenarios

Scenario	Capacity in GW
NZ1	309
NZ2	188
NZ3	406
NZ4	258

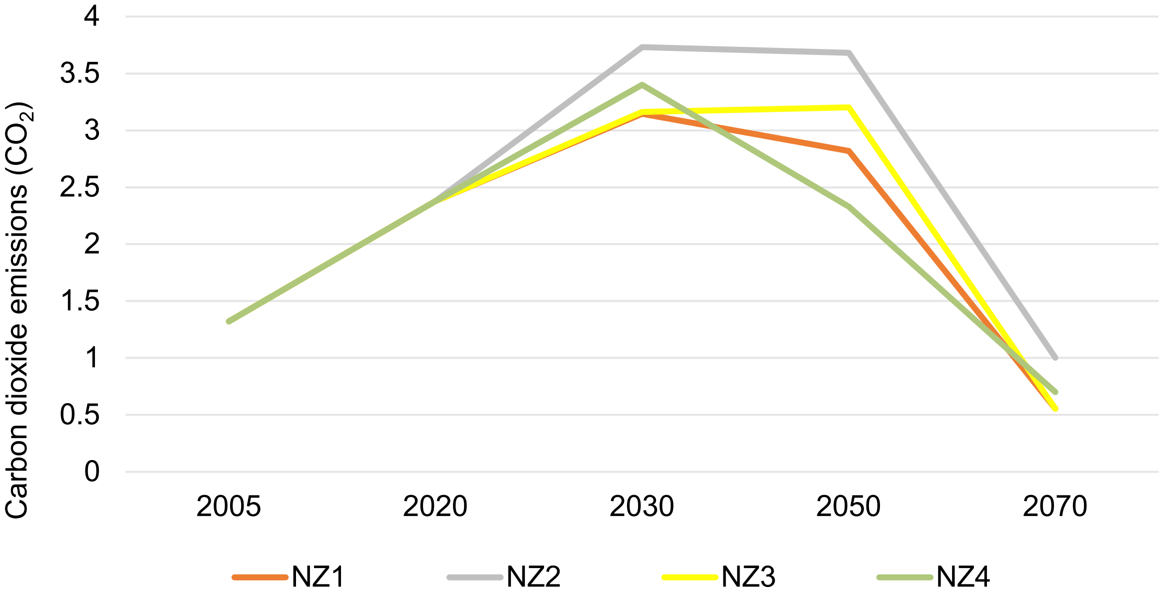
The trends in the existing demand profiles show that peak loads usually occur in pre-evening hours, which coincide with the surge in solar generation. Although renewables have been successfully integrated into the grid, the scenarios require additional capacities, and the required support has been worked out in the model. In addition, nuclear power generation plays a crucial role as a constant base load in supporting the integration of VRE.

6.5 GHG projections

Figure 6.14 illustrates the CO_2 pathways under the NZ scenarios. In the NZ1 scenario, carbon emissions peak at 3.2 $btCO_2$ in 2030 and decrease to 0.55 $btCO_2$ in 2070. In NZ2, emissions peak at 3.7 $btCO_2$ in 2050 and decrease to 1.0 $btCO_2$ in 2070. In NZ3, emissions peak at 3.2 $btCO_2$ in 2050 and decrease to 0.56 $btCO_2$ in 2070. In NZ4, emissions peak at 3.4 $btCO_2$ in 2030 and decrease to 0.7 $btCO_2$ in 2070. The cumulative budget between 2020 and 2050 is estimated to be 87 $btCO_2$ in the NZ1 scenario, 105 $btCO_2$ in the NZ2 scenario, 91 $btCO_2$ in the NZ3 scenario, and 86 $btCO_2$ in the NZ4 scenario. The decarbonization of the power sector is responsible for the major decrease in the NZ scenarios. The decrease in emissions in NZ1 is due to an increase in the share of nuclear capacity and generation. In NZ2, CCUS technologies play a key role in reducing emissions in the power and industry sectors. Under NZ3, the decrease in emissions is mainly due to a shift toward renewables supported by natural gas as the base load. The integrated NZ4 scenario achieves emission reductions through a mix of shifts to renewable and nuclear energies, as well as CCUS technologies. Transport is the second major sector responsible for emission reductions because of an increase in the electrification of all modes.

It may, however, be noted that there are some residual emissions at the national level in 2070 because of some hard-to-abate sectors in industry and some parts of freight transport that are not able to achieve zero emissions. We have also tried to keep power affordable and, therefore, not pushed very strong policies that could increase the cost of transport and industrial goods in the product supply chains, thereby pushing power prices upwards. It is worth noting that our NZ modeling incorporates demand moderation and uptake of energy efficiency measures (e.g. Ujala LED scheme) as per India's commitment to LiFE (Lifestyle for Environment) and exhortation to the global community for mindful and deliberate use instead of mindless and destructive consumption. To reach NZ with lesser resource use and synchronization with nature, the global paradigm of scenarios would need to incorporate these Indian perspectives.

Figure 6.14: CO_2 emissions under NZ scenarios

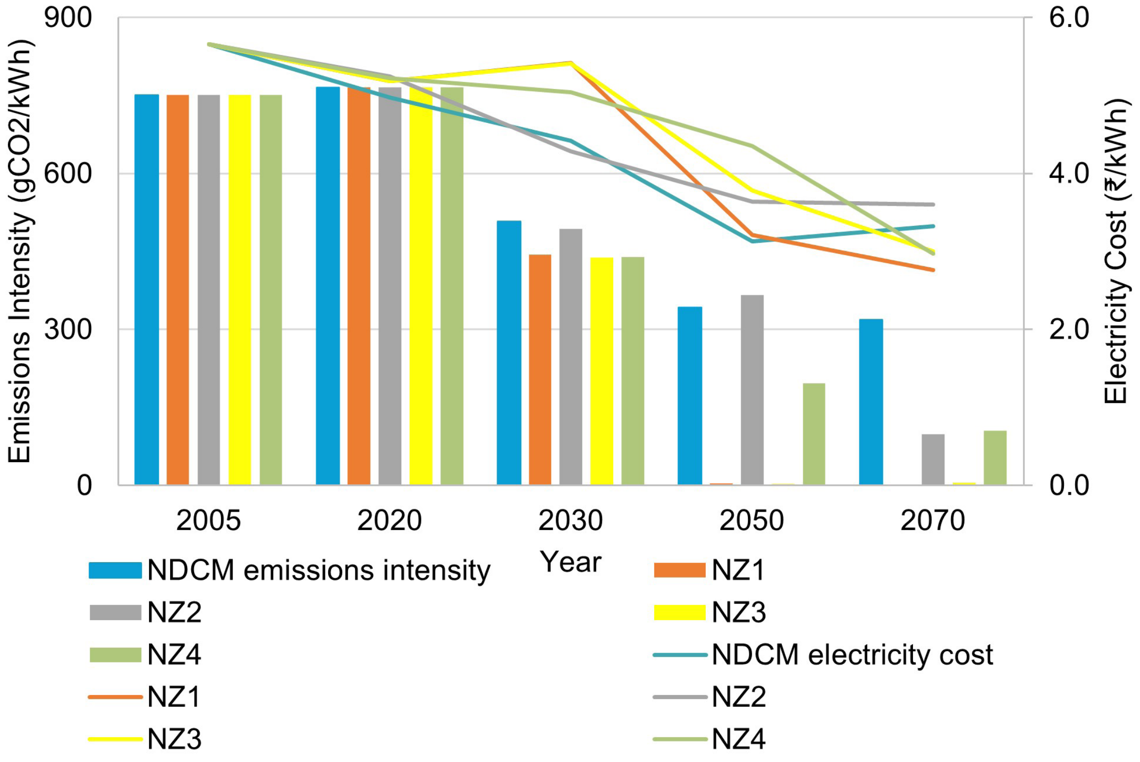


It is assumed that the remaining gap in emissions will be met through sequestration in forestry and agricultural soils. Currently, the AFOLU sectors sequester 500 million tons/year and were responsible for removing about 14% of national GHG emissions in 2016 (MoEFCC, 2021), but they could gradually increase to touch a billion tons/year through policies such as soil organic carbon enhancement, tree plantation outside forests, forest canopy and quality increase, and agroforestry. Indian NDC also refers to create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030 (MoEFCC, 2022). These measures, put together, would propel India to achieving overall NZ emissions by 2070.

6.6 Emission intensity and the cost of electricity

The electricity cost trajectory in the NZ1 scenario remains well below that in the current policy scenario (NDCM), despite the policy measures implemented to achieve NZ emissions from electricity generation (Figure 6.15 and Figure 6.16). The LCOE decreases much after 2050, when the share of nuclear power increases in the national electricity mix. Conversely, the NZ2 and NZ4 scenarios show a slight increase in LCOE compared to the NDCM scenario. Under NZ1 and NZ4, the emission intensity of electricity generation approaches zero from around 765 gCO_2/kWh in 2021, leading to a substantial reduction in LCOE. The nominal LCOE for NZ1 2070 stabilizes around 40% below that for the 2020 NDCM growth scenario. This is projected to be the lowest cost at the consumer end among all the scenarios. The share of VRE and other non-fossil sources is expected to rise in the future because of the falling costs and favorable policy environments. However, the need for electricity storage to stabilize the grid during the intermittent supply of solar and wind and to support flexible grid operation would increase the overall cost of electricity in the NZ3 scenario. In addition, rising concerns about air pollution in coal and gas power plants would make these technologies costly owing to additional pollution control retrofits such as flue gas desulphurization (FGD) for the NZ2 scenario. Other factors for LCOE reductions in future years compared to the 2020 levels are reduced T&D losses and reduced interest rates (WACC is assumed to go down from 9.5% today to approximately 5% in 2070). The carbon intensity of electricity also reduces appreciably to 1–105 gCO_2/kWh in 2070 from around 765 gCO_2/kWh in 2021.

Figure 6.15: LCOE in the NDC vs. NZ scenarios



6.7 Investment requirements

Figure 6.17 provides the annual average investment needs required in the NDCM growth scenarios vs. in the NZ scenarios (NZ1 to NZ4) between 2020 and 2070. NZ1 brings down the cost of electricity below that in the NDCM scenario and reduces the emission intensity of electricity generation below 20 gCO2/kWh. However, the additional investments required in NZ1 are approximately 43% above those in the NDCM growth scenario. Similarly, other NZ scenarios would require investments in the range of 93-140% above those in the NDCM growth scenario.

Figure 6.16: Emission intensity and electricity costs across NZ scenarios in 2070

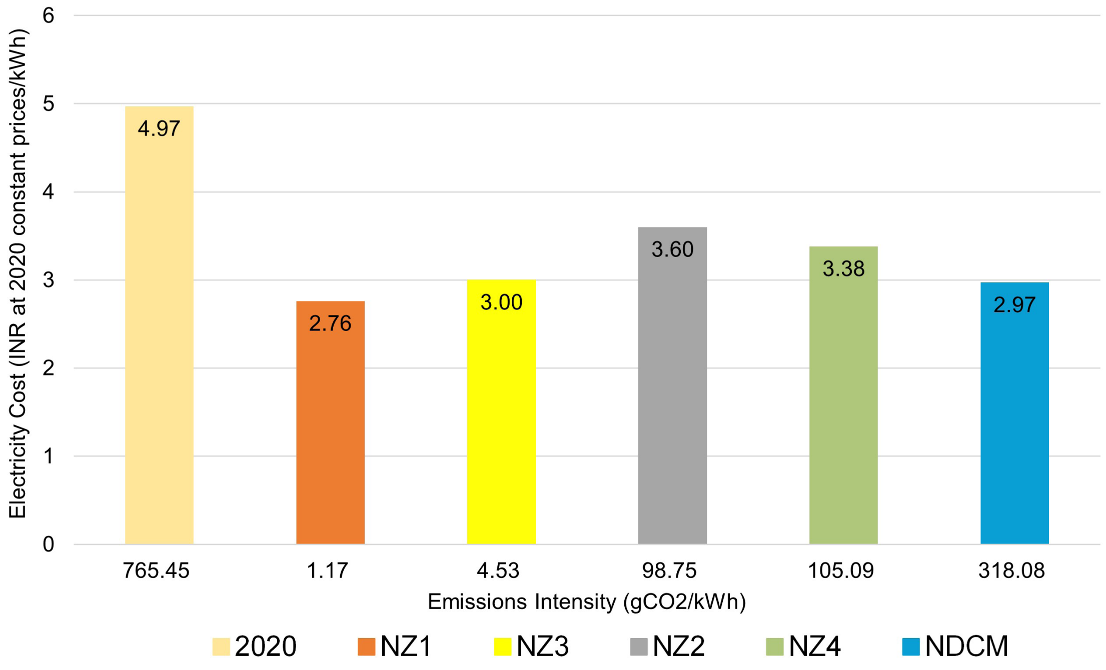
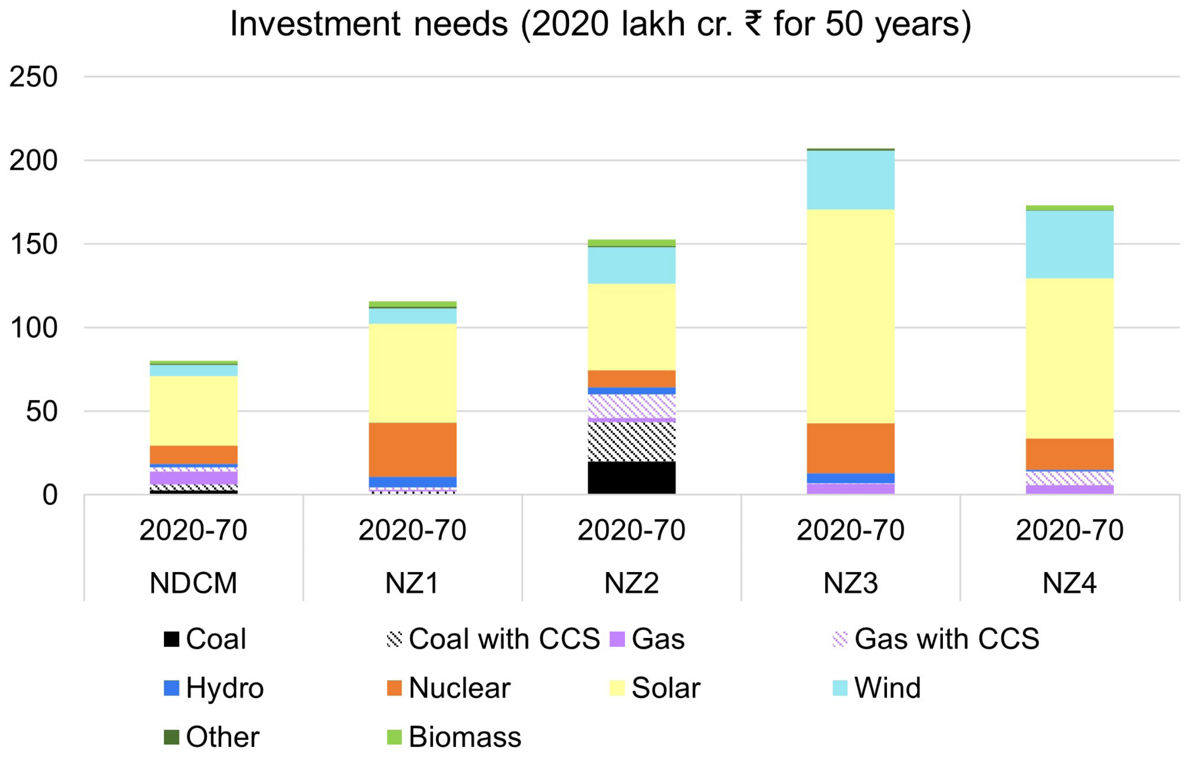


Figure 6.17: Annual average Investment needs for electricity generation between 2020 and 2070 in all NZ and NDC scenarios



Notes: The investment numbers do not include the system costs (grid balancing costs, flexibility in operations, grid-based storage, infrastructure, smart metering, connection costs). Some of these would be common. However, some of these would be different across scenarios, such as the storage costs for BESS systems co-located with the solar and wind plants.

The mitigation strategies discussed for achieving carbon dioxide removal from energy systems rely on early investments in the research and deployment of new and upcoming technologies such as renewables with storage, low-carbon hydrogen, CCUS, BECCS, and next-generation nuclear reactors. As the major NZ interventions happen in the electrification of end-use services and the subsequent decarbonization of electricity generation, most of the research and investments would be required in the electricity sector. An assessment by the IIT Bombay and Vivekananda International Foundation (VIF) estimates that India's energy transition to NZ 2070 would cost USD 11.2 trillion in a nuclear-dominated scenario and USD 15.5 trillion in a renewables-dominated scenario (VIF, 2022).

One way to fund the research and deployment of NZ emission technologies is by introducing a carbon price. According to a report, the estimated carbon prices compatible with the Paris climate goals fall in the range of USD 40–80/tCO_2 by 2020 and USD 50–100/tCO_2 by 2050 (Stiglitz et al., 2017). In the Indian context, compared to the NDCM scenario, the NZ1 scenario brings down the emission intensity of electricity generation close to zero. An average carbon price of around USD 25/tCO_2 (approximately INR 1,700/tCO_2) on the projected savings in the electricity sector when implementing NZ1 (vs. NDCM) would generate a revenue of around 950 billion USD, which would be sufficient to finance the transition to NZ energy systems through the NZ1 scenario. The carbon price required for NZ2, NZ3, and NZ4 scenarios varies between USD 50 and 120/tCO_2. However, for NZ2, we see higher cumulative emissions than for the NDCM scenario because of the high reliance on coal in NZ2 throughout the modeling horizon.

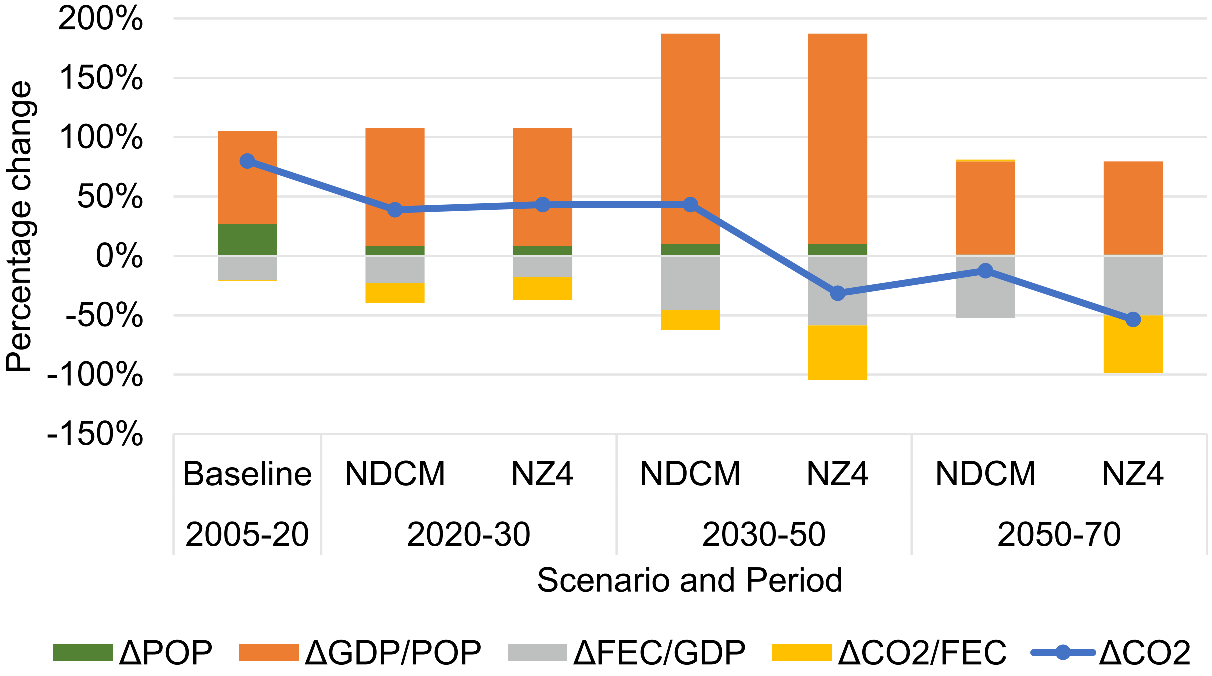
For India, the carbon price for 2050 is INR 1,700/tCO_2 or approximately USD 25/tCO_2. The EU carbon price was Euro 92/tCO_2 in March 2023, and the carbon price expectations around the world are Euro 45–100/tCO_2 during 2026–2030 (IETA, 2022). China's carbon price expectations are Euro 45 during 2026–2030. Our carbon price assumptions are much below these and are, therefore, conservative. Our expectations are based on the total investments required in the power sector and the corresponding emissions in NZ scenarios versus the baseline scenarios.

In the NITI Aayog report, the focus is only on CCUS from the power and industry sectors and the coal cess of INR 400/ton is expected to raise INR 48 thousand crores in 2030 and INR 53 thousand crores in 2050. These funds are expected to finance CCUS projects accounting for 2% and 31% of capturable CO_2 in 2030 and 2050, respectively. In our case, the carbon prices have been calculated assuming the investment gaps in the power sector (excluding the investments required in the grid infrastructure) when comparing the NDCM and the NZ scenarios. Investment cost assumptions are based on the CEA report and expert consultations. See Annexure 2 for the technology-wise investment numbers used for LCOE calculations.

6.8 Kaya analysis for NZ 2070

In terms of drivers of CO_2 emissions, the emission intensity of energy consumption (ΔCO_2/FEC) in the NZ scenarios slightly reduces between 2020 and 2030 compared to that in the NDC scenarios (Figure 6.18). However, as the share of nuclear and renewables in the energy mix increases and old coal-powered plants retire, we see a substantial reduction in the emission intensity of energy consumption in the NZ scenarios compared to that in the NDC scenarios. The drastic reduction in the emission intensity of energy consumption between 2020 and 2050 in the NZ scenario plays an important role in the NZ transitions and highlights the need for early policy actions to start the decoupling of emissions from energy and economic growth in the next two decades. The significant fall in energy (ΔFEC/GDP) and emission intensities (ΔCO_2/FEC) in the NZ scenario compensates for the economic growth, which rises rapidly between 2020 and 2070. The income and population growth are assumed to remain the same in the NDC and the NZ scenarios to compare the effects of mitigation. Furthermore, the per-capita electricity consumption in the NZ scenarios also improves compared to that in the NDC scenarios. Rising electricity consumption is often seen as a proxy for human development, where high electricity consumption is associated with high HDI outcomes (Garg, 2020). Thus, the NZ scenarios present an alternative pathway for deep decarbonization of energy systems without compromising on income growth, which is an important goal for developing countries such as India.

Figure 6.18: Comparison of CO_2 drivers between NDCM and NZ4 scenarios using the Kaya identity



Chapter 7:
ROLE OF NUCLEAR ENERGY

7. Role of Nuclear Energy

7.1 Capacity and generation under all scenarios

Nuclear energy would play a significant role in providing stable base-load power to India's future energy mix toward achieving the NZ emissions (Grover, 2022; IEA, 2022c). Globally, nuclear energy will play an important role in decarbonizing and achieving the NZ targets. A recent study noted that U.S. domestic nuclear capacity has the potential to scale from ~100 GW in 2023 to ~300 GW by 2050 (USDoE, 2023). Over 16 European countries are of an opinion to support nuclear power through its energy policies and green industrial subsidies. The EU government has agreed to allow EU incentives for green industries to certain advanced nuclear technologies (Reuters, 2023). China has approved new nuclear power projects in order to achieve its green energy transition goals (Zheng, X., 2022).

India has an indigenous nuclear program, and the Indian government is committed to growing its nuclear capacity. However, because of trade bans and the lack of indigenous uranium, energy production from nuclear energy has not gained momentum. In May 2017, the current Indian cabinet gave a major push to triple the capacity to 17 GWe by 2024 by adding 10 pressurized heavy water reactors (PHWRs) in the fleet mode, a "fully home-grown initiative with likely manufacturing orders to Indian industry of about USD 11 billion" to transform the domestic nuclear industry[13]. Further, In April 2023 the government announced plans to increase nuclear capacity from 6780 MWe to 22,480 MWe by 2031, with nuclear accounting for nearly 9% of India's electricity by 2047. In the Long-term Strategy (LTS) of India submitted to UNFCCC in 2022, the current policies estimate a threefold rise in the installed nuclear capacity by 2032. As part of the LTS, India plans to explore a greater role for nuclear energy and increase support for R&D into future technologies such as low-carbon hydrogen, fuel cells, and biofuels.

Table 7.1: Peak annual emission, annual emissions, electricity generation, and nuclear capacity in 2070

	NDCH	NDCM	NDCL	NZ1	NZ2	NZ3	NZ4
Peak annual CO2 emissions (btCO$_2$)	4.9	4.6	3.8	3.1	3.7	3.2	3.4
Residual emissions in 2070 (btCO$_2$)	4.3	4.0	2.8	0.55	1.0	0.56	0.70
Generation in 2070 (TWh)	5,025	4,070	3,070	4,398	4,743	4,271	4,958
Nuclear capacity in 2070 (GW)	90	80	40	331	78	207	178
Share of electricity supplied from nuclear in 2070 (%)	13	14	10	50	12	36	27
LCOE (INR at 2020 constant prices /kWh) in 2070	3.40	2.97	2.53	2.76	3.60	3.00	3.38

Table 7.1 provides information on emissions, electricity generation, and nuclear capacity in 2070. Currently, nuclear energy accounts for 3% of the total power generation share, which results in an annual savings of about 41 MtCO$_2$. In light of the recent developments and with India's commitment toward NZ in 2070, the scenarios analyze the future prospects of the power sector, especially the share of coal, renewable, and nuclear, in the power mix. The nuclear generation capacity can save 240–550 MtCO$_2$ under NDC scenarios and about 605–1995 MtCO$_2$ under NZ

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[13] World Nuclear Association (WNA).(2023). Nuclear power in India. World Nuclear Organization, Country profiles, India. https://world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx.

scenarios. Technology and fuel costs will play an important role for nuclear to become a major player in India's NZ scenarios. Hence, financing nuclear growth in India will become crucial for achieving its NZ targets. However, the current sustainable finance guidelines in India do not consider nuclear as a part of its green deposits framework (RBI, 2023).

7.2 Implications of deep decarbonizing electricity

The NZ1 scenario reduces overall emissions to about 0.55 btCO_2—the lowest across scenarios. In addition to a reduction in emissions, nuclear energy provides grid stability, is an alternative to coal and gas, leads to a reduction in air pollution, and has low land requirements compared to renewables. India needs to develop a strategy to build nuclear capacity with a strategic reserve of nuclear fuel to guard against disruption of supply over the lifetime of its reactors. While it helps strengthen energy security, there will be challenges to scaling up the nuclear capacity and generation in the next couple of decades. The barriers include the investment required to develop the nuclear facilities, in addition to social challenges such as the "not in my backyard" viewpoint, proliferation risk, and disposal of radioactive waste. India is a nation with nuclear weapons and follows all international commitments made in the field of nuclear technology. As per an IAEA bulletin:

> Fundamentally, the fear of proliferation is misplaced in the climate change debate. The largest energy consumption market growth is expected in India and China – both of which have weapons capabilities. Thus, almost everywhere carbon emission reductions through nuclear energy could yield critical benefits for climate protection where proliferation is not an issue. (Ritch, 1999)

As far as radioactive waste disposal is concerned, India follows a closed fuel cycle policy and has developed all necessary technologies. The pursuit of a closed fuel cycle policy minimizes radioactive waste volume. Hence, it will be helpful in expanding the nuclear power installed capacity, and India should continue to develop fuel-reprocessing technologies for spent fuel arising from advanced nuclear reactors (Pathak et al., 2022).

The NZ2 scenario focuses on the coal-intensive approach with CCUS technologies used to reduce emissions to 1.0 billion tons of CO2 by 2070. Although coal is the cheapest source of fuel for India, it will become expensive because of the addition of carbon tax/carbon price stemming from the development of national carbon markets. Additionally, the cost of coal with CCUS is an estimate. Its reduction over the next few decades is an expectation. Again, the CCUS process is not 100% efficient and the capture rate is expected to be 80%, indicating residual emissions. Other challenges include the requirement of significant upfront capital cost for the installation of CCUS technologies and the license to capture, transport, and store CO2, which come with their own set of liabilities. To date, most countries have only installed pilot and demonstration projects. As an alternative to geologic sequestration, CO2 capture and utilization (CCU) may be considered another viable option. Here, the captured CO2 is transformed into value-added chemicals, fuels or materials. CCU is not associated with the traditional risks of geologic storage. It also generates long-term revenue options for businesses reliant on traditional fossil fuel supply chains. Consider the case of methanol, which has traditionally been created via reforming of virgin fossil fuels.

The NZ3 scenario places emphasis on renewable energy expansion, with support from coal and natural gas as the base load, reducing emissions to 0.56 btCO2 by 2070. India currently has the fastest rate of renewable electricity growth among major economies. With the cost of renewables decreasing in the last decade, the technology has become competitive with coal in many projects for generation costs, but the concerns about system costs remain. The scaling required for renewable technologies faces major obstacles because of the cost of storage, the investment required for grid flexibility, and land requirements. Decentralized renewables are beneficial; however, they may not be cost-efficient if not connected to a centralized grid.

7.3 Cost of electricity at the consumer end (LCOE)

Nuclear power plants remain expensive to build because of large capital cost requirements per MW, but recent research suggests that this trend could be reversed by addressing two key issues faced by nuclear power technologies today. First, the investment and, in turn, the generation costs have not decreased in recent years because of continuously evolving regulatory regimes and management practices that result in long gestation periods. Second, the concerns regarding the safety of nuclear power plants, especially after the Fukushima accident, have decreased the share of nuclear power in the electricity mix (IEA, 2020a). However, the nuclear technologies belonging to generation III+ and generation IV being developed today are considered safer as they reduce the probability of severe accidents and also limit the offsite consequences of the accidents (MIT, 2018).

In addition, when looked at from the cost-to-consumer point of view, the system costs for nuclear energy are expected to be lower than those imposed by the variability of RE (OECD, 2019). Since RE, especially solar and wind energy, is variable, uncertain, location-constrained, non-synchronous, and modular in nature, the system effects and the system costs thereof make the grid integration challenging. The system effects are in terms of the following:

a) Profile costs: increase in the generation cost of the overall electricity system in response to the variability of the VRE output.

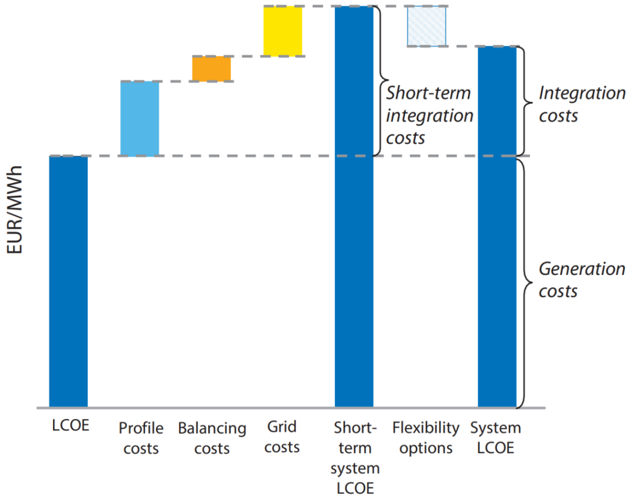
b) Balancing costs: increasing requirements for ensuring the system stability because of the uncertainty in the power generation.

c) Grid costs: increase in the costs for transmission and distribution because of the distributed nature and locational constraint of VRE generation plants.

d) Connection costs: costs of connecting a power plant to the nearest connecting point of the transmission grid.

Figure 7.1 presents an illustration of the LCOE and system costs

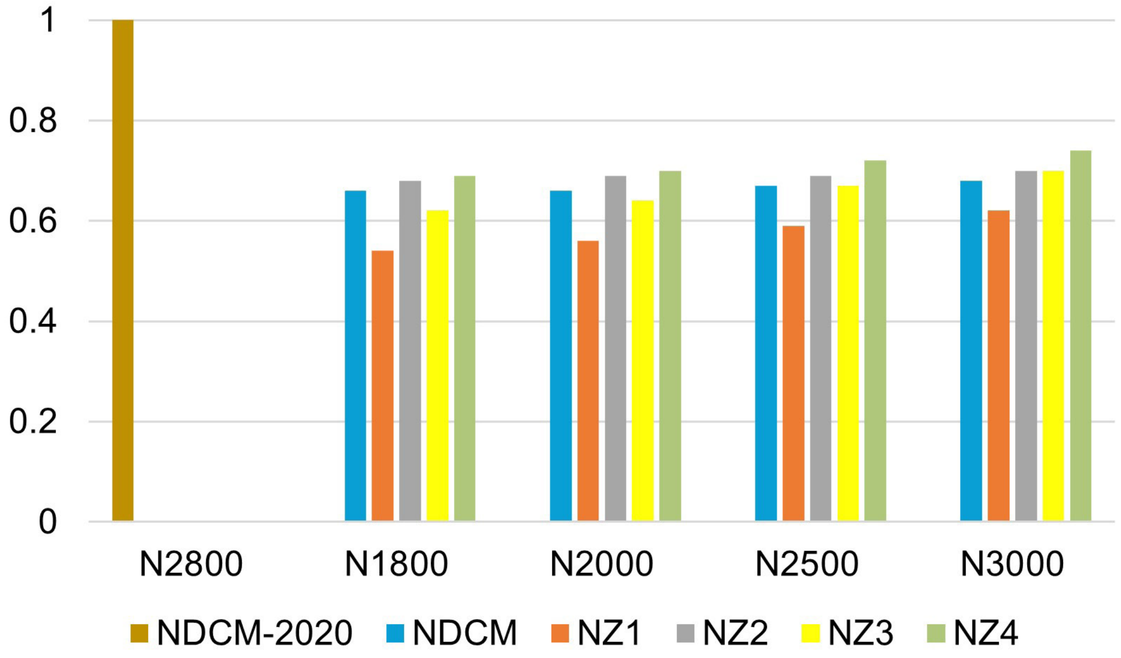
Figure 7.1: Illustration of LCOE and system costs



Source: OECD, 2019

Our LCOE calculations do not include grid-level costs of the electricity systems that are required to compensate for the variability and uncertainty of supply from renewable sources such as solar and wind. A recent study by the Energy Transitions Commission notes that globally up to USD 1.1 trillion needs to be spent on grid infrastructure annually until 2050 to achieve the NZ targets (The Economist, 2023). Meanwhile, India has committed to a USD 29.6 billion plan to build transmission lines to connect renewable generation in Gujarat, Rajasthan, and Tamil Nadu to the national grid (Singh, 2022). Brown et al. (2022) noted that the pace of progress in generation infrastructure is much higher than the pace of building and updating the grid infrastructure. However, we assume a 42% increase over LCOE (NEA, 2022) when the share of VRE (solar, wind, small hydro, and other variable renewables) goes above 50%. This is observed in the case of NZ3 and NZ4 scenarios after 2050. Hence, the cost of electricity is assumed to be approximately 40% higher in 2050 and 2070 in the case of the NZ3 and NZ4 scenarios.

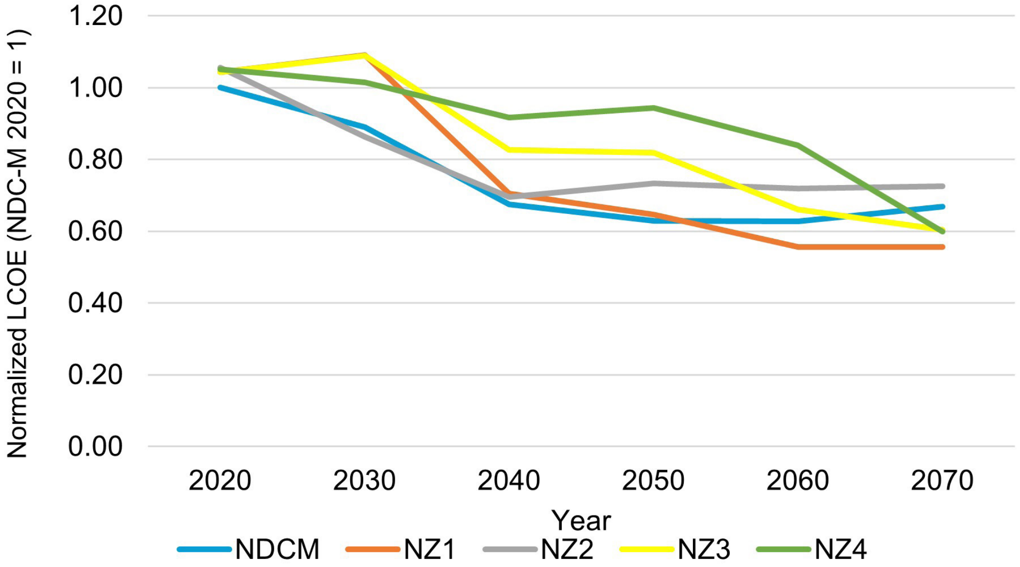
Figure 7.2: Comparison of LCOE under different scenarios and investment cost of LWR nuclear technologies



Source: Adapted from Patange (2022)

Figure 7.2 explores the LCOE across different scenarios for four investment costs of LWR nuclear technologies. The current costs are approximately USD 2,800–3,000/kWe (N2800), and we assume these costs to come down to USD 2,500/kWe (N2500) under the NZ scenarios. Moreover, the MIT (2018) report expects the investment costs to decrease further below USD 1800/kWe (N1800) because of the technological and managerial interventions discussed earlier. Furthermore, the costs reflected here point toward light water reactor use; with PHWRs, these costs may be lowered. As the results suggest, if the investment cost of nuclear technologies falls below USD 2,000/kWe, the NZ1 scenario would be able to achieve near-zero emission intensity of electricity generation with the cheapest cost of electricity across all scenarios. This would mean a 100% reduction in electricity sector emissions and a substantial reduction in electricity prices compared to corresponding emissions and costs in 2020. Figure 7.3 shows a comparison of normalized LCOEs over time, with the 2020 value being considered equal to 1 in the NDCM scenario.

Figure 7.3: Normalized LCOE under different scenarios



Countries, including India and China, are also working on Gen-IV technologies such as sodium-cooled fast reactors (SFRs) and thorium-fuel-based nuclear plants, which could become commercially viable (Mallapaty, 2021; MIT, 2018). An additional concern is the inflexibility of existing nuclear reactors, such as PHWRs prevalent in India, to support the rising share of variable renewables in the generation mix. Nuclear plants were traditionally designed for base load generation but can be adapted to provide load-following generation and flexible operations, as demonstrated by Jenkins et al. (2018). Furthermore, electrolyzers also serve as a dispatchable load and may support in managing the load demand while generating hydrogen (Grover, 2022; MIT, 2022). The flexible grid operation using nuclear power plants is already under work in countries such as France and Canada. Moreover, recent developments in SMR should be noteworthy. According to the NEA SMR dashboard data, globally 414 SMRs are under various stages of implementation across the 21 identified technologies (NEA/OECD, 2023). GE-Hitachi is developing a 300 MW BWRX system. Rolls Royce is developing a 470 MW SMR under funding from the Government of the UK. Both these systems have a reasonable rating, and they have higher chances of being economically competitive than smaller units. Hence, both routes, one based on indigenous efforts and the other based on collaborative development with international partners, need to be explored.

Further, the share of nuclear technologies in electricity generation could be improved through policy and financial support in terms of sharing of regulatory costs, R&D costs, incentives for achieving specific technological milestones, and production credits for successful demonstration of new designs, as suggested by MIT (2018). Nuclear energy in the Indian context has advantages such as decarbonization of electricity, energy security through reduced dependence on imported fossil fuels and critical minerals, reduced air pollution, fuel diversification and grid stability, low land requirement, and new jobs (Patange, 2022).

7.4 Investment needs and policy implications

There are various estimates for the financing needs to achieve India's NZ targets, and these estimates vary widely. As per the first NDC, India would require investments worth almost USD 170 billion per year between 2015 and 2030, a total of USD 2.5 trillion. The IFC estimates investment requirements of USD 3.1 trillion between 2018 and 2030 in India. Another assessment by CEEW suggests a total investment need of USD 10.1 trillion between 2020 and 2070 to achieve the NZ target. The generation capacities considered across NZ scenarios in the study range from 951 GW to 1149 GW in 2070 with a share of nuclear in the range of 78 GW to 331 GW. An assessment by the IEA puts the investment needs at an average of USD 160 billion per year between 2022 and 2030 in India’s energy sector. Another estimate puts it between USD 75 and 200 billion per year.

According to an assessment by the Climate Policy Initiative, the total green finance flow in India was USD 17 billion in 2017 and USD 21 billion in 2018. Approximately 29% of this amount came from public sources and government budgets from the central government ministries, state government departments, or the coffers of the public sector undertakings. A large share of public spending is in the form of grants to the power and transport sectors. India received an average of USD 28 billion annually as foreign direct investment (FDI) between 2009–10 and 2021–22, with the services sector accounting for the largest share. The energy sector, including power, non-conventional power, and oil and gas sectors, received an average of USD 0.98 billion, USD 0.83 billion, and USD 0.57 billion annually in the same period, respectively. In 2021, the Indian EV sector had investment deals worth USD 0.52 billion. However, public funding alone will not be sufficient to meet the estimated climate financing requirements. Private capital must also be mobilized, and financial flows need to be augmented through developed countries. The Paris Agreement has highlighted the need for sustainable financing mechanisms to ensure a smooth transition to NZ emissions. Article 9 of the Paris Agreement specifies that developed countries should provide developing countries with a finance of USD 100 billion annually up to 2025 and beyond to support NZ transition and climate change adaptation actions. At present, 15% of the overall green finance flows is sourced overseas, but only 5% of that comes from the private sector. With the newly established NZ emission target, the need to scale up the financial mobilization becomes more pressing. Reallocation of investment trends toward the transition would be a factor of magnitude lower than the investment requirements for the NZ transition. Domestic public finances cannot fill the gap. Therefore, international finance entities must seize the green business opportunities in India.

Chapter 8:

PROMOTING LOW-COST FINANCING FOR ENERGY TRANSITIONS TOWARD NET ZERO 2070

8. Promoting Low-Cost Financing for Energy Transitions Toward Net Zero 2070

8.1 Climate risks and disclosures for financing

Climate change is already affecting the way businesses operate presently and assessing future opportunities. Climate risks can be classified broadly into two types - physical risks and transition risks. As countries transition to more sustainable energy baskets and net-zero economy, uncertainties could be created in terms of investor expectations, consumer preferences, and regulatory needs. Therefore, transitions risks arise for public and private entities. Corporates and businesses are increasingly becoming sensitive to the additional risks from changing climate. And hence, in the past few years terms like "corporate climate risks" and "climate risk disclosure" have emerged to describe the impacts of various climate related risks and how these risks could be managed by businesses across the world.

Information is the bedrock of the financial markets, as information reduces information asymmetry between firms and market participants such as investors, banks, investment banks, insurance companies, and financial analysts increases, thereby reducing transaction costs for the market participants. Public disclosure of information by firms allows market participants to assess and understand risk profile of the firms in the context of sector, industry, country, and global integration. Till now, the focus has been on the disclosure of material financial information. However, Environment, Social and Governance (ESG) disclosures can be instrumental in assessing the materiality of climate risks.

There are various frameworks and guidelines looking into Climate and ESG disclosures. CDP (formally Carbon Disclosure Project), Global Reporting Initiative (GRI), Sustainability Accounting Standards Board (SASB), and International Integrated Reporting Council (IIRC) are the major institutions involved in creating disclosure frameworks and setting disclosure standards. Even though the Task-Force on Climate-Related Financial Disclosures (TCFD) is one of the most widely referred frameworks and considered best practice for climate-related disclosures, there is a lack of mandatory common international reporting standards. With multiple frameworks and guidelines with varied scopes and requiring different levels of details of information disclosure, reporting becomes a complex task for private sector participants. Hence, there is a need to focus on developing disclosure platforms such as Environmental Social and Corporate Governance (ESG) indicators so that international climate finance can flow to genuine and most vulnerable entities such as SMEs and MSMEs. Again, irrespective of the size and location of the projects/ firms, the disclosure requirements may be linked to the taxonomy definitions. The green/deep green activities may be required to disclose the minimum common measures, whereas the disclosure requirements may increase as the activities move from orange to grey to red.

Niti Ayog as part of the G20 initiatives has developed a dashboard for climate and energy related data (https://iced.niti.gov.in/). The dashboard provides insights and analytics on the status of India's objectives related to reduction in GHG emission intensity, non-fossil fuel power generation and net zero.

Each infrastructure project, including those for energy transition, could be encouraged to assess, analyse and disclose their risks due to climate change. This would facilitate long- term stability and risk management for transitions.

Some countries have also created Sustainable taxonomies to support investments towards low-carbon transitions. There is no internationally agreed taxonomy list available which could become the basis for all investors to pick up green projects for such transitions, which would have lower transition risks, and would be "green" anywhere in the world. Common Ground Taxonomy (CGT) could be a collection of common green technologies included in taxonomies issued by some major geographies such as the EU, the UK, Indonesia, ASEAN, South Africa, Singapore, and other countries. Common ground taxonomy helps identify technologies with a possible global consensus regarding greenness. CGT will reduce information asymmetry for global investors and multilateral agencies. Concerning climate financing, projects based on technologies mentioned in the CGT should be prioritized for low-cost funding globally. Technologies related to energy generation (Solar PV, CSP, BES, Wind, nuclear), CCUS, Low carbon transports, Green buildings, clean hydrogen, Low carbon manufacturing technologies, Agriculture, Water, and Forestry can be included initially in the common ground taxonomy for prioritized funding. Multilateral Development Banks could reduce processing time and documentation requirements for these projects. CGT will also reduce transaction costs for project developers by doing away with the need for third-party verification and other auditing-related tasks.

8.2 Setting up carbon markets and price discovery

Carbon markets are increasingly becoming the instrument of choice for market-based solutions for reducing emissions. As of April 2022, almost 71 carbon pricing instruments (CPIs) were operating worldwide, consisting of 37 carbon taxes and 34 emission trading systems (ETS) covering approximately 23% of global GHG emissions. Three more CPIs are scheduled to be implemented. In 2021, global carbon pricing revenues increased by almost 60% to around USD 84 billion. As of August 2022, EU carbon permits traded at Euro 85/ton CO_2e. China has the world's largest ETS—three times the size of the EU carbon market—and traded carbon at USD 9.29/ton CO_2e in April 2022.

In this context, the GoI's Energy Conservation (Amendment) Act, 2022 recognizing GHG emissions is a welcome move that opens the door for India to create a market to trade in GHG reductions. However, the 71 CPIs did not come about overnight and without learning. As India establishes the carbon market and learns from the experiences of others, the following five things should be kept in mind:

One, although countries first started trading in emission reductions in 2005, firms started it much earlier. The EU spent two years discussing, negotiating, and deciding on initial carbon caps with almost 11,500 firms in the EU in 2003 and then launched the first phase of EU-ETS during 2005–2007. The Chinese ETS took seven years to launch as a full-fledged national carbon market. It took seven regional Chinese markets to demonstrate their ability to trade before the country integrated in 2021. In India, we could leverage our own PAT system to do it more quickly, but there are some differences to consider. PAT is for fixing specific energy consumption (SEC) targets for individual firms. Carbon ETS would require converting these into GHG emissions of scope 1 and scope 2. In addition, later cycles of PAT do not give specific SEC targets to many of the firms included in PAT-1 and PAT-2. Carbon ETS cannot leave any entity uncovered across any ETS cycle.

Two, understanding the scope and coverage of the emissions trading instrument is critical. There are other requirements, such as defining carbon commodities to be traded clearly in their scope (gases) and coverage (sectors and entities). We also need to discuss and decide whether India would like to provide targets in the form of absolute emission caps to entities or GHG intensity of their annual revenue. These targets must be aligned with India's NDCs on GHG intensity of the GDP. Another consideration is whether any free allowances will be allocated or entities will need to buy every emission entitlement they need through an auction. The EU started by allocating free allowances and then gradually moved to the auction. It uses the auction proceeds to promote green transitions.

Three, there have to be deliberations about who would be allowed to trade. This could include individual emitters, business agglomerates, and industry associations. The carbon market cannot be allowed to become an entry barrier for new firms. Trading principles such as floor and ceiling carbon prices (Germany recently set a floor price of Euro 60/ton), limits on trading volumes in real time, controlling carbon price volatility, retiring carbon against NDC commitments, banking of carbon across trading cycles, and how to handle carbon leakages (e.g., outsourcing activities that could transfer carbon from an entity) need to be discussed with the industry and decided upon before implementing an ETS. The 34 ETSs worldwide may be made fungible so that carbon credits could flow across them. This will provide a larger market for Indian emission mitigation credits to flow across the world, and global economic efficiency and a global carbon price could emerge.

Four, one of the important differences between PAT and carbon ETS would be the need to establish a carbon registry for ETS in India. This registry would function like a bank account where all carbon mitigation would flow in or trade out. No carbon ETS is possible without creating a domestic carbon registry system. Any carbon earned must be linked with a robust monitoring, reporting, and verification (MRV) system to authenticate every unit of carbon saved. India has to create an MRV system for carbon. We also have to establish an institutional structure and decide on compliance mechanisms and penalties, if any, for non-compliance by entities. These concerns need to be discussed on open platforms to gain learnings from the EU, China, and others across the world that have established carbon ETS.

A phased implementation would seem most appropriate currently. Instead of a regional focus to start an ETS, an organizational-focused approach may be undertaken. Some of the 15 Maharatna organizations could be requested to start an internal ETS among their plants. For instance, 23 coal-based power plants of NTPC could start a cap-and-trade system internally. NTPC can decide on the targets for each through an internal transparent and consistent process and create systems for monitoring compliance. Similarly, the eight plants of the Steel Authority of India, the nine refineries of Indian Oil Corporation Limited, and all the zones and production units of the Indian Railways could start their own internal carbon ETSs. A single carbon registry could be created for the entire country to be used by each of the organizations. Trading would be done through this carbon registry platform internally within each organization. Once these organizational ETS systems are tested for some time, organizational boundaries could be diminished and consistent carbon caps be given by a national regulator across sectors and units. A carbon price will be discovered in each organization independently, which should be decent enough to attract building carbon mitigation options by individual plants. Funding for new projects could also be linked to their performance on carbon.

Five, we need to calculate carbon baseline emissions for each entity. This would require human resources that can do carbon accounting following accepted international practices and third parties to audit these. It is high time that India creates a National GHG Inventory Management System (NIMS) that is linked to all national GHG reporting requirements to UNFCCC, carbon registry, and all policies and measures to implement our NDCs. This would digitize our national carbon automatically in a bottom-up manner. Paris Agreement's Article 6.2 could also be easily linked to our NIMS.

As per the World Bank, in 2022, some 12.5 billion metric tons of carbon dioxide ($GtCO_2$) were traded in global carbon markets. This was a decline of over 20% from the previous year. However, when compared to 2019 levels, this figure represented an increase of 18.2 per cent. Europe accounted for roughly 74% of the traded volume of CO_2 worldwide in 2022 (The World Bank, 2023).

The USA is a much smaller player in carbon markets globally, although some subnational trade occurs. The EU-ETS became the world's first carbon market in 2005. The price of emissions allowances (EUA) traded on the European Union's Emissions Trading Scheme (ETS) reached a record high of 100.34 euros per metric ton of CO_2 in February 2023. Average EUA spot prices have increased significantly since the 2018 reform of the EU ETS.

8.3 Could carbon finance support part of capital expenditure?

Carbon pricing instruments, currently in use by the GoI, could be deployed to meet the incremental investments required in the NZ scenarios. However, the existing policies also need to be reoriented to support the research and commercialization of cleaner technologies and fuels such as low-carbon hydrogen, innovative solar and battery technologies, advanced biofuels, next-generation nuclear reactors, and CCUS including CDRs. One way to achieve this reorientation is to add carbon finance to ESCerts under the current PAT scheme so that both energy efficiency gains and carbon finance are monetized separately but together as conjoint markets. This reorientation is essential because the use of abatement technologies such as CCUS is associated with energy penalties, which increase the specific energy consumption of power generation and industrial production. Therefore, a scheme targeting emission reduction and allowing carbon trading among industries or state and local governments would be more effective in achieving the goals of the NZ scenarios. Carbon pricing policies would also support the development of CDRs, which could lead to their early-stage deployment and testing in the near term. Additionally, the introduction of carbon pricing could also make CO2-EOR competitive with conventional oil, mostly imported by India. Carbon pricing instruments could also finance CO2 pipeline infrastructure and research on geological sinks to support the CCUS industry and reduce uncertainties on CO2 sequestration potential in India (Patange, 2022).

The NZ1 scenario requires an additional investment of approximately 43% of that of the NDCM scenario. Similarly, the other NZ scenarios would require investments ranging from 93% to 140% of those in the NDCM scenario. The NZ1 scenario reduces the cumulative emissions by approximately 34 billion tons of CO_2 compared to the NDCM scenario and would earn the highest revenues from carbon pricing policies compared to the other NZ scenarios. If we assume a discount rate of 5% and a carbon price that gradually increases from INR 250 to 1,250 per ton CO_2 in 2020–30 to INR 2,000–5,000 per ton CO_2 in 2050–70, the carbon revenue for the NZ1 scenario would be between INR 5.5 and 14 lakh crores in terms of net present value (NPV). For a higher discount rate of 7%, the NPV of carbon revenue reduces to INR 2.5 to 6 lakh crores. For the other NZ scenarios, the highest possible carbon revenues range from INR 4 (7% discount rate) to INR 9 (7% discount rate) lakh crores NPV. In all four NZ scenarios, higher carbon prices in the future—realized through integrated carbon markets and stricter GHG mitigation regimes—would enhance the carbon price expectations even further, thereby increasing the NPV of carbon revenues. See Table 8.1 for the NPV of investments under various scenarios, discount rates, and carbon prices. A positive NPV means that the project is profitable and adds value to investments, while a negative NPV (fossil thrust) means that the project is unprofitable and could diminish the value of investment especially from a carbon lens.

Table 8.1: NPV (INR lakh crores) of investments under various scenarios, discount rates, and carbon prices

Carbon price (USD/tCO$_2$)	2005–2020	1	1	1	1	1
	2020–2030	3	5	10	15	20
	2030–2050	15	25	35	40	50
	2050–2070	25	40	50	60	100
Discount rate 5%	NZ1	11.84	7.26	15.70	18.43	26.86
	NZ2	-3.10	-1.82	-6.07	-8.60	-10.39
	NZ3	11.74	7.20	15.57	18.26	26.61
	NZ4	6.10	3.74	8.07	9.48	13.91
Discount rate 6%	NZ1	7.75	4.74	10.34	12.12	17.42
	NZ2	-2.69	-1.59	-5.14	-7.28	-9.03
	NZ3	7.69	4.70	10.25	12.00	17.25
	NZ4	3.98	2.43	5.29	6.20	8.97
Discount rate 7%	NZ1	5.14	3.14	6.90	8.08	11.45
	NZ2	-2.28	-1.35	-4.29	-6.08	-7.68
	NZ3	5.10	3.11	6.84	7.99	11.34
	NZ4	2.62	1.60	3.51	4.11	5.87

NZ1 is always the highest carbon revenue earner. It is in the range of Rs 5.5 to 14 lakh crore NPV at different carbon price projection and discount rate combinations. Higher carbon prices in future realized through integrated carbon markets and stricter GHG mitigation regimes, would enhance the carbon price expectation even further, thus increasing the NPV of carbon revenue. NZ2 has higher carbon emissions than the baseline. To realize the NZ1 scenario, the additional investment requirement (compared to that for NDCM) in the electricity generation technologies is approximately INR 16 lakh crores NPV with a 5% discount rate. A carbon price that goes up to USD 100/tCO$_2$ (~INR 5,000/tCO$_2$) on the projected carbon savings in the electricity sector when implementing NZ1 (vs. NDCM) would generate a revenue of approximately INR 27 lakh crores, which would be sufficient to finance the transition toward NZ energy systems through the NZ1 scenario. The investment needs in the other NZ scenarios are up to 25% higher compared to those in NZ1 and would require a higher carbon price for implementation.

Carbon revenue could provide substantial financing for NZ transitions, partly or fully, especially under the NZ1 scenario. As discussed in Section 7.3, the capital cost of nuclear technologies could be reduced further by 20–30% through technological and managerial interventions, in which case the investment needs in the NZ scenarios (especially NZ1) would decrease further. Moreover, the nuclear thrust scenario (NZ1) would not rely heavily on critical minerals to deploy renewables with battery technologies (NZ3) or the energy penalty associated with the high deployment of CCUS with coal and gas power plants (NZ2).

8.4 Low-cost financing

Since there are multiple low-carbon technologies at various stages of development and implementation, the implications for low-cost finance to deploy these technologies also vary. For instance, several battery and energy storage technologies are in development, making scalability at a commercial scale a significant risk for project developers.

Thus, there is a need to create an ecosystem through alternative mechanisms that support attracting foreign capital for climate finance to India. The central government established the International Financial Services Centres Authority (IFSCA) in 2019 with the objective "to develop a strong global connect and focus on the needs of the Indian economy as well as to serve as an international financial platform for the entire region and the global economy as a whole." IFSCA is actively exploring becoming a reinsurance hub, hosting alternative investment funds (AIFs) for pooled investments—supporting the India International Bullion Exchange (IIBX)—and initiatives to strengthen access to sustainable finance.

Furthermore, many multilateral development banks (MDBs) and climate funds have deployed resources through blended financing instruments, grants, and concessional loans to de-risk investments in climate action and to crowd in private investments. However, the capital resources of existing funds are insufficient to fulfill current climate financing requirements to meet the Paris Agreement targets.

MDBs and funds such as the Clean Technology Fund are already financing RE projects globally. A dedicated fund supported by MDBs could be created to finance various technology deployment projects globally, with a focus on emerging markets and developing countries (EMDCs). A dedicated fund would provide a single window for project application and appraisal, reducing the time and effort required for project documentation. The experience and expertise of MDBs in project appraisal and monitoring could also be leveraged to address adverse risk perceptions about EMDCs by bridging information asymmetry.

Revenue risks are currently crucial and inhibitory for several low-carbon projects. Because of the large and diversified nature of some clean energy projects, such as CCUS, cross-chain risks also exist because the profitability of each supply-chain component depends on other components, which may not yet be ready. For instance, a coal-fired power plant might have to assume the availability of a post-combustion capture technology, CO_2 compression and transport infrastructure, and storage availability. Failure of any one component may lead to a low load factor for the plant under emission constraints.

Additionally, the products generated by CO_2 savings would be financially viable only if a suitable market price exists. However, several products being considered have price volatility associated with them. This risk is, therefore, bound to exist unless there is some pricing security for "green products."

One of the key gaps in attracting investments is a lack of a consistent and comparable classification system that helps identify activities that could be considered "green" and "sustainable." Hence, the Indian government is preparing a "Taxonomy of Sustainable Activities for India" to establish clear definitions and criteria for eligibility for sustainable activities. The International Platform on Sustainable Finance (IPSF) has a taxonomy working group looking into the EU–China Common Ground Taxonomy to improve comparability and interoperability. European Union (EU) and Climate Bond Initiatives have already developed a taxonomy of green and sustainable activities to attract sustainable finance. The USA's taxonomy has classified nuclear hydrogen as low carbon. The EU's taxonomy calls nuclear hydrogen low carbon and hydrogen produced by VRE green hydrogen.

The taxonomy needs to go hand in hand with the need for transparency in reporting and avoiding greenwashing. In 2021, the Securities and Exchange Board of India (SEBI) mandated that the top 1,000 listed companies in any Indian bourse provide business responsibility and sustainability reports (BRSRs) for non-financial ESG disclosures. Companies following international disclosure reporting frameworks such as Global Reporting Initiative (GRI), Sustainability Accounting Standards Board (SASB), and Task Force on Climate-related Financial Disclosures (TCFD) are allowed to cross-refer (SEBI, 2021).

Another huge gap is financing the transition activities of the informal sector—medium, small, and micro enterprises (MSMEs). MSMEs contribute almost 30% of India's GDP and 45%

of exports and employ 110 million workers, making them the second largest employer after agriculture. A study estimated that the informal sector (mainly MSMEs) in India had a GHG footprint of 110 $MtCO_2e$ during 2015–16 (CSTEP, 2018). However, MSMEs are not only facing severe physical and transitional climate risks, but they are also struggling with urgent financial needs. Unfortunately, they have limited access to the formal banking system. Factors such as lack of awareness, low acceptance in formal financial structures, and high procedural requirements further contribute to the challenge of accessing capital.

Non-monetary or regulatory instruments such as subsidies on clean energy technologies and public programs to promote low-carbon infrastructure (e.g., transfer of clean energy cess on coal for clean energy financing) can also be deployed to promote these technologies to reduce the costs of financing.

8.5 Recommendations to scale-up low-carbon technologies

Chapters 2-7 highlight the role renewables, nuclear, CCUS and hydrogen (among others). Scaling-up these technologies requires a number of policy and technological interventions. Here, we provide some high-level recommendations to inform future policymaking and national R&D directions.

Load balancing remains the biggest challenge for RE integration. Agricultural systems continue to use considerable amount of electricity which may be shifted to other times of the day. A suitable price signal during periods of high supply can help in integration, subject to water stress in each region (IEA, 2021). Rooftop solar, while a positive development, needs to be registered within a common database. Ideally, building codes should specify that rooftop solar use the time-of-use tariff to compensate for the revenue loss being experienced by DISCOMs. Optimal balancing mechanisms also need to be tailored according to states. For instance, existing hydropower infrastructure could be retrofitted to pumped hydro storage in some states. In other places, the Standing Parliamentary Committee on Petroleum and Natural Gas has suggested that gas-fired power plants be used as peaking plants owing to their low PLF of about 26% currently.

A number of important positive policy directions have already been taken in the nuclear domain. This includes resumption of international civil nuclear trade and improved containment features in the new 700 MW PWHRs (Pathak et al, 2022). That said, policies must be reformed to ensure that financing and DISCOM agreement do not rule out nuclear. It is recommended that a reserve of uranium for uninterrupted operation of nuclear power plants may be created to allow for resilience to disruption in supplies. Special economic zones could be setup in areas where nuclear power/hydrogen cogeneration can take place alongside industrial operators with large demand for these commodities. A quota or purchase obligation can also help alleviate some of the risks for nuclear-derived hydrogen (Bhattacharya et al, 2022).

India is in a nascent stage of deploying various CCUS initiatives. There are considerable investment barriers and perceived risks that restrict upscaling novel methods for capture, utilization, or storage unless it is efficient and economically viable (Vishal et.al., 2021). In terms of scaling-up CCUS, associated costs have been identified as one of the biggest deterrents to its large-scale implementation. These are largely dependent on three main factors (i) The concentration of CO2 in the flue gas, (ii) Operating scale of the facility, and (iii) fraction of CO2 from the point source being captured. The costs of geologic storage of CO2 depend on the type of formation that is being utilized, further bringing in variation. Hence, research efforts into

CCU must be diversified given its prospects. Further, it is recommended that funding sources be diversified. The quantum of funding required is large and requires international financial support. Initially, funding may be requested from tailored funds on CCUS (such as from the Asian Development Bank or other Multilateral Development Banks). The key technological challenge here is to characterize the sedimentary basins of India to understand storage feasibility. This requires geological, geomechanical and geophysical surveying of the basins (Vishal et al, 2023). We recommend the basins near the Gandhar oilfield for detailed exploration, as it has already been studied and a pilot is anticipated to start in 2026-27 for EOR. An assured market for EOR and ECBM is also imperative to de-risk investments. For instance, ECBM in eastern India can be clustered with steel industries as methane can reduce coking coal requirement by as much as 30% (Vishal et al., 2023).

As the CCUS industry grows, it may also receive funding from sustainability-linked loans, where interest rates are conversely related to ESG metrics (Garg et al, 2023). CCUS should also be incorporated within the upcoming Indian carbon market. Integrated hubs and clusters of CCUS should be formed in regions of high demand for CO2-derived products, point source concentration and geologic storage. Moving away from one-to-one model to a cluster model helps de-risk investments in this area.

Hydrogen growth requires cost reductions via endogenous learning. As such, initial electrolyzer development can yield hydrogen that may be blended with natural gas. For doing this, it is necessary to match blending limits with end-uses. We also argue that the government may not necessarily incentivize just green hydrogen from renewables, but any form of low-carbon hydrogen below a certain life cycle emission intensity. It could be termed as Clean Hydrogen.

Our results show that short-term carbon intensity of about 6 kg-CO_2e/kg-H_2 and long-term carbon intensity of 2-3 kg-CO_2e/kg-H_2 would be compatible with economy-wide net-zero emissions in 2070. The recently announced criteria by the National Mission of Green Hydrogen says that incentives worth Rs. 17,000 Crore would be given to develop electrolyzers and hydrogen derived from renewables and pyrolysis. This is a welcome step. That said, it could be expanded to be technology-agnostic and expand the scope to hydrogen from nuclear and fossil fuels with CCUS. This is important to develop India's capacity in high-temperature electrolysis and CO2 capture from high-purity streams.

This allowable emissions intensity for hydrogen may be reduced in a phased manner over the next 2-3 decades. Regulatory changes also need to reflect hydrogen blending limits into natural gas networks. Similarly, hydrogen storage requires very low temperature (-252°C) and high pressure (350-700 bar). Alternatively, it can be converted to ammonia at 62 bar and reformed back to hydrogen during end-use, a process which leads to 7% energy loss relative to the hydrogen heating value (Singh and Dunn, 2022).

We have also talked above on the role of National Inventory Management System (NIMS) in developing transparent, robust and complete emission inventories for India. Indian fugitive GHG emissions from natural gas systems are not characterized above a Tier-1 level. In fact, hydrogen is much more susceptible to leakage and it has been postulated that it may further exacerbate global warming potential (Ocko and Hamburg, 2022). As such, moving to a Tier 2-3 level in transmission and distribution networks is essential if a hydrogen economy is adopted. Finally, we also recommend that the government carry out screening analysis for naturally occurring hydrogen, which may be extracted at much lower costs than any other sources considered in this report. Such reserves have been found in Africa, EU and Australia. Research from these countries has shown that the mechanism for generation is serpentinization (Zgonnik, 2020). Accordingly, we recommend analyzing the possibility of occurrence in Northeastern India and Ladakh.

Uranium storage facilities are commissioned to allow for resilience to disruption of nuclear power. Institutional arrangements may be scaled up so that more nuclear power could be commissioned easily and early. This may include public private partnerships. Special economic zones could be setup in areas where nuclear power/hydrogen cogeneration can take place alongside industrial operators with large demand for these commodities.

Chapter 9:
CONCLUSIONS

9. Conclusions

India has enhanced its NDC commitments to reducing the GHG emission intensity of its GDP by 45% by 2030 with NZ 2070 in mind. Given the development needs and related increased energy use, India's climate policies adopt a development-centric approach to strike a balance between its climate change commitments, economic growth, and development. However, achieving "NZ" emissions from the energy systems in the latter half of this century, primarily from a fossil-fuel-dependent electricity sector, will pose additional challenges in balancing global climate targets with domestic development goals. Hence, we undertake a detailed study of future energy systems in terms of the FEC to meet the goals of very high HDI, energy security, technology–fuel mix, electricity load profiles, low cost of electricity for consumers, and other impacts of our mitigation strategies under different policy scenarios.

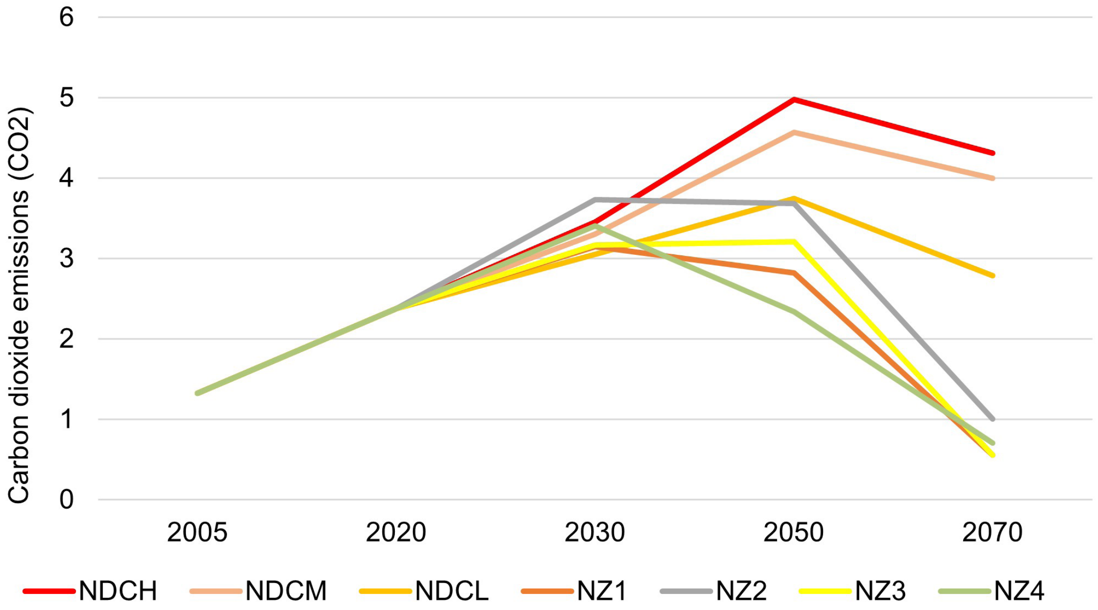
This study explores the current linkages between the FEC, CO_2 emissions, GDP, and HDI and investigates how they would change if India aims to achieve a very high HDI. Moreover, it estimates the energy demand and required energy transitions to achieve NZ 2070 through seven different scenarios.

India's current HDI is 0.645, placing it in the medium-HDI group. We estimate the minimum energy (and electricity) requirements at the final consumption point needed to achieve high HDI and very high HDI levels in India. We analyze these future trends by running alternate scenarios through the technology-centric AIM/Enduse-India model. The FEC–HDI assessment is then corroborated by this model through soft linkages. Currently, India's FEC is at 21 GJ/capita/year (about 5,850 kWh), with electricity contributing about 18% share. Achieving NZ targets by 2070 would boost these figures since more electrification using low-carbon electricity is projected (47–52% while 29–32% under NDC scenarios).

Exploring the links between the HDI and FEC at a state level in India, we compare data from 2011 and 2019. Our findings show that a very high HDI of 0.805 may be achieved at a minimum per-capita energy consumption of 37 GJ/year. The per-capita energy consumption could be higher by up to 40% for achieving an HDI of 0.9 and above, depending on climate change constraints such as NZ, a higher electrification share in the energy mix, higher urbanization, more equitable consumption by all, newer technologies such as low-carbon hydrogen, and nuclear power.

For this study, we have attempted to map out India's future energy requirements under seven alternate scenarios: low-economic-growth scenario, medium-economic-growth scenario, high-economic-growth scenario, NZ 2070 scenario with a thrust on fossil fuels with carbon capture, utilization, and storage (CCUS), NZ 2070 scenario with a thrust on renewable energy (RE), NZ 2070 scenario with a thrust on nuclear power, and integrated NZ 2070 scenario. Figure 9.1 describes the emissions trajectory under various scenarios.

Figure 9.1: CO_2 emissions under across all seven scenarios



One of the key findings of this study is that clean, affordable electricity can be achieved in NZ pathways, especially with a focus on nuclear power. NZ1 scenario shows the lowest residual emissions. Widespread electrification of end-use sectors, especially transport and residential, and eventually low-carbon hydrogen production will lead to a rapid increase in electricity demand after 2050 but not a corresponding increase in the carbon footprint of the power sector.

If India plans to phase down coal in the next three decades, it will need to build adequate infrastructure for alternative sources such as nuclear power, in addition to flexible grid infrastructure and storage to support the integration of RE. Furthermore, the coal phase-down will require undertaking significant imports of critical minerals to fulfill the needs of RE and battery storage sectors. Therefore, the mining sector is expected to face substantial challenges.

Aluminum, chromium, cobalt, copper, graphite, iron, lead, lithium, manganese, nickel, vanadium, and zinc are among the most commonly used minerals across battery technologies. There are supply concerns such as the environmental and energy-use impacts of increased extraction of mineral resources, as well as the relative vulnerability of developed countries to the supply of critical elements required for the clean energy transition.

To reduce its dependence on the import of critical minerals whose large reserves are located in geopolitically volatile nations, India needs to invest in developing renewable and battery technologies that are based on domestically available mineral resources. This could involve the use of vanadium-based flow batteries for stationary applications and EV charging infrastructure, as well as sodium-based batteries. As the demand for energy storage for clean transitions increases, it becomes increasingly important for India to develop technologies for the reuse, recovery, and recycling of critical minerals. Refurbishing, recycling, and mineral recovery will play a vital role in meeting future mineral demands and limiting import dependencies.

If India intends to follow coal-dependent pathways, it will need to explore CDR technologies such as BECCS to fully understand their long-term potential. However, the energy penalty for deploying BECCS at power plants needs a closer examination. CCU must be powered via renewable grids to ensure their compatibility with long-term NZ targets . Challenges such as mismatched operation scale, which may require clustering emitters near a suitable use or storage site to ensure cost-efficient capture and transport, as well as the risks of leakage, the need for monitoring and maintaining storage sites, and accompanying liabilities, could potentially hinder the deployment of CCUS. Without CDR, moving toward NZ pathways will strand the majority of coal and gas assets after 2040. Table 9.1 describes the electricity generation capacity across all seven scenarios.

Table 9.1: Electricity generation capacity (in GW) under all scenarios in the long term

Scenario	Year	Biomass	Coal	Coal with CCUS	Gas	Gas with CCUS	Hydro	Nuclear	Solar	Wind	Other	Total
	2005*	1.1	71	0	16	0	32	3.36	0.5	7	0	131
	2020**	10	206	0	25	0	51	6.7	37	39	1	375
NDCH	2030	34	227	47	82	10	53	11	166	63	19	712
	2050	42	194	92	132	11	65	75	370	70	24	1075
	2070	57	163	98	157	49	69	90	540	100	25	1348
NDCM	2030	35	220	13	95	3	53	11	149	58	16	653
	2050	33	170	25	189	32	67	75	320	70	23	1004
	2070	30	135	25	155	16	67	80	540	80	22	1150
NDCL	2030	22	186	2	95	2	57	18	108	53	10	553
	2050	35	132	12	115	13	63	35	180	70	20	675
	2070	23	96	6	105	14	64	40	180	80	17	625
NZ1	2030	16	123	29	55	0	46	30	281	70	9	659
	2050	43	69	44	40	21	61	265	281	70	23	917
	2070	51	0	29	0	21	117	331	304	100	0	953
NZ2	2030	24	204	29	97	7	43	30	201	70	11	716
	2050	39	404	140	13	178	45	75	251	70	20	1235
	2070	35	0	207	0	126	91	78	233	169	12	951
NZ3	2030	16	122	29	47	0	45	30	301	70	10	670
	2050	18	77	29	172	2	53	75	551	200	28	1205
	2070	13	0	0	0	0	117	207	486	250	0	1149
NZ4	2030	13	123	29	90	0	42	29	281	71	10	688
	2050	41	77	29	166	12	45	95	405	281	15	1166
	2070	23	0	0	0	101	56	178	410	282	12	1088

Note: * *Numbers are based on the Energy Statistics 2007 for financial year 2005-06 and Growth of Electricity sector in India, CEA, 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at around 14 GW.*

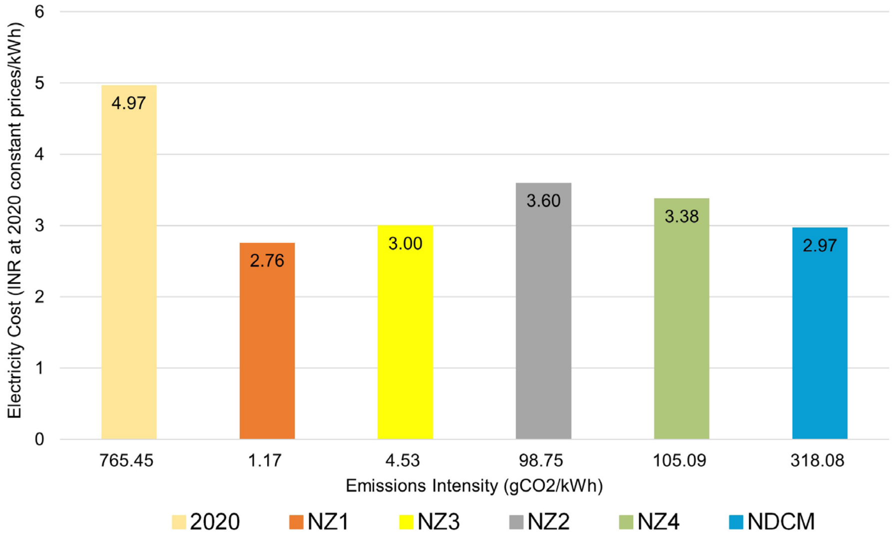
*** Numbers are based on CEA's General Review 2022 and installed capacity reports upto December 2020. The installed capacity for non-utilities (captive capacity) for coal-based plants stood at 47.8 GW.*

No NZ is possible without substantial nuclear power generation in 2070: 331 GW under NZ1 (with a thrust on nuclear energy), 78 GW under NZ2, 207 GW under NZ3, and 178 GW under the NZ4 (integrated) scenario. For India, investments are an important dimension for moving toward NZ 2070. Achieving the necessary levels of nuclear power generation for India to achieve NZ emissions by 2070 would require significant investments in research, development, and large-scale deployment of nuclear technologies. Capital investments in the electricity sector between 2020 and 2070 could be 30–70% higher than under the current medium-growth scenario (without the NZ target). However, the cost to end users under NZ1 is coming out to be the lowest among all NZ options (Table 9.2 and Figure 9.2). This is an important insight and should guide the policy and technology basket at the national level. Moreover, if a carbon price is established in India soon, a drastic reduction in the carbon footprint of electricity could generate about INR 5 lakh crores in today's price (considering carbon price in 2050 of INR 1,700/tCO_2 or approximately USD 25/tCO_2). These funds could be deployed to fill the capital investment gap in achieving the nuclear thrust.

Table 9.2: Peak annual emission, annual emissions, electricity generation, and nuclear capacity in 2070

	NDCH	NDCM	NDCL	NZ1	NZ2	NZ3	NZ4
Peak annual CO_2 emissions (btCO_2)	4.9	4.6	3.8	3.1	3.7	3.2	3.4
Residual emissions in 2070 (btCO_2)	4.3	4.0	2.8	0.55	1.0	0.56	0.70
Generation in 2070 (TWh)	5,025	4,070	3,070	4,398	4,743	4,271	4,958
Nuclear capacity in 2070 (GW)	90	80	40	331	78	207	178
Share of electricity supplied from nuclear in 2070 (%)	13	14	10	50	12	36	27
LCOE (INR at 2020 constant prices /kWh) in 2070	3.40	2.97	2.53	2.76	3.60	3.00	3.38

Figure 9.2: Emission intensity and electricity costs across NZ scenarios in 2070



We have explored how India can achieve clean and affordable electricity under four NZ pathways. To achieve NZ energy systems by 2070, the electricity sector will need to decarbonize well before that year. The study notes that the current net load curve assumes a characteristic duck-shape, with a decrease during the day, especially when solar generation begins, and an increase in the demand profile in the evening. The global push toward decarbonization has put pressure on fossil-fuel-based electricity generation capacities, resulting in high systems costs for renewable and CCUS-based solutions. Moreover, coal power plants demonstrate inflexibilities associated with quick ramping and minimum load operations. Recent notifications from the GoI have further decreased acceptable levels of minimum load operation of coal plants to accommodate renewable integration. In the case of natural-gas-based plants, inadequate gas supply has led to low-capacity utilization factors. Deployable storage technologies typically have shorter durations, around four hours per day, which helps in balancing shorter-duration demand through intraday energy arbitrage. Hydropower, with its quick ramping capabilities, is more amenable to peak load balancing during VRE integration.

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ANNEXURES

Annexures

1. HDI Model Description and Equations

1.1 Data sources

The key data sources for this study include energy and human development metrics. To gather energy data, we used a combination of different GoI sources. First, the FEC in India largely has contributions from electricity, coal (for non-electricity purposes such as steelmaking), oil, and natural gas. Some states, particularly those with large agricultural sectors, rely upon traditional biomass to meet rural energy requirements (Gupta et al., 2019; Srinivasan et al., 2018). Most of the consumption of renewables is for electricity generation. The data for electricity generation for each state is available in several reports of the Central Electricity Authority and was compiled by the IndiaStat database (2020). Data for oil and gas consumption per state is obtained from the reports of the Petroleum Planning & Analysis Cell of the Ministry of Petroleum and Natural Gas (PPAC, 2022). These reports present the petroleum consumption data in terms of the mass of total petroleum products consumed. This is converted into energy values by assuming a crude oil heating value of 42 MJ/kg. Data for traditional biomass consumption is obtained from Yawale et al. (2021). An important consideration here is the completeness of the energy availability data. As mentioned earlier, the key fuels in the final energy mix are coal, oil, gas, traditional biomass, and renewables. Approximately 89% of the domestic coal consumption is for electricity generation purposes and, as such, is directly incorporated in our analysis (NITI Aayog, 2022). Industrial coal consumption may have now been included in the inventory from the NITI Aayog's India Energy Dashboard. Data for oil and gas are considered in completeness. In addition, most non-biomass RE is also incorporated into the analysis as it is consumed via electricity. However, the data set for traditional biomass consumption is not yet incorporated into the results presented below.

The data for human development indicators are obtained from the Global Data Lab's Human Development Indices v5.0. This data set provides the HDI for all states and UTs, as well as individual indices such as HI, EI, and II. Moreover, the data set provides actual data values for life expectancy, school enrolment, and per-capita income on a PPP basis. Other researchers have used the Global Data Lab data set to improve the granularity of the data further (Smits & Permanyer, 2019).

Table A1: Data for key variables

Data	Years available
Electricity generation	1997–2019
Petroleum and natural gas consumption	2009–2021
Traditional biomass consumption	2004, 2009, 2011 (2019 calculated)
Sub-national human development indicators	2002–2019
Population	2001, 2011, 2019

Table A1 shows the years for which the sources provided the data. We made an extrapolation for traditional biomass, for which reporting by Yawale et al. (2021) extended only up to 2011. We applied the national growth rate in traditional biomass consumption, as projected by Ekholm et al. (2010), to obtain 2019 projections. Moreover, the energy consumption data need to be divided by state population to obtain per-capita estimates. Considering this data availability, we performed our baseline calculations for 2011 and 2019. For other years, where presented, we performed analyses using interpolation for missing variables.

1.2 Analytical approach

The literature has suggested several formulations for understanding the energy–HDI linkage. As the shape of the energy–HDI graph is intuitively logarithmic, Pasternak (2001) used a semi-logarithmic fit, as shown in Equation 2:

$$HD = A + B \cdot \log(EC) \tag{2}$$

Here, HD is the HDI and EC is the per-capita energy consumption. *A* and *B* are the coefficients of regression obtained from the observed data. While this formulation was useful in constructing a "trendline," it did not offer acceptable goodness of fit for the regression. As such, Preston (2007) used a logistic form, as shown in Equation 3:

$$HD = \frac{HD_{SAT}}{1+e^{A}\cdot EC^{B}} \Leftrightarrow \quad \log\left(\frac{HD_{SAT}}{HD} - 1\right) = A + B\log(EC) \tag{3}$$

Here, the HD_{SAT} value corresponds to the saturation value of the HDI. The coefficients calculated here offered an appreciable goodness of fit at higher HDIs. However, the error observed at lower HDIs (especially below 0.6) was higher. This makes the particular formulation unsuitable for historical analysis in the Indian context. To reduce this error, Martinez and Ebenhack (2008) suggested the formulation given in Equation 4:

$$HD = A + B\log(EC) + \mathrm{C}\cdot\left\{\log(EC) - \overline{\log(EC)}\right\}^{2} \tag{4}$$

While this formulation offered a good quality of fit, the complicated form with two coefficients and one intercept prohibited the estimation of the threshold function. In other words, this format could help predict the HDI at a given energy consumption, but it could not estimate the threshold energy consumption required to reach a particular level of HDI.

Steinberger and Roberts (2010) have proposed the most widely used formulation, as shown in in Equations 5 and 6:

$$HD = HD_{SAT} - e^{A}\cdot EC^{B} \tag{5}$$

$$(HD_{SAT} - HD) = A + B\log(EC) \tag{6}$$

In this approach, we use the natural log of the annual per-capita energy or the electricity consumption as the independent variable. The natural log of the difference between the saturated HDI and the HDI is represented as the dependent variable. The saturated value of the HDI corresponds to a 10% higher HDI than the highest HDI in the observed data set. On the basis of Equation 5, these two variables can be represented as the equation of a straight line, i.e., $y = mx + c$. Linear regression is used to obtain the values of the coefficients *A* (as the slope) and *B* (as the intercept). The *R*-value is also calculated to evaluate the goodness of fit for each correlation.

The goodness of fit of the regression analysis may differ from that of the past analyses focusing on international data because international energy transport (both via grid electricity and liquid fuels) is much more common within a country than between two countries. Some outliers may skew the regression because of large-time series data across several states. For instance, UTs with predominantly urban populations have high energy consumption. As such, the "1.5 IQR" rule is used to remove the outliers and obtain more accurate predictions for HDI, with per-capita energy/electricity consumption as the *x*-variable. In this method, the independent variable is sorted in increasing order and the interquartile range (25th to 75th percentile) is calculated. The values less than 1.5 times the 25th percentile and those larger than 1.5 times the 75th percentile are considered outliers in the data set and are not included in the regression (Rousseeuw & Hubert, 2011). These values are, nevertheless, considered when calculating the maximum and minimum indices.

As discussed above, the formulation adopted by Steinberger and Roberts (2010) enables the calculation of the threshold function. In doing so, the *A* and *B* coefficients are themselves regressed over the time period on the basis of the formulation given in Equation 7:

$$EC(HD,t) = \left(\frac{HD_{SAT}(t)-HD}{\exp\left(A(t)\right)}\right)^{1/B(t)} \tag{7}$$

The threshold functions are applied to estimate the trends in threshold energy consumption to reach the HDI, HI, EI, and II of 0.805.

2. Data and Assumptions for Energy Modeling

2.1 Model assumptions

Sector	NDC scenarios	NZ scenarios
Power	Renewables: 450 GW by 2030 T&D losses: reduce by 6–8% Introduction of smart grids	Additional policies and measures being included, early retirement of low-efficiency coal-based power plants, super Cr PC, IGCC brought in more strongly with CCS Gas-based power generation (gas sourcing) Increased nuclear capacity (NSG entry) Increase in renewables with storage Enhancing smart and microgrids
Industry	PAT (enhanced sectoral and plant coverage). Addition of railways, refineries, and distributed companies	More aggressive PAT. Reduction in energy intensity, the reuse and recycling of energy (waste heat) and materials (aluminum, steel), demand reduction for end-use materials
Transport	Share of railways: 36–45%, DFC, improve vehicle efficiency, introduce EVs, increase public transit (metro)	Electrification of passenger and freight transport, demand reduction, e.g., encourage 5–15% to work from home, encourage non-motorized transportation
Buildings	LEDs to save 100 TWh annually, S&L program for 21 equipment, LEED and ECBC standards.	A complete shift to EE electric appliances, LEED- and ECBC-standard buildings, demand-side management

2.2 Plant load factor

PLF (%)	2010	2020	2030	2050	2070
Coal	0.77	0.54	0.6–0.9	0.7–0.9	0.7–0.9
Gas	0.8	0.4	0.6–0.9	0.8–0.9	0.8–0.9
Hydro	0.4	0.4	0.4–0.6	0.6–0.7	0.6–0.8
Nuclear	0.65	0.8	0.70–0.85	0.75–0.85	0.80–0.85
Solar	0.1–0.2	0.1–0.2	0.18–0.25	0.18–0.25	0.18–0.25
Wind	0.1–0.2	0.1–0.2	0.2–0.42	0.2–0.42	0.2–0.42

2.3 Technology costs

A. Capital Costs

Technology	2020	2030	2050	2070	Uncertainty Range
Coal + Lignite	8.30	8.30	8.30	8.30	7-9
Coal with CCS	14.94	14.94	13.28	13.28	10-17
Gas	5.00	5.00	5.00	5.00	2-6
Gas with CCS	9.00	9.00	8.00	8.00	7-10
Hydro	8.30	8.26	8.23	8.23	3-18
Nuclear	15.00	15.00	15.00	15.00	13-22
Solar Photovoltaics	5.44	3.90	2.27	2.27	1-6
Wind onshore	6.66	6.24	5.91	5.91	5-8
Wind offshore	--	13.80	11.97	11.97	12-24
Biomass	5.00	5.00	4.83	4.83	4-6
Pumped Storage	5.00	5.00	4.00	4.00	3-8
Battery Storage	6.73	3.87	3.09	3.09	3-9

(All figures are capital costs in INR crores/MW in 2020)

B. Fixed O&M Costs

Technology	2020	2030	2050	2070
Coal + Lignite	0.20	0.20	0.20	0.20
Coal with CCS	0.33	0.33	0.29	0.29
Gas	0.18	0.18	0.18	0.18
Gas with CCS	0.27	0.27	0.24	0.24
Hydro	2.5% of Capex			
Nuclear	0.43	0.43	0.43	0.43
Solar Photovoltaics	1% of Capex			
Wind onshore	1% of Capex			
Wind offshore	1% of Capex			
Biomass	2% of Capex			
Pumped Storage	5% of Capex			
Battery Storage	1% of Capex			

(All figures are capital costs in INR crores/MW in 2020)

Variable costs in INR 2020/kWh – Coal + Lignite (1.65); Coal + Lignite with CCS (2.97); Gas (0.9); Gas with CCS (1.26); Nuclear (0.65)

Sources: Costs based on the first edition of technology data for Indian power plants published by CEA (2022), National Electricity Plan 2022-23 (CEA, 2023) and expert consultations.

3. AIM Model Description and Equations

AIM/Enduse-India is a techno-economic, bottom-up model designed to analyze country-level policies related to efficient material and natural resource use, GHG emission mitigation, and local air pollution control. It assists in energy, climate material, and resource policy analysis. The model simulates the flows of energy, resources, and materials in an economy, from the supply of primary energy and materials, through the conversion and supply of secondary energy and materials, to the satisfaction of end-use services. The model uses a linear optimization framework to select technologies across sectors, minimizing system cost under several constraints such as the required service demands and availability of energy and material supplies. The system cost includes fixed costs and operating costs of technologies, energy costs, and other costs such as taxes or subsidies. The model can perform calculations for multiple years simultaneously. In the current AIM/Enduse-India model, 2000 is selected as the starting year and 2070 as the end year. The model has been validated for 2005, 2010, 2015, and 2020.

3.1 Formulation of AIM/Enduse

3.1 Indices and sets

The suffixes of indices and sets are defined as follows in the AIM-Enduse model:

i :	Sector and region
j :	Service type
k :	Energy type
l :	Device or measure (i.e., mitigation option)
h :	Device cohort
m :	Gas (emission) type
p :	Gas (emission) removal process
t :	Simulation year
t_0 :	Base year
W_j :	Set of combinations of device and removal process (l,p) that can satisfy service type j
MQ :	Group of sectors and regions i categorized for emission constraints
Y_{MQ} :	Set of sectors and regions i belonging to the group MQ
MG :	Group of gases m categorized for emission constraints
Z_{MG} :	Set of gases m belonging to the group MG
ME :	Group of sectors and regions i categorized for energy supply constraints

Y_{ME} : Set of sectors and regions i belonging to the group ME

MR : Group of sectors and regions i categorized for internal energy balance constraints

INT : Group of combinations of internal energy and internal service (k, j)

Y_{MR} : Set of sectors and regions i belonging to the group MR

J_{INT} : Set of services j belonging to the INTth internal service

K_{INT} : Set of energy k belonging to the INTth internal energy

n : Number of share ratio constraints for group of devices l

U_n : Set of devices l that is targeted in the nth group share ratio constraints

G_n : Set of combinations of sectors/regions and service (i, j) that is targeted in the nth group share ratio constraints

R_{NQ} : Set of sectors and regions i' belonging to the group NQ

R_i : Group of NQ belonging to sector and region i

GWP_m : Global warming potential of a gas m

3.1.1 *Expression for emission quantity estimation*

Emission quantity (CO_2 equivalent) Q_i^m of gas m in sector and region i is expressed by Equation 8. Emission quantity Q_i^m is calculated by multiplying operating quantity $X_{l,p,i}$ by emission quantity $e_{l,p,i}^m$ of a gas m per unit operation of a combination of device l with removal process p in sector and region I and adding up the quantity of emissions from all devices. Emission quantity $e_{l,p,i}^m$ of gas m is composed of energy-related emissions and non-energy-related emissions and is expressed by Equation 9.

$$Q_i^m = \sum_j \sum_{(l,p)\in W_j} X_{l,p,i} \cdot e_{l,p,i}^m \qquad \text{EQ\_EMISS}(i,m) \qquad (8)$$

$$e_{l,p,i}^m = \left(f_{0,l}^m + \sum_k f_{k,i}^m \cdot \left(1-\xi_{l,i}\right) \cdot E_{k,l,p,i} \cdot \left(1-U_{k,l}\right) \right) \cdot \left(1-d_{l,p,i}^m\right) \qquad \text{EQ\_EM}(i,p,l,m) \qquad (9)$$

where

Q_i^m : Emission quantity of gas m in sector and region i (*note*: CO_2 equivalent)

$X_{l,p,i}$: Operating quantity of a combination of a device l with removal process p in sector and region i

$e_{l,p,i}^m$: Emission quantity of a gas m per unit operation of a combination of a device l with removal process p in sector and region i

$f_{0,l}^m$: Emission of gas m from operations other than energy combustion of a unit of device l (i.e., same as gas m's emission coefficient of a device l)

$f^m_{k,i}$: Emission of gas m from combustion of energy type k by a unit energy use of device l in sector and region i

$\xi_{l,i}$: Energy efficiency improvement ratio by device l in sector and region i due to efficiency improvement of operation and management

$E_{k,l,p,i}$: Energy consumption of energy type k per unit operation of a combination of a device l with removal process p in sector and region i (i.e., same as specific energy input to a device)

$U_{k,l}$: Proportion of energy type k used for non-combustion operations in a device l (i.e., used as a material process in a device l)

$d^m_{l,p,i}$: Removal ratio of gas m per unit operation of a combination of a device l with removal process p in sector and region i.

3.1.2 Expression for energy consumption estimation

Consumption of energy type k in sector and region i is estimated by adding up consumption of energy k from all devices, expressed by Equation 10.

$$Q^e_{k,i} = \sum_{j} \sum_{(l,p)\in W_j} (1-\xi_{l,i}) \cdot E_{k,l,p,i} \cdot X_{l,p,i} \qquad \text{EQ\_ENG}(i,k) \qquad (10)$$

where

$Q^e_{i,k}$: Consumption of energy type k in sector and region i

3.1.3 Constraint conditions

1) Emission constraints

   The emission quantity of gas m in sector and region i must not exceed its allowable maximum emission limit.

2) Energy supply constraints

   The total quantity of supply of energy type k cannot exceed its allowable maximum energy supply quantity or fall below its allowable minimum energy supply quantity.

3) Total operating capacity constraints
4) Total service demand-and-supply balance constraints
5) Internal energy and internal service balance constraints
6) Device share ratio constraints on service output
7) Share ratio constraints on service output for a group of devices
8) Share ratio constraints on service output in sector and region i
9) Device recruitment quantity constraints
10) Annual growth rate constraints on device recruitment quantity
11) Device stock quantity constraints

3.2 Sectors and services

The current model includes the energy supply and conversion sectors and energy demand sectors. The energy supply sectors include electricity generation and supply, natural gas demand, and oil demand (petrol, diesel, and so on) (Table A2). The choice of services within each sector is based on a) the importance of the service to the sectoral energy use and b) the availability of data on service demand and technologies.

Table A2: Classification of sectors and services in the current AIM/Enduse-India model

Feature	Description
Time frame	2000–2070 (70 years)
End-use sectors	Four major demand sectors: ***Agriculture:*** More than 15 crops, including rice, wheat, other cereals, pulses, sugarcane, fruits, and vegetables ***Power***: Coal (sub-critical, super-critical, IGCC), gas (OGCT, CCGT), oil (diesel), nuclear, hydro (large and small), bioenergy, solar (PV, concentrated solar power (CSP)), wind, waste to energy, CDRs ***Industry***: More than 15 energy-intensive industries (iron and steel, cement, aluminum, fertilizers, chemicals, paper and pulp, and so on), CDRs ***Building***: Includes residential sectors (cooking, lighting, cooling, heating, ICT), commercial sectors (hotels, educational buildings, and so on), and smart grids
Technologies	Over 550 devices in the end-use demand sector
Services	Over 75 services have been captured

3.1 Scenario drivers and sectoral service demands

We use a top-down method to estimate the service demand based on population, gross domestic product and urbanization rate. The details on the population profile and GDP are provided below.

3.1.1 Scenario drivers

India has the second largest human population in the world with more than 1.35 billion people with 64% of the population is in the age group of 15-59 years (UNPP 2019). A significant section of its large population depends on climate-sensitive sectors such as agriculture, fisheries and forestry for livelihood. India's population is expected to overtake China by 2025 and peak at 1.75 billion in 2060 (UN 2015). India is also amongst the fastest growing economies in the world with average GDP growth rate from 1980–2014 observed to be about 6.2%; however, per capita GDP in India is still lower than global average. India has detailed domestic targets such as power for all by 2019 (deficit around 200 million people by 2018), housing for all by 2022 (deficit of about 15% households), education for all (deficit around 15%), health for all. Integrating these domestic developmental policies with India's climate change commitments as per India's NDCs could be a challenge especially since coal is the mainstay of the Indian energy system. India is also the third largest consumer of oil in the world, mainly for transport use and with very little domestic production, making it macro economically vulnerable to i. International oil prices will impact the transport sector significantly.

We follow the future projections for population and urbanization presented in the UN population database 2022. We have assumed the mitigation policies across three growth scenarios high, medium and low to capture the economic growth of the country.

a) NDC High: NDC high growth scenario follows a high growth rate of about 8% and 7% between 2020-2030 and 2030-2040 respectively, which lowers 4% between 2040 and 2070. Overall, the CAGR between 2020 and 2070 is at 5.2%.

b) NDC Medium: NDC medium growth scenario follows a slightly high growth rate of about 7% between 2020-2030, followed by medium rate at 6% between 2030-2040, which lowers 4% between 2040 and 2070. Overall, the CAGR between 2020 and 2070 is at 4.9%.

c) NDC Low growth: NDC low growth scenario follows a high growth rate of about 6.1% and 5.2% between 2020-2030 and 2030-2040 respectively, which lowers to 3.5% between 2040 and 2070. Overall, the CAGR between 2020 and 2070 is at 4.45%.

Sectoral demand may increase or decrease based on the market environment and customer demand. Historical trends have shown the decline in the share of agriculture sector from 60% in 1950 to 14% in 2015-16 to the overall GDP, and an exceptional rise in the service sector to 64% in 2015-16. The share of industry in GDP is projected from the logistic regression of the past data, and assuming a long run saturation level of 29-31% in 2050. Next, using similar logistic regression, the projection for service sector is made in terms of its share in the balance future trajectory of non-industrial GDP (assuming a long-term saturation share of 61-63%). Branching in this manner ensures consistency with the total GDP and Industry GVA projections. The share of transport in the balance non-industrial and non-commercial GDP is then projected in the similar way (assuming a 25% long-term saturation share). The projections for the GVA in agriculture sector are automatically obtained as the final balance. To counter-validate for consistency, the projections for net-irrigated area are made separately using logistic regression of past data. These are checked for correlation with the projections for the agriculture GVA.

Industry sector constitutes seven energy-intensive aluminium, cement, chlor-alkali, fertilizer, iron and steel, paper and pulp and textile plants, in addition to other manufacturing units. The share for agriculture is assumed to decrease in the next decade, while that of industry will increase. Biochar could be an input for the steel sector and decarbonizing steel industry gradually. Use of biochar in sectors such as steel making and agriculture itself could propel and incentivize supply. This would in turn incentivize farmers supporting their incomes, industries established in rural areas and the whole green ecosystem transitions in India. The services share to GDP may slightly increase.

These driving forces influence a combination of parameters based on which supply and demand for a service can be determined. These include:

a. Sectoral demand

The demand in each of the sector is dependent on various factors which are described in detail in section 3. This parameter explains the growth in service demand in each sector based on the socio-economic drivers such as population, and economic growth. This is also depended on the service demand of each sub-sector/industry in every sector. “Energy service” refers to a measurable need within a sector that must be satisfied by supplying an output from a device. It can be defined in either tangible or abstract terms, thus “service demand” refers to the quantified demand created to satisfy the exogenous service demand.

b. Energy

Energy parameters are inserted in the model for each of technology along with the energy prices. Energy inputs are in the form of specific energy consumption for each of the technology collected or estimated. The model links the energy supply with demand, hence the electricity supply and demand is consistent across sectors.

c. Technology

The model selects a set of energy technologies in order to minimize the total annual cost of fulfilling energy service demand under energy, emission constraints, technology diffusion and so on. The payback time period selected can impact on simulation results of mitigation cost analysis. The payback period represents the period of time required for the return on an investment such as energy savings to break cost; i.e. capital cost, and operational cost, maintenance cost, overhead cost, and other costs. The changes that are taken into account simultaneously in the AIM/Enduse model include: 1) recruitment of a new technology at the end of the service life of an older technology or to meet with the increase in service demands; 2) improvement of energy efficiency of an existing technology; and 3) replacement of an existing technology by a new technology, even though the existing technology remains in service but is stopped immediately because a new technology is due to a policy or more cost effective in total.

3.1.2 Sectoral Demands

3.1.2.1 Industry

Industry sector contributed about 27% to the current GDP. The industrial sector consumption of electricity has increased from 34% in 2000 to about 44% in 2015 (MOPSCI, 2016). The model covers over fifteen industries, however the study will be describing only seven of these energy intensive industries as they constitute more than 60% of the industrial energy consumption mentioned in PAT cycle I (BEE, 2011).

The GVA in industry includes contributions from manufacturing, and mining activities. For the purpose of energy projections, the industry is disaggregated into sub-sectors, viz, steel, aluminium, cement, paper and pulp, textiles, fertilizer, caustic soda, soda ash, and other industrial sub-sectors. The choice of this segregation is based on the energy intensive industries selected in PAT scheme. The end-use demands in these sub-sectors is projected in the final physical units, e.g. million tons of aluminium (or other metals), billion number of bricks, billion metres of textiles/cloth, etc. `Other industries' category includes diverse manufacturing and non-manufacturing activities, its end-use demand is expressed directly in the energy units of electricity, coal, diesel and fuel oil consumed.

The methodology described above, though captures recent and past trends, and ensures consistency with macroeconomic growth, however it does not explicitly capture the inter-sectoral substitution of demands. For example, a major end-use of paper products is to cater to the needs of communication in written form is being replaced by rapid development and commercialization of electronic and computer communication technologies. The estimates of the extent of such inter-sectoral substitutions are highly subjective, and can at best be based on expert opinions and secondary literature. This study incorporates such opinions exogenously while setting the saturation level and compounded annual rate of growth of sub-sectoral demands.

3.1.2.2 Transport

Transport sector accounts for more than 15% of the total energy demand in 2015, accounting for one-fifth of the total energy consumption. The increase in energy demand in this sector presents a challenge to energy security as majority (almost 75 per cent) of its demand is met by imported oil. Another concern is related to its impact on air quality, which results in impacting human health especially in urban cities. In India, the road and rail have been the most preferred mode of transport for passenger as well as freight.

3.1.2.2.1 Passenger transport

The CAGR for passenger transport between 1990 and 2010 was 7.4 respectively. A large part of this demand was from road transport, which accounted for 88 per cent. Indian Railways is the largest railway network in Asia, with a daily ridership of nearly 23 million passenger-kilometres (Dhar et.al, 2015). The share of mode of passenger transport by road and rail has increased from 83.1% in 2001-02 to 85.9% in 2011-12. The high growth of road transport occurred both for intercity transport (including transport from rural areas to cities) and within the cities. Buses and personal modes of transport like cars and two-wheelers provide point-to-point connectivity and have shorter waiting times, and are therefore preferred over rail. The share of cars in intercity road transport has increased due to higher incomes and improvements of selected highways in the country.

The demand for passenger transport is dependent on a variety of factors including travel demand in terms of time, and distance, in addition to change in lifestyle due to increasing income levels and type of vehicle at an individual level, and policy environment (for example: odd and even rule) and traffic management which are exogenous, but are equally important. The passenger traffic in 2011-12 was about 10,375 billion passenger kilometre (bpkm) which is expected to grow about 15% till 2030. The mode share of public transport will be overtaken by private transport by 2040. NMT is expected to grow in line with population growth.

Intercity passenger demand would increase at a much slower pace compared to the urban transport demand, and reach 25,941 bpkm in 2050 (Dhar et.al, 2015). The transport demand is mainly met by road-based modes, and the diminishing role of rail would not see a major turnaround. The growth in road and rail traffic will be around 15.4 and 9% for the next 14 years. The demand for air transport is gradually increasing and the traffic estimated to grow at the rate of 12% for domestic and 8% for international travel . There is an observed increase in the individual vehicle ownership over the past few decades. A combination of poor traffic management due to overcrowded roads, energy security (oil dependency) and environment concerns (local and global emissions) have encouraged the government to enhance public transport and non-motorized transport in addition to establishing vehicle efficiency standards.

3.1.2.2.2 Freight transport

Road and rail are two major modes for freight transport. Rail freight increased from 127 billion tkm in 1970 to 626 billion tkm in 2010 at a CAGR of 4.06 per cent, whereas road freight increased from 67 billion tkm to 1,128 billion tkm during the same period at a CAGR of 7.3% (Dhar et.al., 2015) There was a significant shift in the share of freight transport from rail to road; however, since 2000, the share of rail has remained at around 40% (Figure 20). The freight transport also includes a small share from coastal shipping, barges on inland water ways, and pipelines. In 2010, the share of freight taken by coastal shipping accounted for less than 6% of overall demand.

The freight traffic was estimated to be around 2000 billion transport kilometre (btkm) in 2011-12 and expected to grow at 9.7% with an elasticity of 1.2. In the BAU scenario the per capita demand is expected to increase to 5,941 tkm in 2050, and consequently the overall demand for freight transport is expected to be 10,052 billion tkm in 2050 with a growth rate of 4.4 per cent. The road and rail traffic has been projected to grow at a rate of 12 and 8% per annum respectively. The modal share of rail and road was assessed to be 35:65 in the 12th plan (2012-17), 39:61 in the 13th plan (2017-22), 45:55 in the 14th plan (2022-27) and 50:50 in the 15th plan (2027-32).

3.1.2.3 Buildings

Rapid urbanization, and increased income levels have led to demand for improved quality of life. Increased penetration of electrical appliances and shift of cooking fuels accounts for the increasing energy demand in residential sector. For the current study, household energy consumption is based on the following categories: Cooking, lighting, cooling appliances, and others include refrigeration and ICT services.

The penetration of electric appliances has been observed to increase in all classes in both rural and urban areas. The ownership of assets is projected to increase with increase in income, however the quantity of assets will vary across the expenditure classes. The type and amount of fuel consumption (including electricity) also differ between rural and urban areas. For the current study, the segregation in the residential sector has been according to the energy used for the afore-mentioned listed purposes. The demand in households is projected based on a combination of their past trends, global trends, intensities in the private final consumption expenditure (PFCE), and expert opinion about the future shares.

3.1.2.4 Agriculture

India had been an agrarian economy since time in memorial. After liberalization the share from agriculture and allied sectors to the GDP has been observed to steadily decline, however it still remains as the main source of income to more than 50% of the population. This sector is essential to the Indian economy as it maintains the food security for India. It also provides raw material to major industries such as food processing, sugar, milk and milk products, textiles, jute and paper. It is also the driver to many industries including fertilizers, pesticides, automobiles such and tractor and irrigation related devices. The demand in agriculture is dependent on the increase in per capita food consumption by satisfying the dietary requirements of the growing population in addition to meeting the non-food industry consumption.

The production of crops is dependent on a combination of factors including land holding size, cropping intensities, nutrient intake, weather patterns, and irrigation mechanisms. There has been substantial increase in the agricultural productivity, and irrigated land in spite of the total amount of land in the past few decades have remained the same. Agriculture land accounts for 43% of total land, of which about 50% in under some form of irrigation and only about 8% land is under micro-irrigation. The yield for each of the crops have increased in the past seven decades, however it is yet to meet the global standards. After the green revolution, a marked increase was observed and has been maintained in the production of crops.

Garg (et. al., 2012) found that the N-fertilizer applied per unit cropped area and crop yield have wide differences across the Indian states and districts. Such differences and high fertilizer use in several regions are found mainly due to unsustainable practices such as excessive use of water along with imbalanced use of chemical fertilizers, decreased use of organic fertilizer, decreasing carbon/organic matter content, deficiency of micro nutrient etc. Such effect is found very strongly in the 'green revolution' areas of northern and north-western parts of India, where fertilizer consumption is comparatively high, and the response ratio of grain output to fertilizer input has declined over recent years.

The energy required for crop production is comparatively lesser than other sector. However, with green revolution, building of dams and canals, and tube wells in addition to mechanization of large farms, the demand for energy in agriculture has been observed to increase in the past four decades. Energy in required at three stages: 1) to prepare the land, 2) to procure water, and 3) post-harvest purposes. For the current study, the energy demand in end-use are based on tillers, tractors and pumps.

4. TIMES Model Description and Equations

TIMES-India is a bottom-up energy systems optimization model developed using The Integrated MARKAL-EFOM System (TIMES) model generator (Loulou et al., 2016) and the TIMES-Starter platform (DecisionWare, 2016).

In TIMES-India, the complex realities of the national energy system are converted into a conceptual representation called the reference energy system (RES). The RES broadly divides the energy system into four parts: primary supply, secondary conversion processes, final energy, and end-use services. The primary sources include all the domestic and imported energy sources such as coal, crude oil, natural gas, solar, and wind. The secondary conversion processes consist of electricity plants, refineries, and hydrogen plants. The third and fourth parts represent final energy in different forms available for end use in demand sectors such as agriculture, industries, transportation, and buildings (residential and commercial). Moreover, the model structure is based on three entities: commodities, processes, and commodity flows. Commodities include fuels, energy services, emissions, materials, and financial flows. The processes are used to transform commodities from one form to another (for example, a primary fuel such as coal is converted into electricity). Commodity flows are used to link commodities and processes.

TIMES belongs to the MARKAL/TIMES family of energy system models (Loulou et al., 2016), developed by the IEA's Energy Technology Systems Analysis Programme (IEA-ETSAP). It is an optimization model used for undertaking systemwide analysis of energy and climate policy instruments to inform energy and environmental policy decisions. It uses linear programming to produce a least-cost energy system for given data, boundary conditions, and assumptions. The total system costs are optimized across sectors and the model time periods. The TIMES model is formulated in GAMS (Rosenthal, 2007). The TIMES objective function is given in Equation 11 (Loulou et al., 2016).

$$NPV = \sum_{r}\sum_{y}\left(1 + d_{r,y}\right)^{REFYR-y} \ . \ ANNCOST\,(r,y) \tag{11}$$

where

r represents regions ($r = 1$ for TIMES-India), y represents a set of years for which the data on costs is available, NPV is the NPV of the total costs of all the regions, $REFYR$ is the reference year for discounting, and $d_{r,y}$ is the general discount rate.

$ANNCOST\ (r,y)$ is the total annual cost in region r and year y. It represents the total annual costs minus the revenues and includes elements such as investment costs for new purposes, fixed and variable costs of processes, costs for domestic resource production, and exogenous imports, taxes, and subsidies in the system.

Constraints

While minimizing total discounted cost, the TIMES model must satisfy a large number of constraints (the so-called equations of the model) that express the physical and logical relationships that must be satisfied to properly depict the associated energy system.

1) Capacity transfer (conservation of investments)

2) Process activity variables
3) Use of capacity
4) Commodity balance equation
5) Flow relationships in a process
6) Limiting flow shares in flexible processes
7) Peaking reserve constraint (time-sliced commodities only)
8) Constraints on commodities
9) User constraints
10) Growth constraints
11) Early retirement of capacity
12) Electricity grid constraints

From an economic standpoint, TIMES is a partial equilibrium model with exogenous demands and does not consider the feedback of demands on technological changes. TIMES-India has perfect foresight where decisions in each period are made assuming full knowledge of future events.

5. Load Curve Model Description and Equations

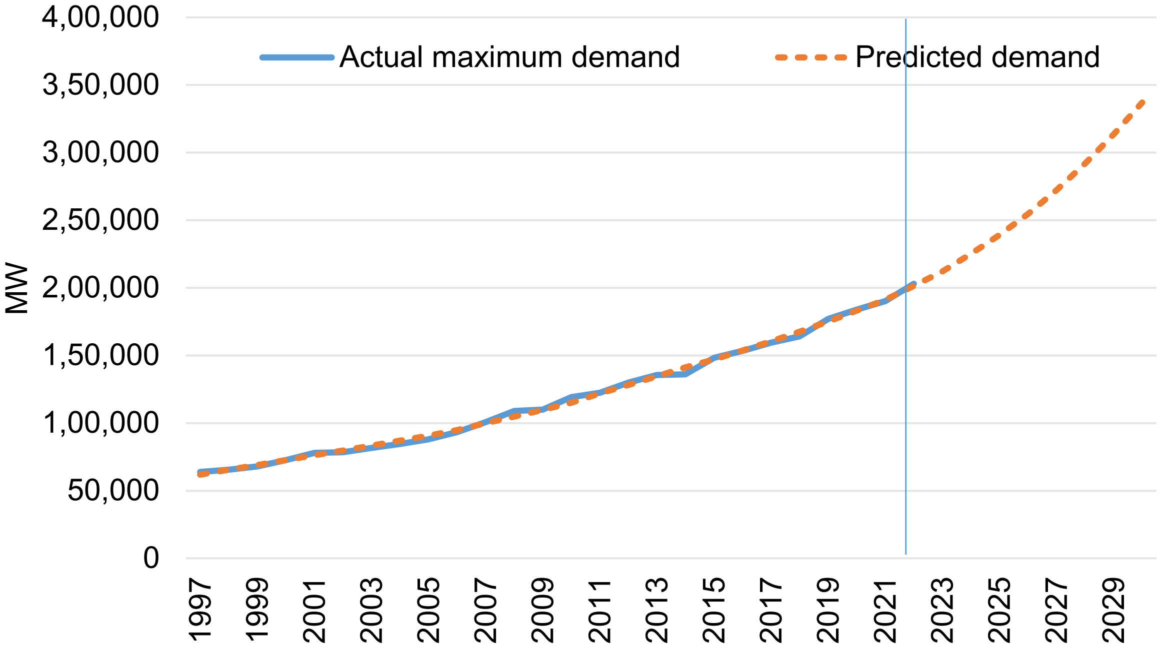
5.1 Forecasting demand and supply

Electricity load curve scenarios are projections of future changes in the demand for electricity over time. A scenario is defined as "a coherent, internally consistent, and plausible description of a possible future state of the world" (IPCC, 1994)[14]. These scenarios help identify when and where additional generation capacity may be needed and how RE sources can be integrated into the grid to meet demand. Currently, the base scenario (BAU) follows the capacity mix constraints set up by the Standing Committee on Energy 2021–22 and CEA. Ramping needs, plant availability, and variable/marginal costs play a key role in these scenarios. Regardless of the specific scenario, the goal is to ensure that the electricity supply always matches demand.

5.1.1 Demand forecasting

On the basis of the above data and maximum demand data collected from publicly available documents of POSOCO, the maximum demand was forecasted for 2029–30 (Figure A1). The forecast was carried out on the deseasonalized trend with maximum demand as the dependent variable. Independent variables included peak demand (*t*-1), peak demand (*t*-12), GDP, IIP, population, COVID dummy, annual average temperature, and annual rainfall. In addition, the daily data set used weekday/weekend dummies.

Figure A1: Load forecast in MW for 2029–2030



Our forecast was compared with the forecasts of the CEA and the Draft NEP. The forecast was found to be similar to that of the CEA, although the estimations based on the Draft NEP forecast data were a bit lower. We have used our forecast as a baseline for the study. See Table A3 for the comparison of forecast demand.

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[14] See: https://archive..ch/ipccreports/tar/wg2/index.php?idp=125

Table A3: Comparison of demand forecast by various studies

Forecast name	Max demand forecast	Time horizon	Source
This study forecast	337.060 GW	2030	Data used in the study
CEA forecast	339.973 GW	2030	Report on optimal generation capacity mix
20th EPS forecast	334.811 GW	2030	20th EPS, November 2022
Draft NEP (estimated)	323.4 GW	2030 (5.94% CAGR)	Estimated from the Draft National Electricity Plan, September 2022
Draft NEP forecast	272–363 GW	2027–2032	Draft National Electricity Plan, September 2022

The forecast in this study compares favorably with that in other similar studies with the same time horizon.

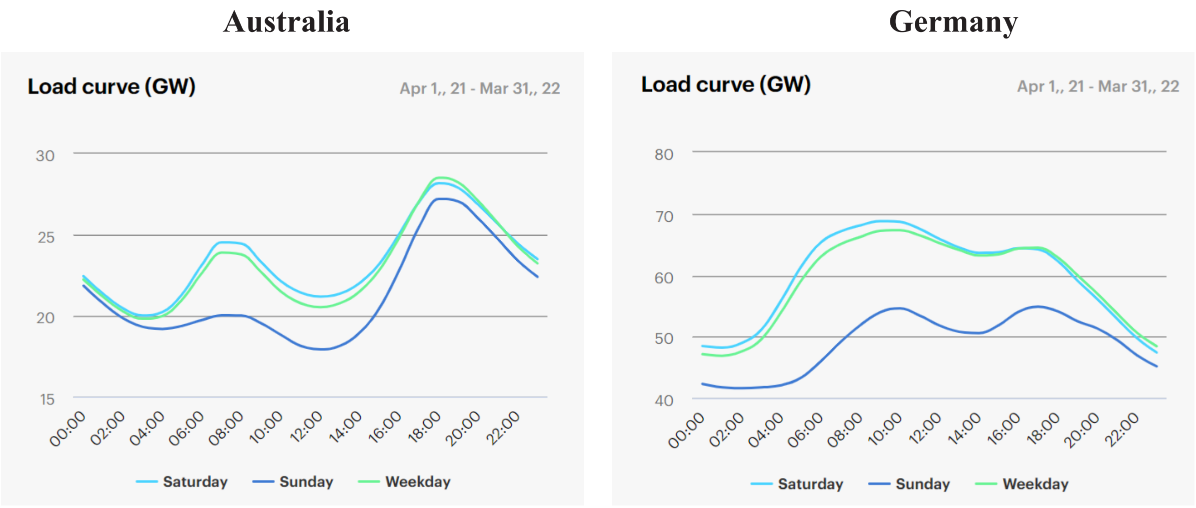
5.1.2 Load profiling

The study is limited to grid-connected sources and does not consider off-grid distributed generators. One of the starting assumptions of load profiling has been the projected capacity across different technologies and the development of maximum shape curves. This capacity would later be fitted to match demand and supply on the basis of various constraints. Special emphasis was placed on high-growth time-varying loads such as solar and wind as separate modeling exercises were conducted for them.

5.1.2.1 Load profile: Very high HDI countries

See Figure A2 for some load profiles of very high HDI countries for 2021–22 (April–March). The data presented in Figures A2 and A3 is as reported by IEA to maintain uniformity of data from a single acceptable source. Load curves are available at IEA (9 May 2022), Real-Time Electricity Tracker, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/real-time-electricity-tracker . For countries, the data may have been adjusted for GMT and may not represent local time as the objective was to represent the variances in the load curve internationally. For future studies focussed on the exploration of country-wise VRE integration, which is not an objective of the present study, the load profiles as per local times may be used.

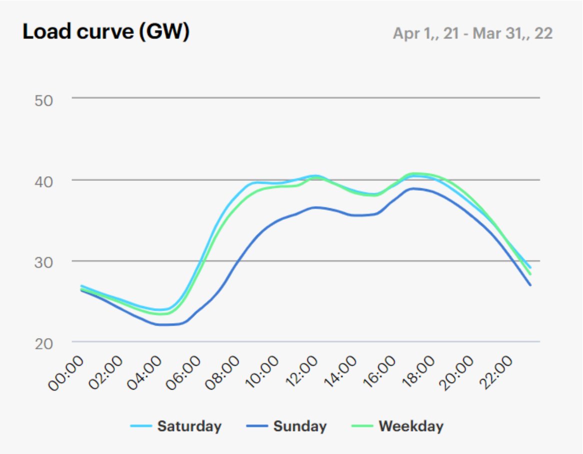
Figure A2: Load profiles of very high HDI countries for 2021–22 (April–March)



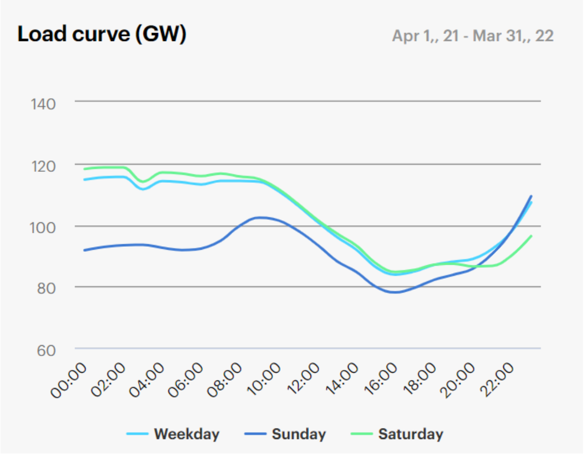
Australia

Germany

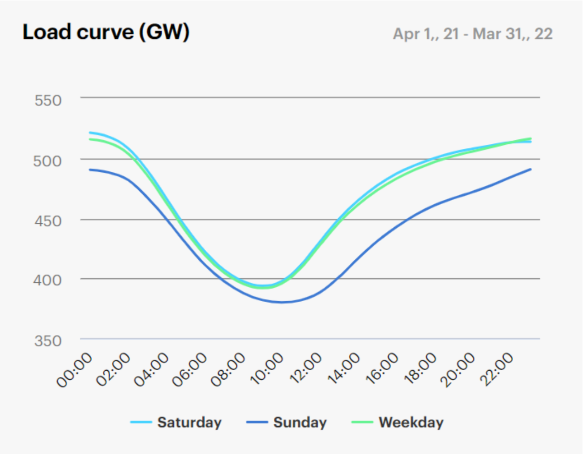
United Kingdom



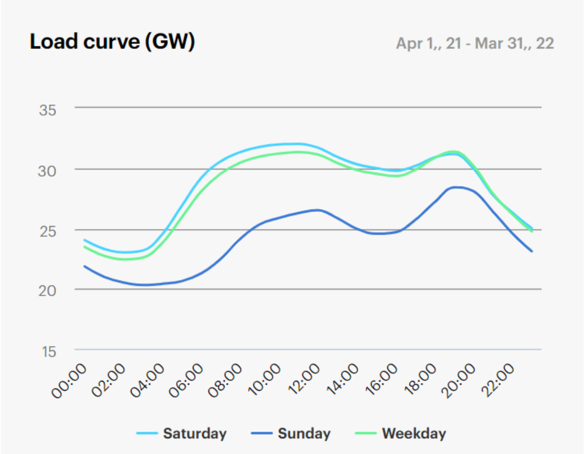
Japan



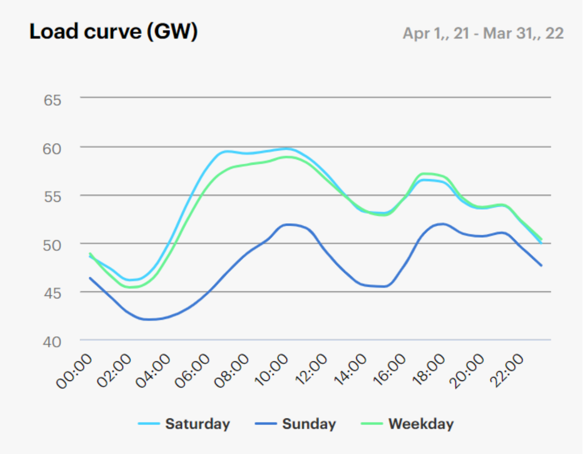
USA



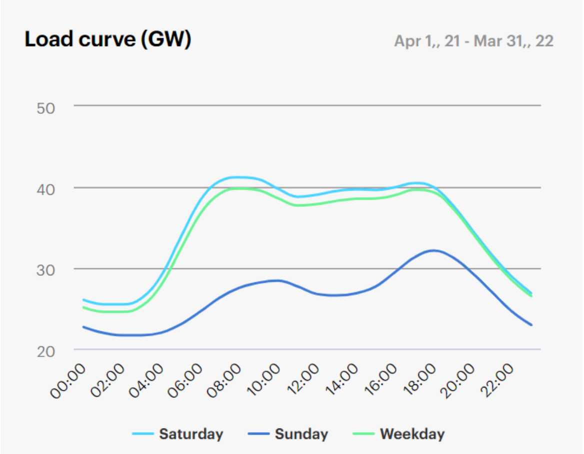
Spain



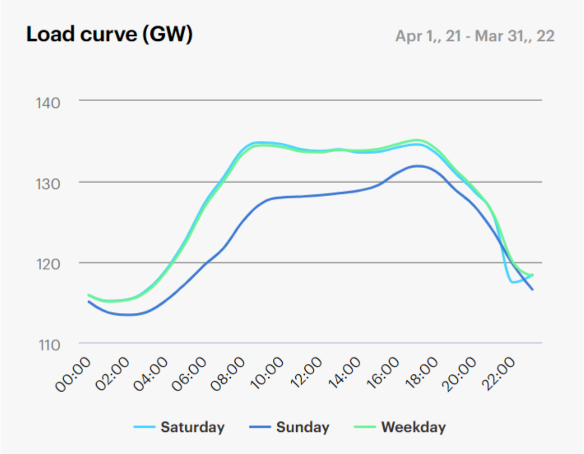
France



Italy



Russian Federation



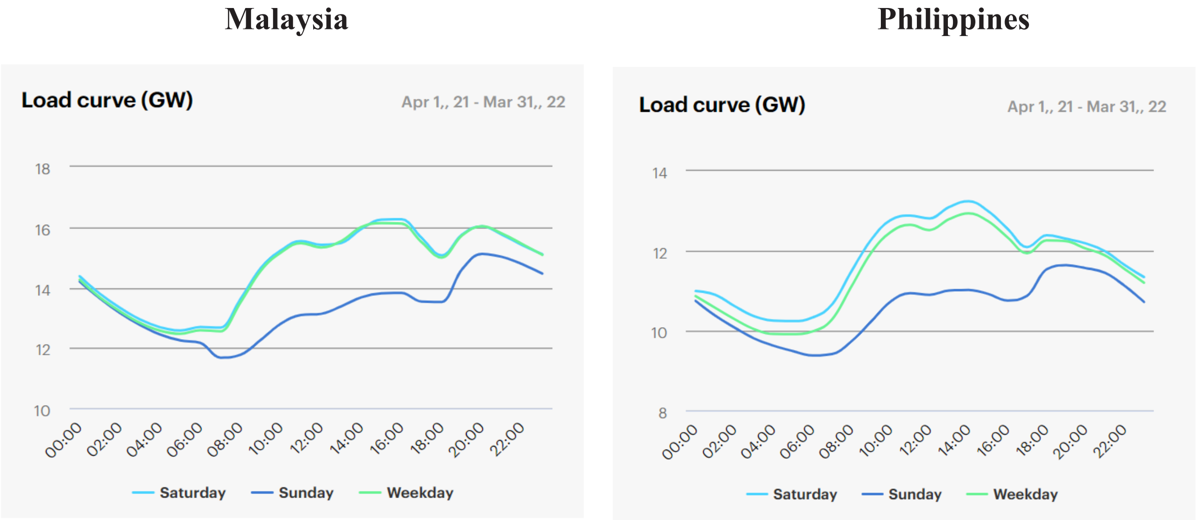
as reported in IEA' with time adjustment. Load curves are available at

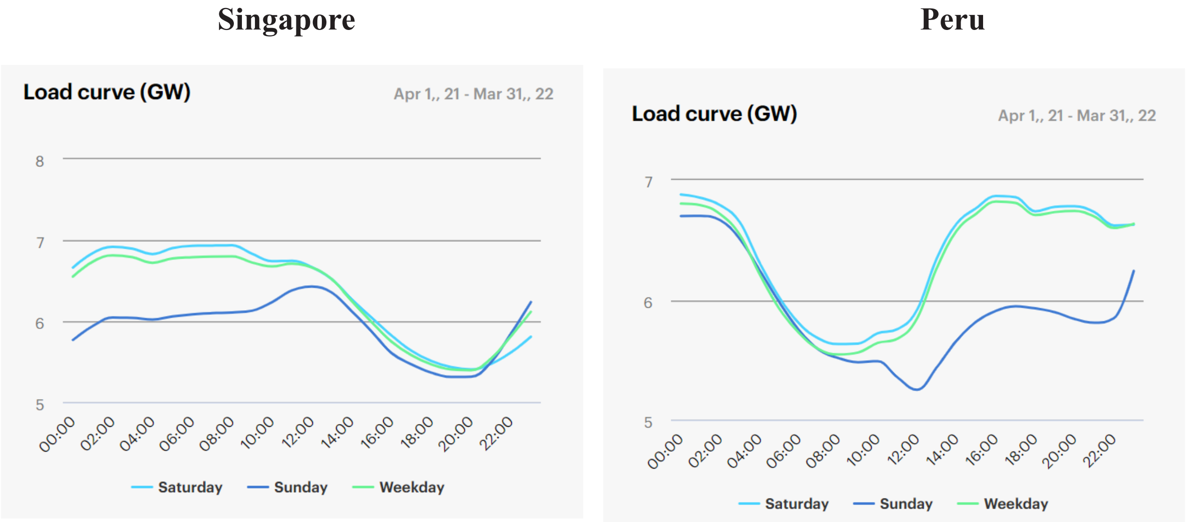
IEA (2022), Real-Time Electricity Tracker, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/real-time-electricity-tracker

5.1.2.2 Load profile: Tropical countries

The list of fully tropical countries was accessed from https://worldpopulationreview.com/ to understand load curves in these countries (Figure A3).

Figure A3: Load profiles of tropical countries for 2021–22


Malaysia Philippines


Singapore Peru

as reported in IEA' with time adjustment. Load curves are available at

IEA (2022), Real-Time Electricity Tracker, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/real-time-electricity-tracker

5.2.2.3 Wind power load shapes

On the supply side, wind loads were profiled using the System Advisory Model (SAM) developed by the National Renewable Energy Laboratory (NREL). The study collected wind data across seven windy states in India, which was then scaled up to the proposed capacity of 140 GW. Hourly time profiles were developed further using Gamesa wind turbine data of 2 MW.

The study used the average wind parameters described in Table A4.

Table A4: Wind power potential and input parameters

Sr. No.	State	Wind potential at 100 m (GW)	Wind potential at 120 m (GW)	Mean wind speed (m/s)	Mean power density (W/m^2)
1	Gujarat	84.43	142.56	6.77	283
2	Rajasthan	18.77	127.75	5.73	196
3	Maharashtra	45.39	98.21	6.3	282
4	Tamil Nadu	33.79	68.75	7.93	715
5	Madhya Pradesh	10.48	15.4	5.8	196
6	Karnataka	55.85	124.15	6.76	318
7	Andhra Pradesh	44.22	74.9	6.45	295
	Total of seven windy states	292.97	651.72		
8	Others	9.28	43.78		
	Total	302.25	695.5	6.58	316

Source: 1) MNRE, https://mnre.gov.in/wind/current-status/

2) Global Wind Atlas, https://globalwindatlas.info/area/India

The wind energy Atlas of NIWE provides the capacity utilization factor according to various parameters, as available in Table A5.

Table A5: Wind power: Mean wind speed, power density, and CUF

Mean wind speed (m/s)	Mean power density (W/m²)	CUF (%)
5.4	180	18
5.4–5.6	180–210	18–20
5.6–6.0	210–250	20–22
6.0–6.4	250–300	22–25
6.4–6.7	300–350	25–28
6.7–7.0	350–400	28–30
>7.0	>400	>30

Source: NIWE, Wind Energy Atlas, https://niwe.res.in/assets/Docu/Wra_100m%20agl%20map.pdf

For wind power, Gamesa 97, 2-MW turbine profiles were used across several locations, which were then extended to the overall model. These data were then normalized and scaled up to the proposed capacity of 140,000 MW in 2029–30.

The wind power model was developed in SAM using mean wind speed and mean power density and using Weibull factor "*k*" as 2 with reference to NIWE, India's Wind Potential Atlas at 120 m above ground level. Approved turbine model characteristics were selected from the MNRE site (https://mnre.gov.in/wind/manufacturers-and-quality-control).

However, along with the above parameters, the time slice parameters were based on average wind turbine profiles across 12 different test sites in India for Gamesa 97, 2 MW turbine (Table A6).

Table A6: Gamesa 97, 2 MW turbine time profile

Day hour	Average wind speed	Average generation (in kWh)	Capacity factor (%)
1	6.00	801.26	40
2	5.67	771.42	39
3	5.38	750.67	38
4	5.30	732.25	37
5	5.42	713.49	36
6	5.61	696.31	35
7	5.81	681.92	34
8	5.80	590.80	30
9	5.78	574.08	29
10	6.39	782.35	39
11	6.75	884.07	44
12	6.85	921.45	46
13	6.81	933.76	47
14	6.63	926.98	46
15	6.24	893.43	45
16	5.79	847.23	42

Day hour	Average wind speed	Average generation (in kWh)	Capacity factor (%)
17	5.24	776.54	39
18	5.08	763.35	38
19	5.34	824.87	41
20	5.60	880.71	44
21	5.85	950.20	48
22	5.98	1,001.72	50
23	6.02	1,018.51	51
24	6.08	1,010.49	51

Source: ICF, Shakti Foundation, 12 sites

The monthly variation of wind speed was taken to be representative of two locations across Karnataka. The annual mean speed of these locations of 6.72 m/s compares favorably with 6.76 m/s as per the global wind atlas for Karnataka. It is noteworthy that the wind speed is at its peak in July. The maximum demand days occur in May for 2019–20, January for 2020–21, July for 2021–22, and June for 2022–23 (until July) (Table A7).

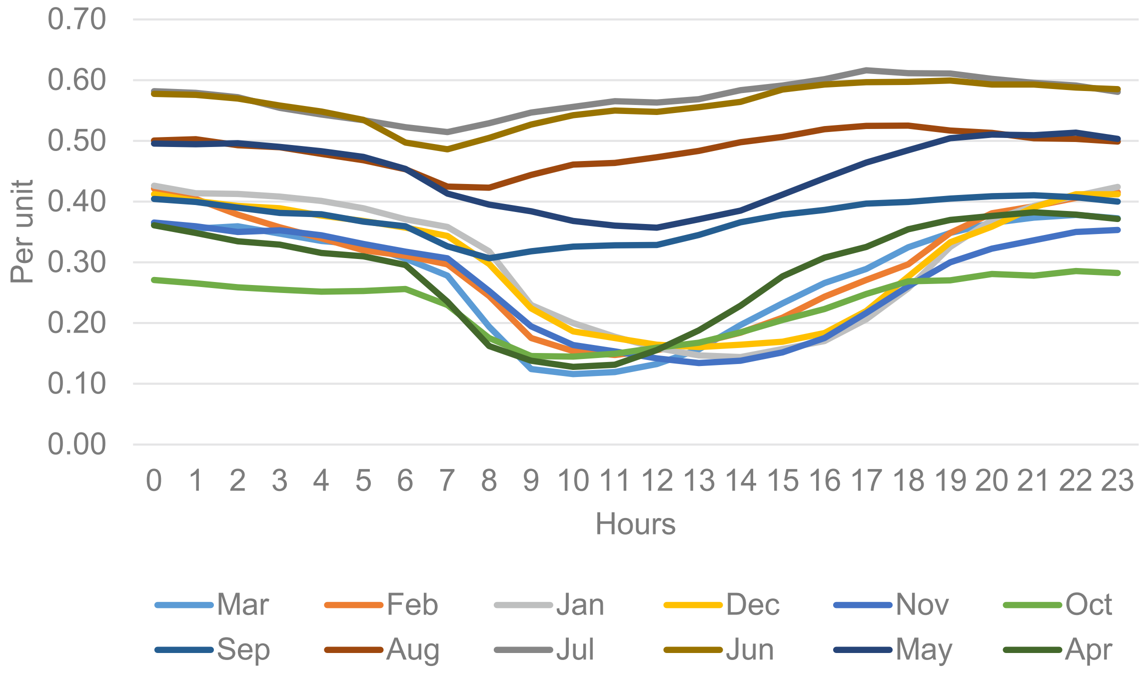
Table A7: Wind speeds in Karnataka in m/s

Month	Honnavar	Shirali	Average
January	5.95	6.78	6.37
February	6	6.87	6.44
March	6.1	7.03	6.57
April	6.2	7.25	6.73
May	7.21	7.84	7.53
June	7.5	8.3	7.90
July	7.72	8.5	8.11
August	6.66	7.64	7.15
September	4.87	5.56	5.22
October	4.55	5.42	4.99
November	5.04	6.76	5.90
December	6	9.51	7.76

Source: ENVIS Technical Report: 58, June 2013

See Figure A4 for the month-wise hourly variation of the average wind profile.

Figure A4: Monthly average wind profile



Source: Data for 2018

5.2.2.4 Solar power load shapes

On the supply side, solar loads were profiled using SAM developed by the NREL. Solar insolation data across multiple locations in India were used to model solar energy availability across all 12 months. These data were then normalized and scaled up to the proposed capacity of 280,155 MW in 2029–30.

Hourly solar insolation data in terms of GHI were collected from the National Solar Radiation Database of the NREL for the states with higher solar installation: Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Andhra Pradesh (Table A8).

Table A8: Average solar insolation data across selected states in GHI

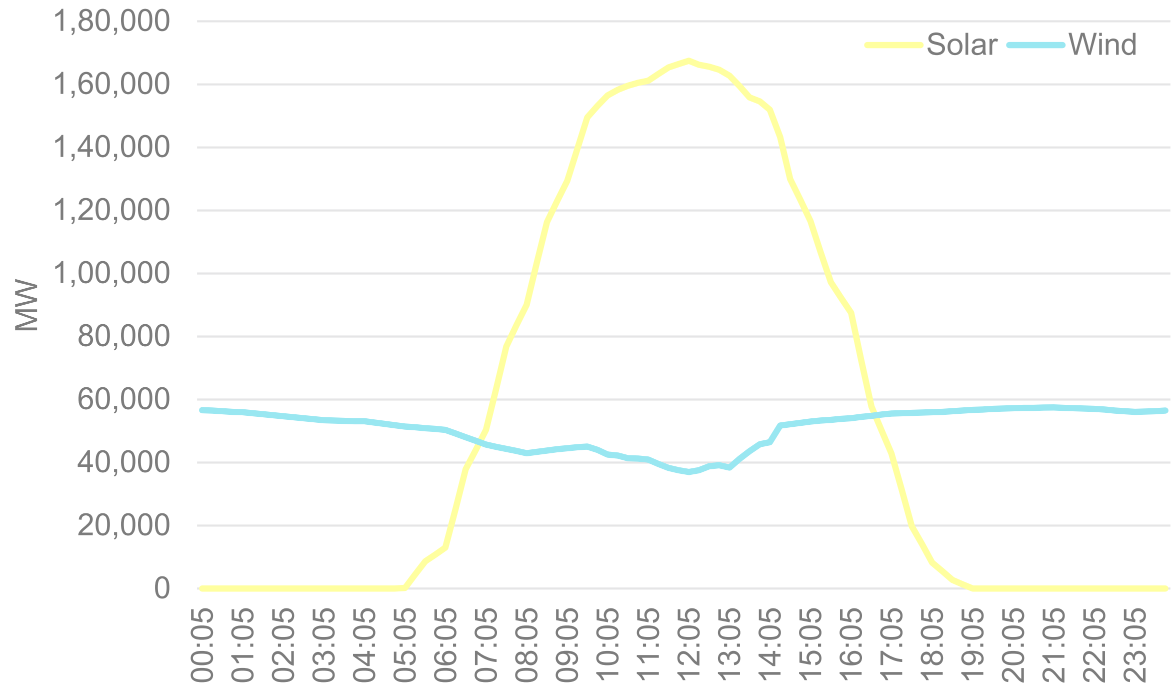
Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	1.2	4.9	5.1	3.1	1.6	0.2	0.0	0.0	0.0
6	0.4	2.6	19.3	202.5	377.2	361.2	256.5	209.8	124.7	35.6	14.7	2.2
7	108.9	242.7	672.6	1,158.2	1,331.9	1,239.6	996.9	937.8	901.7	765.6	405.3	174.7
8	910.6	1,158.7	1,772.4	2,289.2	2,417.4	2,107.4	1,782.3	1,901.7	1,921.0	1,840.7	1,324.7	999.0
9	1,780.7	2,038.7	2,856.4	3,330.2	3,421.6	2,885.7	2,561.9	2,788.8	2,888.6	2,785.3	2,208.3	1,874.2

Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
10	2,508.3	2,847.0	3,782.1	4,156.6	4,178.1	3,564.7	3,159.8	3,412.8	3,550.1	3,409.5	2,839.8	2,598.8
11	2,945.0	3,319.6	4,306.6	4,545.3	4,631.2	3,986.9	3,290.8	3,644.8	3,839.9	3,760.2	3,196.5	3,013.4
12	3,217.0	3,501.9	4,457.5	4,650.0	4,772.0	4,034.9	3,494.3	3,495.3	3,773.6	3,774.4	3,270.8	3,080.7
13	3,022.8	3,384.8	4,296.0	4,348.3	4,473.5	3,795.0	3,418.4	3,313.6	3,510.2	3,458.4	2,888.2	2,877.4
14	2434.1	2,798.7	3,632.6	3,803.6	3,836.8	3,336.8	3,101.7	2,664.6	2,955.0	2,850.1	2,302.1	2,242.2
15	1762.6	2,182.1	2,839.0	2,899.9	2,835.0	2,715.8	2,307.1	2,062.9	2,291.3	1,919.2	1,491.8	1,451.8
16	862.3	1,215.8	1,778.9	1,876.8	1,863.1	1,751.0	1,732.4	1,356.0	1,284.2	905.7	501.3	509.8
17	66.7	286.8	598.4	796.4	866.3	876.2	847.5	563.7	420.5	71.3	5.6	7.8
18	0.0	0.1	1.9	26.9	113.6	189.6	163.2	69.9	1.3	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: National Solar Radiation Database for India, NREL

The draft estimated solar and wind profiles are provided. These are subject to change on the basis of additional information (Figure A5).

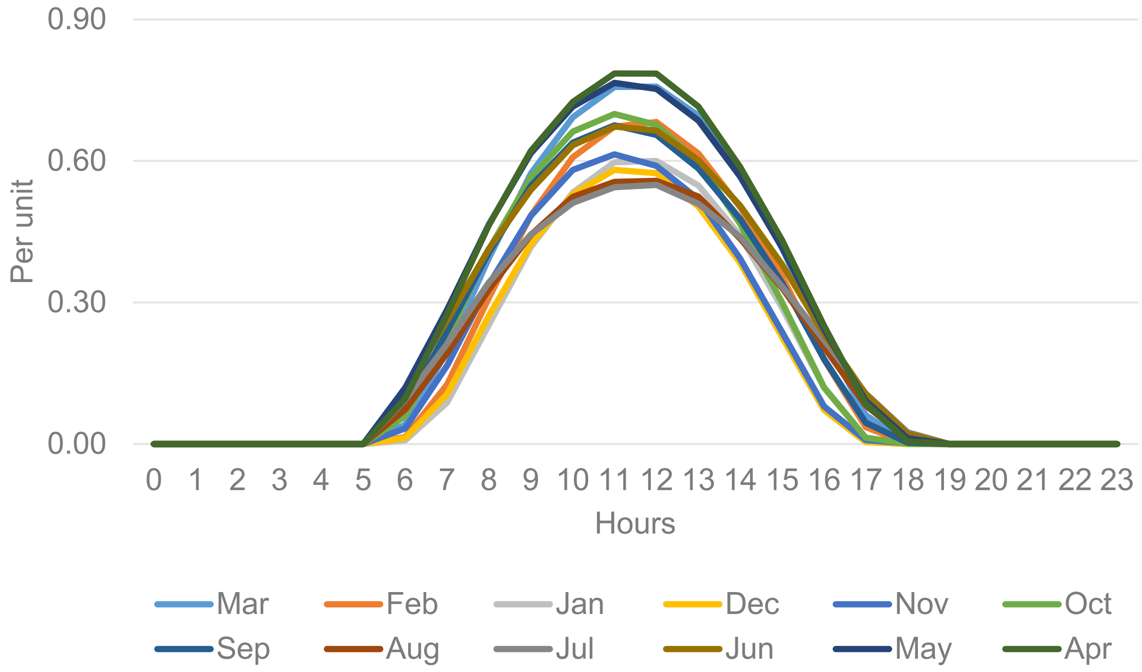
Figure A5: Solar and wind load in MW for 2029–2030



The plot depicts that as the solar PV load starts to increase from morning hours into noon hours, the net load on the system that needs to be met from non-variable supply goes down steeply. It increases again steeply as the solar PV supply decreases from late noon hours into evening hours. In addition, the load on the system goes up between 6 pm and 9 pm because of coincidental power usage by domestic, commercial, and industrial customers. This creates an additional requirement to increase the power supply between 6 pm and 9 pm.

See Figure A6 for the month-wise hourly variation of the average solar profile.

Figure A6: Monthly average solar profile



Source: Data for 2018

5.2.2.5 Non-renewable availability

The capacity available to the grid may differ from the installed capacity primarily for two reasons. First, capacities may be backed down because of a) fuel shortages, b) planned maintenance or forced outage due to technical issues, and c) scheduling issues. Second, auxiliary consumption must be accounted for. See Table A9 for capacity outages for the four RLDCs except for the northeast.

Table A9: Capacity outages for the four RLDCs except for the northeast

Date (DD-MM-YY)	Total non-RE capacity of the RLDCs	Capacity outage	Capacity outage as a percentage of the total non-RE capacity
	MW	MW	%
05-01-2018	266,787	64,976	24.4
06-02-2018	267,637	61,789	23.1
05-03-2018	267,384	65,560	24.5
03-04-2018	271,294	60,170	22.2
08-05-2018	271,174	60,966	22.5
05-06-2018	271,174	57,769	21.3
05-07-2018	271,174	71,193	26.3

Date (DD-MM-YY)	Total non-RE capacity of the RLDCs	Capacity outage	Capacity outage as a percentage of the total non-RE capacity
	MW	MW	%
07-08-2018	271,174	78,022	28.8
05-09-2018	270,314	78,516	29.0
09-10-2018	270,344	59,803	22.1
05-11-2018	270,419	66,513	24.6
04-12-2018	274,016	65,908	24.1

Source: CEA Monthly Reports

Additionally, Table A9 is in line with very recent reporting as of September 14, 2022, provided in Table A10:

Table A10: Net capacity online as of September 14, 2022

	Monitored capacity	Capacity outage	Capacity in line	Max power gross	Max power net	Capacity on line: net/monitored
	MW	%	MW	MW	MW	%
Coal	204,080	26	150,930	146,729	133,523	65
Lignite	6,620	23	5,095	4,870	4,431	67
Gas	24,846	84	3,978	4,107	4,025	16
Nuclear	6,780	37	4,280	4,464	3,951	58
Hydro	46,850	10	42,072	41,370	40,956	87

Source: CEA, https://npp.gov.in/public-reports/cea/daily/dgr/14-09-2022/dgr16-2022-09-14.pdf

5.2.2.6 Coal and lignite

With the aim to increase the flexibility of coal plants to accommodate increasing VRE integration, a circular from the CEA dated June 22, 2021, states that thermal plants under specific administrative controls may run at 55% load. The circular further instructs for the identification of 50% of the plants and to initiate discussions with OEMs to run at a) 200–600 MW units at 40–45% load and b) 660–800 MW units at 45–50% load and c) to conduct ramping tests (2%–3%) with a required ramp rate of 1% per minute, though the actual ramp rate may be slightly higher (CEA, 2021). This has been factored in while generating scenarios. Table A11 presents the net power supplied (MW) as a constituent of the load curve through various sources (fuel).

Table A11: Maximum net power in MW supplied as a constituent of the load curve

		Gas	Hydro	Nuclear	Coal
Installed capacity as of 31.3.2022	MW	24,900	46,723	6,780	211,210
Max load net as of 31.3.2022 (Max demand day in March 22)	MW	7,636	27,427	4,785	150,954
Max load net as of 7.7.2021 (Max demand day in 21–22)	MW	6,435	31,922.5	4,392.5	136,388

		Gas	Hydro	Nuclear	Coal
Max load net as of 30.5.2019 (Max demand day in 21–22)	MW	7,669.5	23,546.5	4,864	137,344.5
Max load net as of 10.6.2022 (Max demand day in April–July 2022)	MW	5,239	27,829	4,849	145,825
Net availability	%	31	59	71	71
Minimum net power (CERC regulations)	%	60			55
Maximum net load (assumption)	%	60	68	72	71
Minimum net load (assumption)		31	0	72	55

For developing the load curve, we have taken the maximum and minimum ranges as the upper and lower range, respectively, for constituting the load curve.

The data in the study can be further strengthened with data and projections of wind and nuclear capacities and peak loads from NIWE and NPCIL, respectively.

5.2 Balancing load and supply

Load profiling has been performed for various types of loads, and their alignment with technology/fuel mix and cost data has been carried out. The projections will be in alignment with WP2: National Energy Systems Modeling using the AIM/Enduse-India model. Each of the three scenarios will be modeled using the AIM/Enduse model for India developed by the National Institute for Environmental Studies and Kyoto University in Japan. The AIM/Enduse model is a bottom-up energy, technology, and service optimization model that accounts for the FEC and CO_2 emissions in end-use sectors on the basis of actual energy use and the way energy services are performed by energy devices. The model focuses on the selection of end-use technology in energy production and consumption. It calculates the future demand for energy services for several sectors and determines the optimal set of technologies that can be used to satisfy the service demand through total cost optimization. On the basis of the energy consumed by the selected set of technologies, the model estimates the future energy consumption of the devices as well as the system. The model minimizes the NPV of all system costs, including capital, fuel, O&M, and all other cost components. The projections have been aligned with the projected peak demands until 2029–30.

This study is not a load flow study with various nodes. Instead, the study estimates demand and demand composition from the aspect of the integration of renewables and the perspective of nuclear energy. The model uses a modified merit order dispatch, where the dispatch is aggregated by fuel/source with economic dispatch rules and peak/base plant categorization, rather than operating a full merit order dispatch at the unit level. A pure economic dispatch by marginal cost would prioritize hydro, solar, wind, and other renewables, followed by nuclear, gas, and coal/lignite. However, if we earmark hydro as the peak load supply, it will face maximum ramping. In addition, ramping constraints guide that nuclear plants have very limited ramping flexibilities, and thus, it is best to use them for constant base load. Therefore, the supply mix is guided not only by economics but also by plant characteristics and ramping constraints.

If the model were developed solely on the basis of marginal costs, hydro backdown would not happen, leading to sharp coal backdown with high ramping rates and violating the 55% base level for coal plants, which becomes an unrealistic scenario. However, the results are included here for the sake of the comprehensiveness of this study.

The optimization model formulation is provided below:

For each time block of 15 mins:

Objective

Minimize $\sum_{i=1}^{n} C_{ij}$

where C_{ij} denotes the variable cost of technology *i*.

subject to

$S_{ij} \leq S_{ijmax}$ S_{ij} denotes the supply of technology *i* and the maximum supply possible from technology *i*.

$S_{ij} \geq S_{ijmin}$ S_{ijmin} denotes the minimum supply possible from that technology.

$\sum_{i=1}^{n} S_{ij} = D_j$ D_j is the demand in time block *j*.

$R_{ij} \leq R_{ijmax}$ R_{ijmax} denotes the maximum ramping possible from technology *i*.

Backdown priority (BP): k ∈ $\{BP_k | k = 1, n\}$.

6. Life-Cycle Assessment Model Description

The LCA framework, as indicated in ISO 14040, has been considered here. Here, the product system is defined using a cradle-to-gate approach, which includes sugarcane farming, sugarcane transport, and ethanol production. Although the inventory data for producing 1-ton ethanol is used, the functional unit for this study is considered as the production of 1 liter of ethanol for easy understanding of emission trends and comparison.

The activities involved in sugarcane farming include soil preparation, plantation, cultivation, and harvesting. Land quality and climatic conditions impact agriculture to a great extent and, hence, lead to variations in the yield and quality of sugarcane and the inputs required from one region to another. Therefore, we have considered the assessment of sugarcane production for three states in India. We collected secondary data from various sources, including the Ministry of Agriculture, Directorate of Sugarcane Development Board-Lucknow, ICAR-Indian Institute of Sugarcane Research, National Sugar Institute-Kanpur, Vasantdada Sugar Institute-Pune, India's Third Biennial Update Report to UNFCCC, and peer-reviewed journal papers.

Trucks with an average carrying capacity of 12 tons and a mileage of 2 km per liter transport sugarcane from the field to the mill at an average distance of 30 km. The assumptions regarding transportation distance and mileage are based on technical reports and literature. Ethanol production involves five steps: preparation, extraction of sugar juice, clarification, fermentation, and distillation and dehydration. Sugarcane fermentation leads to the production of ethanol and CO_2. However, since the CO_2 so produced is biological, we have not included it in the current assessment.

Moreover, we have conducted an assessment of the energy return on energy invested (EIER) for ethanol production from sugarcane in India. The EROI calculations are simple output-to-input ratios. For ethanol production, the inputs include diesel and electricity consumption for sugarcane farming—diesel to transport sugarcane from the farm to the ethanol plant and electricity consumption at the plant for ethanol processing. All inputs are computed for generating 1 ton of ethanol. The output is the energy obtained from 1 ton of ethanol. All the units are considered in megajoules (MJ).

7. Assessment of Critical Minerals

7.1 Methodology

The methodology has been developed using secondary data considering a range of estimates of all clean technologies and raw material production in India to determine future estimates on the basis of different scenarios for all relevant mineral requirements for 2030 and 2050. All data and future estimates of mineral requirements in the Indian context are based on various reports, including The World Bank (2017), European Commission et al. (2020a), Hund et al. (2020), and Indian Mineral Yearbook 2016–2019 (Indian Bureau of Mines, 2016, 2017, 2018, and 2019). The data for 2030 and 2050 are calculated on the basis of the 2019 demand for raw minerals. It is worth noting that this study excludes the current and future costs of energy technologies and the costs of minerals required for the energy transition. The study has considered the general minerals used in different technologies. For instance, different types of solar PV panels currently exist, but each has slightly different mineral requirements. Wind turbines also have other models, such as onshore and offshore wind turbines, which require different amounts of minerals. Similarly, there are sub-technologies for batteries and nuclear energy. The range of estimates considered in this study is based on the amount of minerals required to build 1 megawatt (MW) of the capacity of a particular technology, which is expressed by the weight of minerals in kilograms (kg) of installed megawatt (Kg/MW).

7.2 Mineral needs assessment

Table A12 provides a summary of the necessary raw and processed materials and components used in the manufacturing of wind, solar PV power, battery storage, and nuclear energy.

Table A12: Summary of the necessary raw and processed materials and components used in the manufacturing of wind, solar PV power, battery storage, and nuclear energy

Clean technologies	Component/material	Parts	Materials used	Source
Wind (large and small turbines*)	Rotor (% by weight)	Hub	Steel (95–100) Aluminum (5)	(Ancona & Mcveigh, 2001) (Brøndsted et al., 2005) (Mishnaevsky et al., 2017)loads, as well as available materials are reviewed. Apart from the traditional composites for wind turbine blades (glass fibers/ epoxy matrix composites
		Blades	Steel (5) Glass-reinforced plastic (95) Wood epoxy (95) Carbon-filament-reinforced plastic (95)	
	Nacelle (% by weight)		Permanent magnetic materials (17) Steel (65–80) Aluminum (3–4) Copper (14) Glass-reinforced plastic (1–2)	
		Gearbox	Steel (98–100) Aluminum (0–2) Copper (<1–2)	
		Generator	Permanent magnetic materials (50) Steel (20–65) Copper (30–35)	
		Frame, machinery, and shell	Steel (85) Aluminum (9–50) Copper (4–12) Glass-reinforced plastic (3–5)	
	Tower (% by weight)		Pre-stressed concrete (2) Steel (98) Aluminum (2)	

Clean technologies	Component/material	Parts	Materials used	Source
		Blades	Polymer matrix composites (PMCs) (e.g., glass-fiber-reinforced polyester; sandwich structures consisting of PMC face sheets and lightweight closed-cell polymer foam or end-grain balsa wood cores; isotropic materials (adhesive, steel, polymer foam, gelcoat); orthotropic material (glass fiber/epoxy composites, carbon fiber/epoxy composites), wood, bamboo)	(Sørensen et al., 2010)
		Box grinder	Glass fiber composites or carbon fiber composites	
		Infusion tool	Silicon	(Nolet, 2011)
	Rotor blades		Iron	(European Comission et al., 2020a)
	Tower		Aluminum, chromium, copper, iron, manganese, molybdenum, nickel	
	Nacelle		Aluminum, chromium, copper, iron, manganese, molybdenum, nickel	
		PMG generator	Copper, permanent magnets (neodymium, dysprosium)	
		Generator (non-PMG)	Copper	
		Generator	Boron, cobalt, copper, iron, rare-earth (dysprosium, neodymium, praseodymium, terbium)	
		Gearbox	Chromium, iron, copper, molybdenum, nickel	
	Foundation		Iron, concrete	
	Submarine cables		Copper, lead	

Clean technologies	Component/material	Parts	Materials used	Source
	Nacelle	(Bearings, coupling, gears, generator, and shafts) and the analytical and auxiliary equipment (anemometer, brakes, controller, converter, cooling system, sensors, and yaw drive system)	Aluminum, cast iron, copper, plastic, stainless steel, and steel alloys	(Wilburn, 2011)"title":"Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030.
		Gearbox	Cast iron and stainless steel, with minor amounts of aluminum and copper	(Wilburn, 2011)"title":"Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030.
		Electromagnets	Iron cores surrounded by wound copper wire, small turbines (aluminum or copper)	
		Permanent magnets	Iron oxide (ferrite) and barium or strontium carbonate; neodymium, iron, and boron	
	Rotor blades		Steel, cast iron	
	Tower		Steel, concrete	

Clean technologies	Component/material	Parts	Materials used	Source
Solar (PV MODULE, C-SI, CIGS, OR CDTE)	C–Si cell	Silver paste	Silver	(European Comission et al., 2020a)
	CIGS panel	CIGS powder	Copper, indium, gallium, selenide	
		Glass	Silica	
	CdTe panel	CdS powder	Cadmium telluride, aluminum, copper	
		CdTe powder		
	Frame		Aluminum	
	Balance of system		Copper	
	c-Si technologies and a-Si tech		Silicon, silver, gallium	
	CdTe technologies		Cadmium, tellurium	
	CIGS tech		Copper, indium, gallium, selenium	
		System support structures	Concrete, steel	
		Substrates, module encapsulation	Glass	
		Mule frames, racking, supports	Aluminum	
		Earthing, inverters, transformers, PV cell ribbons	Copper	

Clean technologies	Component/material	Parts	Materials used	Source
Battery	Li-ion batteries	Anode	Graphite, hard carbons, lithium titanium oxide	(Nitta et al., 2015)
		Anode	Graphite, lithium, sodium, magnesium, aluminum	(Borah et al., 2020)
		Cathodes	Sulfur, titanium	
	Li-ion cells		Cobalt, lithium, graphite, nickel, manganese, silicon, copper, iron, aluminum, phosphorus, titanium, fluorspar, tin	
	Whole battery		Cadmium, cobalt, copper, graphite carbon, lithium, manganese, nickel, lead, antimony, zinc	(European Commission et al., 2020b)
	Lithium-sulfur batteries	Cathode	Sulfur	(Remler et al., 2020)
		Anode	Lithium	
	Sodium-ion batteries	Cathode	Sodium	
	Aluminum ion batteries		Aluminum	
	Lead-acid batteries	Cathode	Lead oxide	
		Anode	Lead	
		Electrolyte	Sulfuric acid	

Clean technologies	Component/material	Parts	Materials used	Source
Nuclear	CANDU fuel channel	Fuel sheathing, pressure tubes, calandria tubes, control mechanism tubes	Zirconium alloys (Zircaloy-2 and Zircaloy-4), stainless steel	(Nuclear Reactor Materials, n.d.)
			Zircaloy-2: Tin: 1.2–1.7 wt% Iron: 0.07–0.2 wt% Chromium: 0.05–0.15 wt% Nickel: 0.03–0.08 wt% Carbon: 150–400 ppm Oxygen: 900–1,400 ppm Zirconium: Balance Zircaloy-4: Tin: 1.2–1.7 wt% Iron: 0.18–0.24 wt% Chromium: 0.07–0.13 wt% Nickel: – Carbon: 150–400 ppm Oxygen: 900–1,400 ppm Zirconium: Balance	
		Coolant	Sodium or lead, helium	(CEA, 2016)
		Fissile material (nuclear fuel)	Natural uranium, enriched uranium, plutonium	
		Moderator	Graphite	
	UNGG reactor (natural uranium graphite gas)	Fuel	Natural uranium (0.7% uranium-235)	
		Moderator	Solid carbon (graphite)	

Clean technologies	Component/material	Parts	Materials used	Source
Nuclear	CANDU reactor	Fuel	Natural uranium	(CEA, 2016)
	RBMK reactor (Bolchoe Molchnastie Kipiachie reactor)	Fuel	Enriched uranium with 1.8% uranium-235	
		Moderator	Carbon (graphite)	
	Boiling water reactor	Fuel	Enriched uranium with 1.8% uranium-235	
	Pressurized water reactor	Fuel	Enriched uranium with 1.8% uranium-235	
	Fast reactor	Fuel	Enriched uranium or plutonium	
	Advanced heavy water reactor	Fuel	Thorium, plutonium, uranium	(Todosow et al., 2012)
		Cladding tube material	Zircaloy-4 Tin: 1.2–1.7 wt% Iron: 0.18–0.24 wt% Chromium: 0.07–0.13 wt% Nickel: – Carbon: 150–400 ppm Oxygen: 900–1,400 ppm Zirconium: Balance	
	Most types of reactors	Fuel	Uranium	https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx
		Moderator	Heavy water or graphite	
		Control rods or blades	Cadmium, hafnium, boron	
	Indian PHWRs		Steel, cobalt, light water, boron, cadmium, gadolinium, etc.	(Powering the Nation – Research & Power Reactors, n.d.)
		Reflectors	Heavy water	https://matmatch.com/resources/blog/materials-in-nuclear-reactors/
		Control rods or blades	Boron, cadmium, hafnium	
		Moderator and coolant	Graphite, heavy water, sodium, and CO2	

** Values in brackets are for small turbine*

Wind energy is one of the fastest-growing clean technologies. The power industry will need massive deployment of wind technology to meet future energy demand through RE sources. Consequently, the need for raw materials used to manufacture wind turbines is expected to rise significantly in the future (European Commission et al., 2020a). A wind turbine comprises approximately 25,000 components that are structured into several vital components such as the tower, nacelle, and rotor. Several of these components, including the tower, nacelle, rotor, and foundation, are made of steel or stainless steel. In addition to iron, a wide range of minor and base metals such as nickel, molybdenum, manganese, and chromium are used to produce steel. Concrete, steel, plastic, glass, aluminum, and copper are widely used for the structural and electrical elements of solar PV installations across all technologies (European Commission et al., 2020a).

See Tables A13 and A14 for an overview of the raw minerals needed for wind turbines under different scenarios.

Improvements in materials can lead to potential efficiency gains in using neodymium in wind turbines by reducing the reliance on permanent magnets through alternative designs and increasing the use of hybrid turbines that use a medium-speed gearbox and permanent magnet generator. By implementing such changes, the demand for neodymium in wind technology would fall by 45%, compared to the present mineral composition of current wind technology.

Solar energy has been the most rapidly used form of RE. See Tables A13 and A14 for an overview of the raw minerals needed for solar PV technologies under different scenarios. The four widely used sub-technologies for solar PV include crystalline silicon (crystal Si), copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (amorphous Si). The three thin-film sub-technologies—CIGS, CdTe, and amorphous silicon—are assumed to grow from 20% to 50% of solar panels. There will be greater demand for aluminum and indium, which are predominantly used in CIGS solar cells.

Battery storage technology is a crucial technology that stores power generated from intermittent sources such as solar PV and wind farms. It is also used to power EVs. See Tables A13 and A14 for an overview of the raw minerals needed for battery storage under different scenarios. Batteries consist of three basic elements: anode, cathode, and electrolyte. The minerals used for these elements differ between and within battery sub-technologies. The estimates include storage from solar and wind energy generation in the future and do not consider battery requirements for EVs. The estimates also do not factor in the replacement needs for batteries every 10 years.

Lithium-ion batteries are currently the dominant technology because of their ability to store more energy per unit weight. However, the limited availability of lithium resources and rising costs have led to a growing need for alternative energy storage technologies to meet the increasing demand for energy. Owing to sodium's abundance, cost-effectiveness, and very suitable redox potential (similar to that of lithium), sodium-ion battery technology has great potential to be a counterpart to lithium-ion batteries for stationary energy storage and EVs (Tapia-Ruiz et al., 2021)"ISSN":"25157655","abstract":"Increasing concerns regarding the sustainability of lithium sources, due to their limited availability and consequent expected price increase, have raised awareness of the importance of developing alternative energy-storage candidates that can sustain the ever-growing energy demand. Furthermore, limitations on the availability of the transition metals used in the manufacturing of cathode materials, together with questionable mining practices, are driving development towards more sustainable elements. Given the uniformly high abundance and cost-effectiveness of sodium, as well as its very suitable redox potential (close to that of lithium by 2030. Although the current market share of NA-ion batteries is small compared to that of Li-ion batteries, efforts are underway to make them commercially feasible globally, and their share is expected to increase substantially in the future.

The next-generation batteries are vanadium-based redox flow, solid-state Li-ion, and zinc-air batteries. Zinc-air batteries could reduce the demand for minerals used in Li-ion batteries and shift demand toward nickel, manganese, zinc, lanthanum, or silver. Zinc-based batteries incorporate zinc with various compounds and are in a more advanced phase of development than some other battery technologies. Previously, zinc batteries could not be recharged, but researchers are overcoming obstacles to create fully rechargeable zinc-based batteries. This technology is well known for being lightweight, inexpensive, and non-toxic (Energy Storage System (ESS) Roadmap for India: 2019–2032, 2019).

Table A13: Minerals used in wind turbine, solar PV, and battery storage and future estimates of mineral requirements based on different scenarios for 2030

Sr No.	Material	Production (India)**	Future estimates of mineral requirement ('000 tons)				
			2030				
		Average quantity 2015–2019 (in '000 tons)	NZ1	NZ2	NZ3	NZ4	NDCM
1	Aluminum	3,087.09	93,381,349,796	93,381,349,796	93,381,349,796	93,381,349,796	111,758,443,248
2	Graphite (g/kWh)	85.34	2,579,998,866	2,579,998,866	2,579,998,866	2,579,998,866	3,088,373,027
3	Iron		3,135,882	3,135,882	3,135,882	3,135,882	2,459,515
4	Steel	8,816.95	7,630	7,630	7,630	7,693	5,813
6	Iron (cast)	188.85	1,536.50	1,536.50	1,536.50	1,549.20	1,170.67
7	Cobalt	0.04	682.18	682.18	682.18	682.18	535.04
8	Copper	466.72	546.70	691.60	691.60	691.60	692.80
9	Tin	15.31	65.90	47.14	70.59	65.97	25.49
10	Chromium	3,518.35	59.19	59.19	59.19	59.67	45.09
11	Lead	163.39	48.01	34.34	51.42	48.06	18.56
12	Nickel	0.19	42.70	2,913.58	2,913.58	2,913.58	2,913.58
13	Iron (in magnet)		17.75	17.75	17.75	17.89	13.52
14	Tellurium		13.36	9.56	14.31	13.37	5.17
15	Indium		12.40	8.87	13.29	12.42	4.80
16	Selenium		11.93	8.53	12.78	11.94	4.61
17	Cadmium	0.05	11.86	8.49	12.71	11.88	4.59
18	Molybdenum	19,371.70	8.82	8.82	8.82	8.89	6.72
19	Zinc	729.67	8.43	389.93	389.93	389.93	393.08
20	Neodymium		6.51	6.51	6.51	6.56	4.96
21	Manganese	2,487.58	3.96	42,838,800.85	42,838,800.85	42,838,800.85	42,838,800.85

Sr No.	Material	Production (India)**	Future estimates of mineral requirement ('000 tons)				
			2030				
		Average quantity 2015–2019 (in '000 tons)	NZ1	NZ2	NZ3	NZ4	NDCM
22	Silver	481.65	3.42	2.45	3.67	3.43	1.32
23	Silicon		2.59	1.85	2.77	2.59	1.00
24	Praseodymium		1.37	1.37	1.37	1.38	1.04
25	Dysprosium		0.97	0.97	0.97	0.98	0.74
26	Gallium		0.88	0.63	0.95	0.88	0.34
27	Terbium		0.27	0.27	0.27	0.28	0.21
28	Boron	74.20	0.00	0.27	0.27	0.27	0.28

Source: Compiled by the authors

Table A14: Minerals used in wind turbine, solar PV, and battery storage and future estimates of mineral requirements based on different scenarios for 2070

Sr No.	Material	Production (India)**	Future estimates of mineral requirement ('000 tons)				
			2070				
		Average quantity 2015–2019 (in '000 tons)	NZ1	NZ2	NZ3	NZ4	NDCM
1	Aluminum	3,087.09	452,656,633,423	452,277,093,253	493,443,989,766	493,534,471,505	389,118,059,115
2	Graphite (g/kWh)	85.34	12,507,637,239	12,497,150,091	13,635,219,530	13,637,719,790	10,753,980,665
3	Iron		12,465,091	12,454,311	12,453,927	12,456,211	6,639,624
4	Steel	8,816.95	10,900	22,755	16,350	18,868	8,720
6	Iron (cast)	188.85	2,195.00	4,582.22	3,292.50	3,799.47	1,756.00
7	Cobalt	0.04	2,711.64	2,709.29	2,709.21	2,709.71	1,444.38
8	Copper	466.72	657.10	753.70	978.83	857.20	905.01
9	Tin	15.31	105.77	101.62	137.43	187.87	126.64
10	Chromium	3,518.35	84.55	176.50	126.83	146.35	67.64
11	Lead	163.39	77.05	74.03	100.11	136.85	92.25
12	Nickel	0.19	2,294.37	11,454.41	11,444.54	11,444.19	11,446.28
13	Iron (in magnet)		25.35	52.92	38.03	43.88	20.28
14	Tellurium		21.44	20.60	27.86	38.08	25.67
15	Indium		19.91	19.13	25.87	35.36	23.84
16	Selenium		19.15	18.40	24.88	34.01	22.93
17	Cadmium	0.05	19.04	18.29	24.74	33.82	22.80
18	Molybdenum	1,9371.70	12.60	26.30	18.90	21.81	10.08
19	Zinc	729.67	299.09	553.43	1,146.15	825.93	951.80
20	Neodymium		9.30	19.41	13.95	16.10	7.44
21	Manganese	2,487.58	33,599,060.34	170,283,689.65	170,136,424.46	170,131,180.60	170,162,377.18
22	Silver	481.65	5.50	5.28	7.14	9.76	6.58

Sr No.	Material	Production (India)**	Future estimates of mineral requirement ('000 tons)				
			2070				
		Average quantity 2015–2019 (in '000 tons)	NZ1	NZ2	NZ3	NZ4	NDCM
23	Silicon		4.15	3.99	5.39	7.37	4.97
24	Praseodymium		1.95	4.07	2.93	3.38	1.56
25	Dysprosium		1.39	2.90	2.09	2.41	1.11
26	Gallium		1.42	1.36	1.84	2.52	1.70
27	Terbium		0.39	0.81	0.59	0.68	0.31
28	Boron	74.20	0.16	0.39	0.81	0.59	0.68

Source: Compiled by the authors

Nuclear power will also be one of the largest sources of low-carbon energy with low mineral intensity in the future. See Table A15 for an overview of the raw minerals needed for nuclear energy under various scenarios. For our study, we have included minerals used for nuclear reactor applications. The general minerals are considered because the amount of minerals differs with various types of nuclear technologies.

Table A15: Minerals used in nuclear energy and their future estimates of requirements based on different scenarios

Mineral used in nuclear energy				Future estimates of mineral requirements ('000 tons)							
Sr. No.	Material	Range of estimates (kg/MW)	Production (India)**	2030				2070			
			Average quantity 2015–2019 (in '000 tons)	NZ1	NZ2	NZ3	NZ4	NZ1	NZ2	NZ3	NZ4
1	Cadmium	0.5	0.04	0.03	0.03	0.03	0.01	0.17	0.05	0.05	0.10
2	Chromium	427	3,518.35	21.35	21.35	21.35	12.38	140.91	42.70	42.70	81.13
3	Cobalt	0	0.04								
4	Copper	59.6	264.70	2.98	2.98	2.98	1.73	19.67	5.96	5.96	11.32
5	Hafnium	0									
6	Indium	1.6		0.08	0.08	0.08	0.05	0.53	0.16	0.16	0.30
7	Lead	4.3		0.22	0.22	0.22	0.12	1.42	0.43	0.43	0.82
8	Molybdenum	20–71	19,371.70	2.28	2.28	2.28	1.32	15.02	4.55	4.55	8.65
9	Nickel	256	0.19	12.80	12.80	12.80	7.42	84.48	25.60	25.60	48.64
10	Niobium	2	0	0.10	0.10	0.10	0.06	0.66	0.20	0.20	0.38
11	Silver	8.3	531.08*	0.42	0.42	0.42	0.24	2.74	0.83	0.83	1.58
12	Steel	–	100.44								
13	Tin	4.6		0.23	0.23	0.23	0.13	1.52	0.46	0.46	0.87
14	Titanium	1.5		0.08	0.08	0.08	0.04	0.50	0.15	0.15	0.29
15	Tungsten	5	87,387.46	0.25	0.25	0.25	0.15	1.65	0.50	0.50	0.95
16	Vanadium	0.6	24,633.86	0.03	0.03	0.03	0.02	0.20	0.06	0.06	0.11
17	Yttrium	0.5		0.03	0.03	0.03	0.01	0.17	0.05	0.05	0.10
18	Zirconium	30.5	18.66	1.53	1.53	1.53	0.88	10.07	3.05	3.05	5.80

Source: Compiled by the authors

8. LCOE Model Description and equations

Equation 12 provides a simplified formula for calculating the LCOE.

$$LCOE = \frac{[(C_{INV} * CRF) + C_{O\&M}]}{8760 * PLF} + C_{VAR} \tag{12}$$

where,

$$Captial\ Recovery\ Factor\ (CRF) = \frac{r(1+r)^n}{(1+r)^n - 1}$$

C_{INV}	Investment Cost of power plant (Million Rs/GW)
$C_{O\&M}$	Annual Fixed Operations and Maintenance cost (Million Rs/GW/yr)
C_{VAR}	Variable cost of generation, including fuel cost (Million Rs/GWh)
r	Discount rate or weighted average cost of capital (WACC) (%)
n	Amortization period (years)
PLF	Plant load factor

For the calculations, we have assumed that the solar and wind capacity does not include battery energy storage systems (BESSs) for 2020 but includes BESSs for all years beyond 2020. This is true for all scenarios. Costs are based on the first edition of technology data for Indian power plants published by CEA (2022), National Electricity Plan 2022-23 (CEA, 2023) and expert consultations. These are already described in Section 2 of the annexure. The discount rate (r), based on assumptions for the weighted average cost of capital (WACC) for the power sector, is assumed to be 9.55% until 2020 and then gradually reduce to 5% by 2070 as the economy develops. The PLFs are based on model outputs.

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