WRI INDIA

WORKING PAPER

Long-term emissions scenarios for India's power sector: An analysis using the India Energy Policy Simulator

Varun Agarwal, Subrata Chakrabarty, Devadathan Biju, and Deepthi Swamy

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues.

Suggested Citation: Agarwal, V., S. Chakrabarty, D. Biju, and D. Swamy. 2024. "Long-term emissions scenarios for India's power sector: An analysis using the India Energy Policy Simulator." Working Paper. WRI India. Available online at: https://doi.org/10.46830/wriwp.23.00030

HIGHLIGHTS

- We estimate India's annual electricity demand to quadruple by 2050 despite energy efficiency across the economy more than doubling over this period. A transition to low-carbon electricity supply is critical given India's net-zero 2070 target.
- We present three scenarios for electricity supply through 2050—Ambitious Policy, No New Policy, and Renewable Energy Bottleneck—and their implications for technology choices, costs, emissions, and water use.
- All three scenarios exhibit a growing share of fossil-free electricity generation that increases to at least 41 percent by 2030 and 61 percent by 2050 from 24 percent at present (in 2022). Only the Ambitious Policy scenario, however, cuts greenhouse gases to a quarter of present levels by 2050, which is likely needed to put the sector on a net-zero 2070 pathway. Further, water savings and air quality improve considerably over the other scenarios.
- Expenditure on the electricity system across the scenarios is comparable, indicating that the benefits in the Ambitious Policy scenario entail no additional monetary cost. However, the massive scale-up in solar and onshore wind capacity seen in this scenario would require overcoming the challenges of grid integration, financing, potential land constraints, and the socioeconomic impacts of a coal phase-down.

EXECUTIVE SUMMARY

Context

As part of its Nationally Determined Contribution (NDC) under the Paris Agreement, India has committed to achieving 50 percent of its total installed electricity capacity from non-fossil sources by 2030 (PIB 2021b). The prime minister also announced India's intention of achieving 500 gigawatts (GW) of non-fossil installed electricity capacity by 2030 (PIB 2022). This would require almost tripling the present non-fossil-based capacity of 178 GW (CEA 2023d) over the next seven years. Non-fossil-based capacity less than doubled during 2016–2022 from about 95 GW in 2016 (CEA 2016b).

Despite these ambitious targets, coal is expected to continue to play a dominant role in electricity supply in the near future, contributing over half of the total projected electricity generation in 2030 (CEA 2023c). Although India has released its long-term low-carbon development strategy (LT-LEDS) outlining a vision for achieving net-zero emissions by 2070 (MoEFCC 2022), it has not set any targets for the power sector after 2030. Transition pathways for the sector consistent with India's 2070 vision will likely require a phase-down in fossil fuel capacity or a significant uptake of carbon capture and storage (CCS) by 2050 (Durga et al. 2022).

Exploring various transition scenarios for the power sector that can inform long-term target setting and policy planning in line with the 2070 vision is essential. The power sector is particularly important, given India's growing electricity demand and the expected role of electrification and green hydrogen—both reliant on a low-carbon electricity supply—in decarbonizing the industry, buildings, and transport sectors.

About this working paper

We use the India Energy Policy Simulator (EPS) version 3.1.3.5, an open-source, system dynamics model with economy-wide coverage to explore three scenarios for the power sector. We first use the model to estimate electricity demand through 2050, considering the electrification and green hydrogen uptake required in the buildings, industry, and transport sectors to put the economy on course toward its net-zero 2070 target. We then present three alternative scenarios for power supply to meet the calculated electricity demand, together with a comparative analysis of outcomes of interest—greenhouse gas (GHG) emissions, technology mix, investment, air pollution, and water use—across the three scenarios:

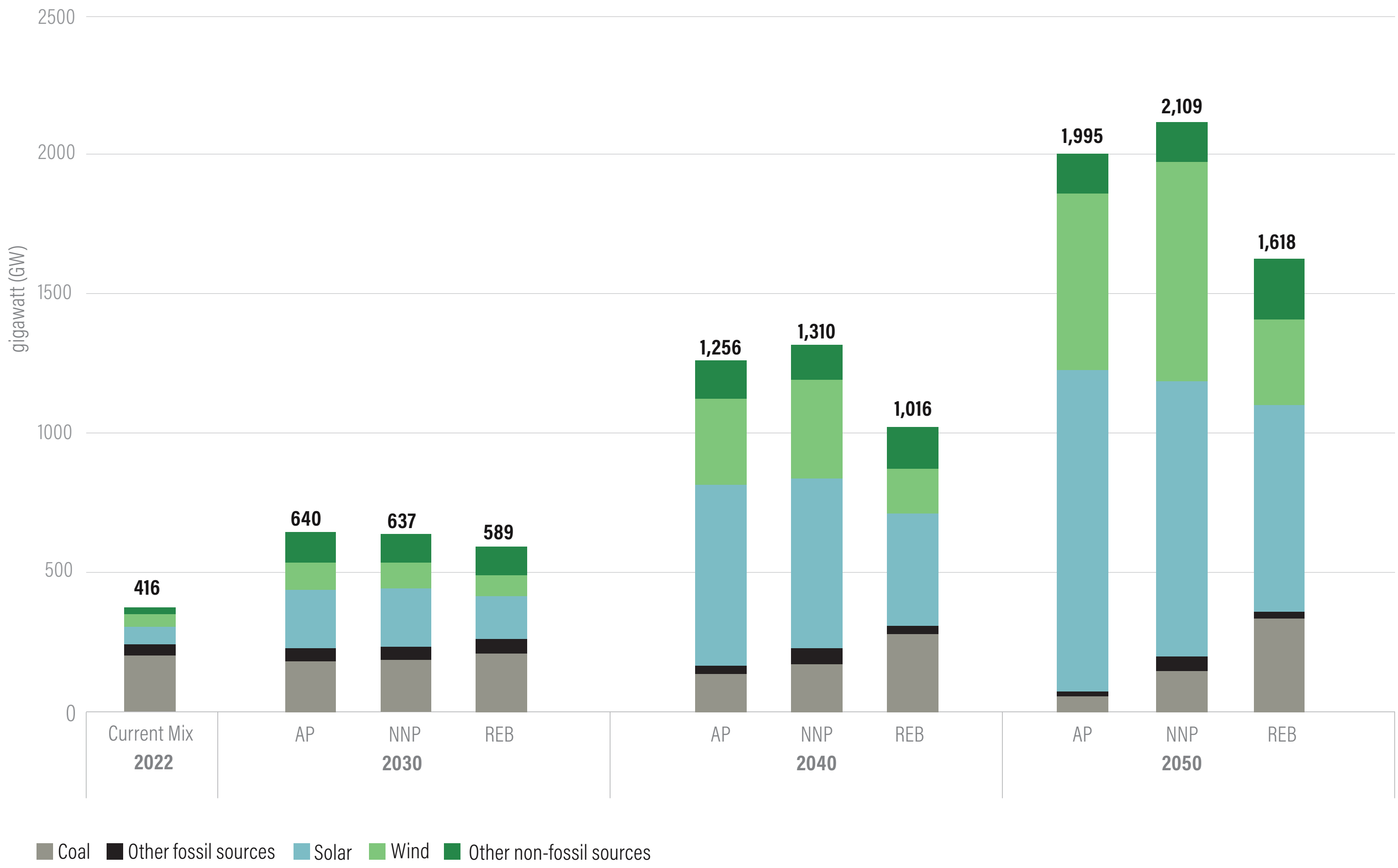
- An Ambitious Policy (AP) scenario, which assumes policies for deep decarbonization of the power sector that build upon existing policies.
- A No New Policy (NNP) scenario, which assumes that no new policies—beyond existing ones, running until their stipulated durations—are implemented and power generation capacity is added on a least-cost basis.
- A Renewable Energy Bottleneck (REB) scenario, which assumes no new policies and reflects additional constraints on the growth of annual renewable energy (RE) capacity additions due to on-ground implementation challenges.

Details of the structure, approach, data sources, and assumptions of the India EPS can be found in the model's technical note (Swamy et al. 2021a). It is a national model with annual time steps and consequently does not represent the seasonal and diurnal variability in electricity demand and supply. It instead models the average variability of resources such as wind and solar to meet the annual peak demand by using peak time capacity factors. Further, an analysis of the potential regional and socioeconomic impacts of the low-carbon transition in the power sector, although relevant, is beyond the scope of this working paper.

Key findings

- **We estimate India's annual electricity demand to quadruple from the present level to reach 5,188 terawatt-hours (TWh) by 2050 in a pathway aligned with India's net-zero 2070 target, despite a decline of 58 percent in energy consumption per unit of gross domestic product (GDP) over this period.** The increase is driven by the growing per capita energy demand and the switch from fossil fuels to electricity in end-use sectors, such as transport, industries, and buildings, to meet their future energy demand.
- **Across all our supply scenarios, non-fossil capacity additions—predominantly solar photovoltaic (PV) and onshore wind—outpace coal.** Only the REB scenario sees a net addition of coal capacity over this period. All the three scenarios see the share of coal in installed electricity capacity decline to below 25 percent by 2050 from 49 percent at present. Solar PV capacity emerges as the dominant technology in India's future electricity supply, followed by onshore wind across all the three scenarios (Figures ES-1 and ES-2). However, the shares of solar and wind differ across scenarios, depending on the availability of storage. India's NDC target of achieving 50 percent of its total installed electricity capacity from non-fossil sources by 2030 is achieved in all the three scenarios.

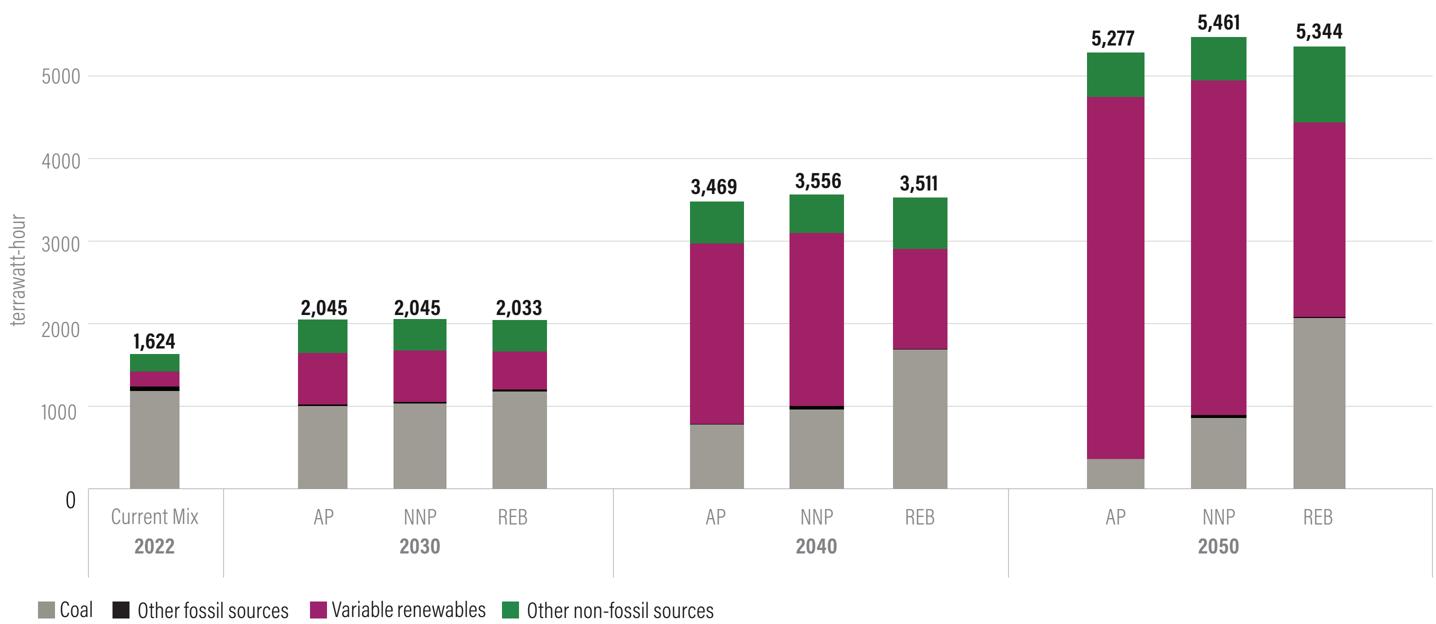
Figure ES-1 | **Total installed electricity capacity by power plant type in 2022 and in 2030, 2040, and 2050**



Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck.

Source: MoP (2023b) for 2022 and the authors' analysis using India Energy Policy Simulator for future years.

Figure ES-2 | **Annual generation by fuel source in 2022 and in 2030, 2040, and 2050**

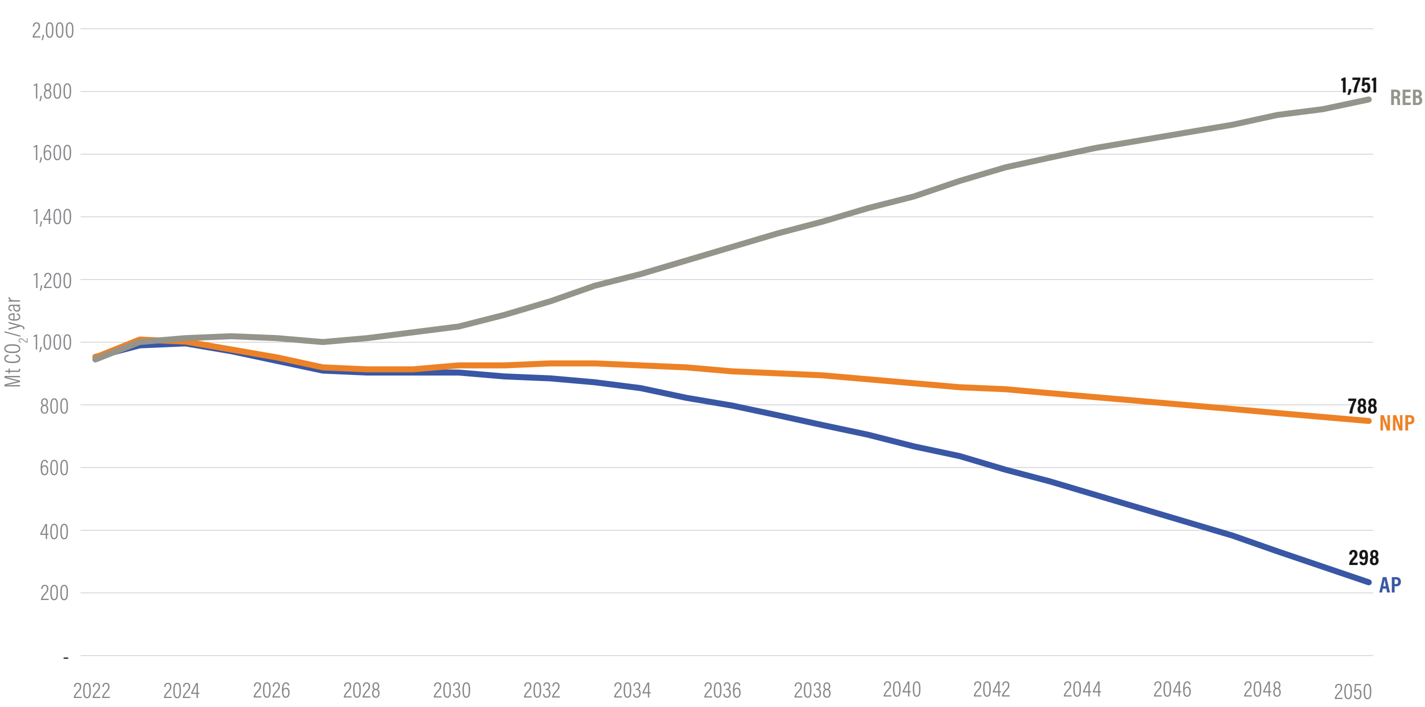


Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck.

Source: Central Electricity Authority (CEA 2023c) for 2022 and the authors' analysis using India Energy Policy Simulator for future years.

- **Despite the significant growth of RE across all scenarios, only the AP scenario sees a notable decline in GHG emissions in the power sector from the present level** (Figure ES-3), implying that India's rapidly expanding power sector would require additional policies for long-term deep decarbonization consistent with its 2070 net-zero vision. On the other hand, emissions in the NNP scenario remain approximately stagnant and rise 1.6 times the present level in the REB scenario. To cut emissions, the AP scenario relies on the phased implementation of two key policy mandates—generate carbon-free electricity (linearly increasing over time from 24% in 2022 [CEA 2023a] to 75% in 2050) and gradually retire coal-fired power plants (linearly increasing over time from 0 GW/year in 2027 to 7 GW/year in 2050)—and a carbon tax on power-sector emissions at the point of generation (linearly increasing from US$4 in 2022 to US$50 by 2050).
- **The technology transition to non-fossil sources yields significant co-benefits: reduced water consumption and improved air quality.** The AP scenario, on average, saves 266 billion liters and 2 trillion liters per year over the NNP and REB scenarios, respectively, between the present and 2050. The latter saving is more than New Delhi's annual water demand in 2020 (1.7 trillion liters [Rumi 2020]). Similarly, by 2050, annual $PM_{2.5}$ emissions in the AP scenario are negligible. In contrast, the NNP and REB scenarios see $PM_{2.5}$ emissions of 312 and 716 kilotonnes in 2050, respectively. The latter is more than the amount of particulate matter emissions from all of India's coal plants in 2010 (about 580 kilotonnes [Guttikunda and Jawahar 2014]).
- **The total projected expenditure on electricity supply—including capital, operations and maintenance (O&M), and fuel costs—across the three scenarios is comparable.** The total expenditure is in the range of INR 139–145 trillion (US$2,032–2,119 billion) in 2018 prices across the three scenarios, with the REB scenario being marginally more expensive than the other two scenarios, primarily due to greater fuel expenditure and O&M costs. However, the AP scenario is the most capital intensive, in spite of accounting for declining unit costs of RE with technology diffusion over time, emphasizing the need for up-front capital investment in the RE transition.

Figure ES-3 | **Annual CO_2 emissions in the power sector through 2050**



Note: CO_2 = carbon dioxide. AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. Mt = megatonne.

Source: Authors' analysis using India Energy Policy Simulator.

Policy implications

- **India's rapidly expanding power sector would require additional policies for long-term deep decarbonization.** Whereas India's 2030 NDC targets are met in all the scenarios, only the AP scenario sees a decline in GHG emissions consistent with its 2070 net-zero vision, underscoring the need for additional policies. The analysis suggests that the phased implementation of two policy mandates—carbon-free electricity generation and gradual retirement of coal-fired power plants—and a carbon tax in the power sector could reduce emissions to a quarter of present levels by 2050. All these policies can be implemented by gradually building upon existing policies.
- **Supporting policies to integrate the rapidly growing share of variable RE into the electricity grid will be crucial.** The massive projected scale-up in solar PV and wind in India's future electricity mix emphasizes the need for scaling up grid battery storage capacity, demand response programs, and improvements in transmission infrastructure, which are all in a nascent stage at present. Besides, we show that a more balanced growth of solar PV and wind could also help reduce supply-side intermittency, suggesting a potential rethink of long-term policy targets, which presently prioritize solar PV.
- **Policies to spur investments in RE are critical.** The average annual investment required in solar PV and onshore wind in the AP and NNP scenarios is about thrice the level of present investment. Thus, policies to spur investment are critical for achieving the required transition scale. Policies to reduce financing costs will be critical: the weighted average cost of capital for green investment in India is estimated at 8.2 percent, almost double that of the United Kingdom and the European Union (Ameli et al. 2021).
- **Measures are required to ensure a more just and equitable transition away from fossil power generation.** Planning for economic diversification and livelihood generation within coal-rich areas will be crucial. Moreover, the massive projected scale-up of RE, estimated to be over 10 times more land-intensive than coal per unit of electricity produced (Gross 2020), warrants a careful evaluation of potential land-use impacts and suggests the need for proactive policy measures such as incentives for rooftop solar or offshore wind (Poojary et al. forthcoming).

INTRODUCTION

Background

India's electricity demand increased at a compound annual growth rate (CAGR) of 6.4 percent from 2000 to 2019 (IEA 2021b). Electricity consumption has grown faster than the overall energy demand over the past two decades, mostly due to rapid urbanization and industrialization (IEA 2021a). Among end-use sectors, over three-fourths of this electricity was consumed in the buildings and industry sectors (CEA 2020).

The trend of increasing electricity consumption is likely to continue because India's present (2022) per-capita electricity consumption is still about a third of the global average (CEA 2020). New policy initiatives such as vehicle electrification and green hydrogen production (through electrolysis) are expected to play a crucial role in achieving India's 2070 net-zero vision (MoEFCC 2022) and will significantly increase India's long-term electricity demand.

India's annual electricity generation was estimated at 1,624 terawatt-hours (TWh) in fiscal year (FY) 2022–23 (MoP 2023a). Coal is the dominant source of electricity generation, contributing about 73 percent of the total generation (CEA 2023a). According to a Central Electricity Authority (CEA) report, the projected electricity generation by 2029–30 will increase by 50 percent to nearly 2,440 TWh, of which over half will still be from coal (CEA 2023c).

Planning a transition from a primarily coal-based- to a low-carbon electricity-supply system is essential, given India's growing electricity demand and its long-term climate target. Among the sectoral transitions, the power-sector transition is especially important because it will also impact the decarbonization trajectory of various end-use sectors, such as transport, industries, and buildings, as they switch from fossil fuels to electricity to meet their future energy demand.

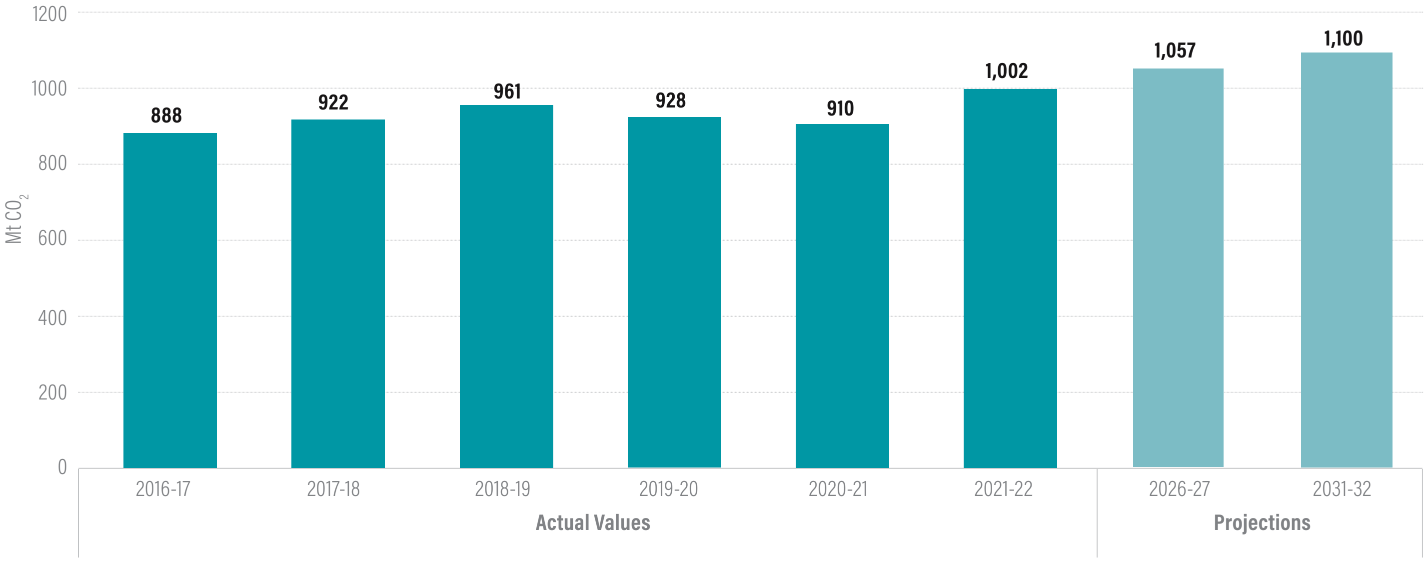
Profile of India's power sector

Emissions

About half of the total carbon dioxide (CO_2) emissions in India at present are estimated to originate in the power sector (CEA 2023b), with emissions from the sector in FY2021–22 estimated at about a billion tonnes of CO_2 (Figure 1).

Almost all the power-sector emissions can be attributed to coal-based power plants due to their dominant share of about 73 percent in the electricity generation mix, whereas gas accounts for a negligible share, about 1.5 percent (Figure 2). Non-fossil sources[1] (solar, wind, hydro, biomass, and nuclear), which together account for about 25 percent, do not contribute to direct power-sector CO_2 emissions.

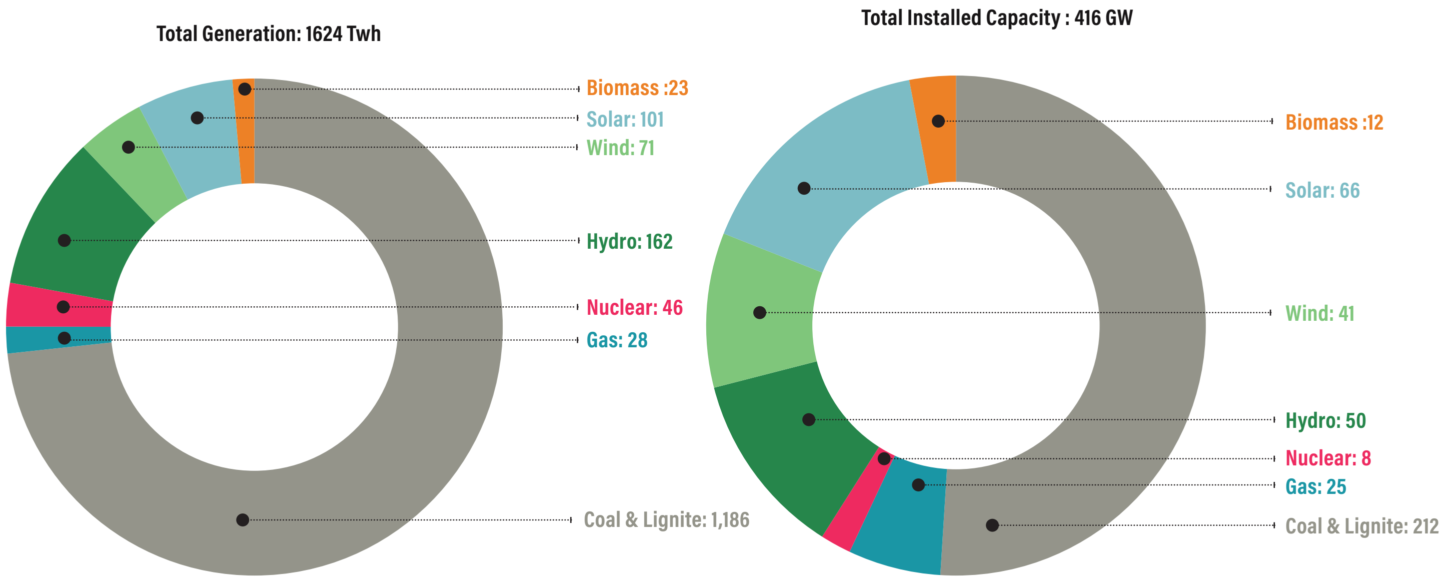
Figure 1 | **Absolute CO_2 emissions from the power sector (actual and projected)**



Note: CO_2 = carbon dioxide. Mt = megatonne.

Source: CEA 2023b.

Figure 2 | **Installed electricity capacity by March 2023 and annual gross generation for FY2022-23**



Note: FY = fiscal year. GW = gigawatt. TWh = terawatt-hour.

Source: CEA 2023c.

At 0.70 kgCO_2/kWh, the weighted average emission factor of India's grid remains among the highest in the world (IEA 2021b), and efficiency improvements alone will not achieve deep decarbonization of the power sector.

Moreover, coal-based generation is responsible for 60 percent of particulate matter ($PM_{2.5}$), 30 percent of nitrogen oxides (NOx), and 45 percent of sulfur oxides (SOx) (Bhati and Ramanathan 2017). Northern India is plagued by poor air quality, and thermal power plants are an important contributing factor (CAG 2022).

Coal use

The power sector has consistently been the main consumer of domestically produced coal. During FY2022–2023, the Ministry of Coal reported that 524 megatonnes (Mt) of coal—83 percent of the total supply of non-coking coal—was supplied to the power sector (MoC 2023).

Coal is the most abundant fossil fuel in India, whose total measured reserves were over 350 billion tonnes in 2022 (MoC 2022b). Coal production has steadily grown by 60 percent over the last 11 years, from 556 Mt in 2013 to 778 Mt in 2022 (MoC 2022a). The coal industry employs about 3.6 million people from 159 districts (Pai 2021).

Water use

Freshwater consumption by thermal power plants rose from 1.5 to 2.1 trillion liters between 2011 and 2016, paralleling the corresponding growth in generation from 708 TWh to 994 TWh over the same period, and is expected to continue to rise (Luo et al. 2018). The gravity of the power sector's water intensity is evident given that 39 percent of freshwater-cooled thermal capacity, which generates 34 percent of total electricity, is installed in high-water-stress regions (Luo et al. 2018). When other critical competing water uses are considered, such as in the agriculture sector, the opportunity cost of using water in the power sector is very high.

Announced targets for the power sector

In August 2022, India submitted its updated first Nationally Determined Contribution (NDC) under the Paris Agreement for the period 2021–30 (UNFCCC 2022). The updated document sets three targets for 2030, one of which pertains to the power sector, namely, to achieve 50 percent cumulative installed electricity capacity from non-fossil sources; the earlier target of 40 percent was reached in 2021 (PIB 2021b). Earlier, at the 26th Conference of Parties (COP 26) in November 2021, the prime minister had announced India's intention of installing 500 GW of non-fossil electricity capacity by 2030 (PIB 2022), although this was not included in India's updated NDC.

India also unveiled its Long-Term Low-Carbon Emissions Development Strategy (LT-LEDS) in November 2022 (MoEFCC 2022). Although the document sets no quantifiable long-term power-sector targets, it identifies expanding RE capacity, adding flexibility and stability to the electricity grid by scaling up storage capacity and exploring the role of green hydrogen, fuel cells, and biofuels as elements of its strategy for long-term low-carbon development of India's electricity system.

Despite India's ambitious NDC commitments, coal is expected to continue to play an important role in electricity supply in the short to medium term, contributing to over half of the total projected electricity generation in 2030 (CEA 2023c). This, together with the contribution of domestic coal production to economic output and employment, has motivated India's position in favor of a considered phase-down of coal-based power generation (as opposed to a phase-out) in international climate negotiations (Volcovici 2021).

MOTIVATION FOR THE STUDY

A review of the Indian government's power-sector plans reveals short- to medium-term planning. The National Electricity Plan 2023 outlines a detailed electricity-supply plan for the period 2022–27 and a prospective plan for the period 2027–32 (CEA 2023b). Similarly, another report explores a least-cost technology mix in the power sector to meet the projected demand by FY2029–30 (CEA 2023c).

These reports, though comprehensive, do not include long-term plans beyond 2030. By several accounts, India is set to meet its NDC commitments by 2030 (PIB 2021a). Beyond 2030, however, there is scope for exploring various power-sector policy scenarios that can inform long-term target setting and policy planning for a successful power-sector transition in line with the 2070 vision. Transition pathways for the sector consistent with India's 2070 vision are likely to require a significant phase-down in fossil fuel capacity or a significant uptake of carbon capture and storage (CCS) by 2050 (Durga et al. 2022).

Toward this end, we present three scenarios of electricity supply through 2050, based on different assumptions related to power-sector policies and technology uptake. This is followed by a comparative analysis of outcomes of interest—technology choices, financial costs, CO_2 emissions, air pollution, and water use—across the three scenarios and their policy implications.

Literature review

Scenario modeling is a reliable method of informing long-term power-sector planning that extends beyond the time frame of existing government reports. The literature on long-term policy scenarios for India's power sector is limited. Appendix A lists relevant publications since 2021 and summarizes their respective modeling approaches.

Durga et al. (2022) present a systematic literature review of national modeling studies on India's 2030 and 2050 decarbonization pathways that considers 16 national and 9 sectoral power-sector pathways that differ in their approach, assumptions, and time frame. Due to these differences, data are insufficient to establish a robust, comparative analysis of power-sector transitions, particularly for the long term. Notably, the authors observe a large variance in the electricity demand projected by these models, which is attributed to the lack of integration of the demand and supply sectors of the economy in a single framework. Durga et al. suggest that there is ample scope for assessing alternative long-term pathways, particularly those that explore a higher share of variable renewable energy (VRE). Existing studies have limitations in capturing systemic changes due to a high share of VRE in generation, such as the scale and type of energy storage technologies and demand response implementation. These are some aspects of the power-sector transition that will be explored in this study.

Methods

We explore three scenarios for the power sector using the India Energy Policy Simulator (EPS) version 3.1.3.5, an open-source system dynamics model with economy-wide coverage.[2] The model divides the economy into power, industry, buildings, transport, and land-use sectors and enables users to simulate the implications of climate policies enacted within these sectors for emissions and economic performance through 2050 within an integrated framework that captures cross-sectoral interactions. The model can simulate policy options such as pricing policies (e.g., taxes on fossil fuels and subsidies for clean energy) and mandates (e.g., for the adoption or retirement of specific technologies).

In the power sector, the EPS uses a least-cost logic to determine which technologies to use for constructing power supply to meet a given demand, subject to the fulfillment of any specified policy mandates. To project energy-demand growth, economic growth at a CAGR of 6 percent through 2050 is assumed (see Appendix B). The model simulates price effects by combining exogenous projections of technology (and fuel) costs, with the effects of any specified pricing policies (taxes or subsidies) in a scenario. The model also uses an endogenous learning curve to account for the "learning-by-doing" effects of local technology diffusion on technology costs in the case of emerging technologies, namely, solar photovoltaic (PV), wind, battery storage, and hydrogen. All monetary estimates are in constant 2018 prices. Full details of the model's structure, approach, data sources, and assumptions can be found in the model's technical note (Swamy et al. 2021a).

The systems dynamics framework of the model allows for a more realistic representation of the dynamic interaction between the chosen policies and the economy than is possible with existing modeling approaches (most of which use a computational general equilibrium or partial equilibrium approach), potentially giving rise to overall effects that are different from the sum of the effects of the enacted individual policies. For example, mandates or subsidies to promote the uptake of a technology can create a reinforcing loop, whereby increased uptake of the technology due to these policies further reduces technology prices due to learning effects. The reduction in technology prices, in turn, reinforces technology uptake, allowing the model to represent S-curve growth dynamics, a well-recognized and widely accepted phenomenon in technology transitions (Schilling and Esmundo 2009) that is not represented in conventional models.

We first use the EPS to estimate long-term electricity demand, considering the transition from fossil fuels to electricity and green hydrogen required in the main energy end-use sectors of the economy—buildings, industry, and transport—to put the economy on course toward its 2070 net-zero target, based on Swamy et al. (2021b) with minor updates to policy settings to align it with subsequent policy announcements.

We then construct three alternative power-supply scenarios to meet the calculated electricity demand. The scenario narratives and underlying assumptions are discussed in the next section (titled "Long-Term Electricity-Demand Projection"). The assumptions and policy choices modeled in the scenarios are based on a literature review (see Appendix C) and validated through expert consultations (see Appendix D). The scenarios represent three alternative power-supply futures and their implications for technology choices, costs, CO_2 emissions, air quality, and water use. The scenarios use what-if analysis, simulating the plausible outcomes of a set of policy actions (or inaction) as opposed to representing an optimal solution for reaching a specified future target. By presenting a comparative assessment of our scenario outcomes, we aim to inform medium- to long-term policy development in the sector.

Limitations

The economy-wide coverage of the EPS enables the model to capture interactions between power-sector policies and the rest of the economy within an integrated framework. However, its representation of the power sector is less detailed than that of power-sector-specific models:

- The India EPS version 3.1.3.5 matches national electricity demand and supply at annual timescales.[3] Unlike power-sector models, it does not endogenously model regional and seasonal variability in electricity demand and supply; rather, the EPS estimates peak hour demand and aggregate supply capacity based on exogenous inputs. Because the EPS simulates in annual time steps, it uses the concept of a "flexibility point" to reconcile the intermittency of variable generation technologies. A flexibility point is a notional unit that can support one unit of solar and/or wind generation. Each year, the demand for the minimum number of required flexibility points to optimally utilize the installed capacity of solar and wind power plants is calculated. Flexibility points can be supplied through different means – by building natural gas peaker plants and battery energy storage, enhancing demand response capacity, and improving transmission infrastructure. If more solar PV or wind is built than can be supported via available flexibility points, the model begins curtailing power from these sources, and the expected capacity factors of new plants of those types are reduced accordingly, which in turn affects relative technology costs and consequently the selection of power-supply technologies, based on the model's least-cost logic.
- The India EPS does not represent different sub-technologies within each given technology type. For example, coal plants are a single category, and no distinction is made between subcritical, supercritical, and combined cycle types. Pumped hydro is not considered a form of energy storage.
- A quantitative analysis of the potential socioeconomic impacts of India's energy transition (e.g., on employment, income distribution, and energy security), although relevant, is beyond the scope of this working paper. Evaluating such impacts is a critical element of long-term policy planning for a just transition and is an important area for future work.

LONG-TERM ELECTRICITY-DEMAND PROJECTION

The India EPS projects the total electricity demand in a Reference scenario—which considers existing policies as of 2020 (Swamy et al. 2021a)—to reach 2,104 TWh by 2030 and 3,561 TWh by 2050, from about 1,300 TWh in 2021 (CEA 2022b).[4]

The growth in electricity demand, approximately 1.6 times by 2030 and 2.8 times by 2050 since 2021, is primarily driven by increasing urbanization and industrialization. Moreover, new policies to replace fossil fuels in the industry and transport sectors with electricity and green hydrogen are expected to play a crucial role in achieving India's 2070 net-zero vision (MoEFCC 2022), adding considerably to India's long-term electricity demand over and above the Reference scenario projections.

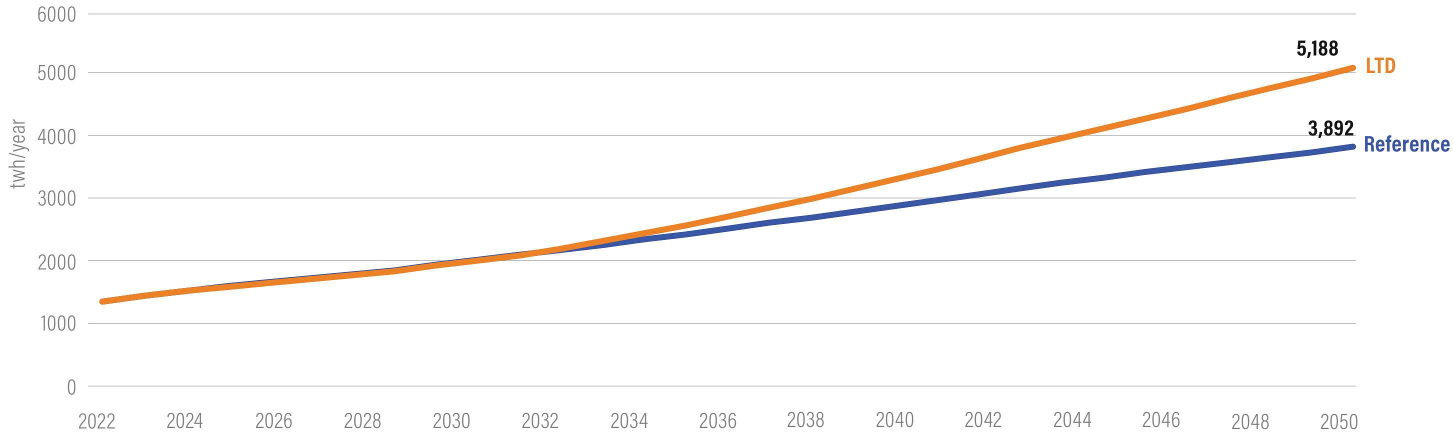
A scenario using the India EPS that considers such a case is the Long-Term Decarbonization (LTD) scenario (Swamy et al. 2021b), which assumes additional policies for the uptake of electricity and green hydrogen in industry and transport from 2030 to put the Indian economy on a pathway aligned with its 2070 target. Table 1 presents a comparison of key assumptions between the LTD and Reference scenarios.

Table 1 | **Comparison of key determinants of long-term electricity demand in the EPS Reference and LTD scenarios**

POLICY	REFERENCE SCENARIO (2050)	LTD SCENARIO (2050)
Industrial electrification and hydrogen mandate (% fossil fuel use substituted in industrial sector)	0	50
EV/H_2V[a] sales mandate (% of new vehicle sales)		
Cars	35	80
Buses	23	50 (+25 H2V)
Light-freight vehicles	14	70
Heavy-freight vehicles	4	25(+45 H2V)
Two-wheelers	38	100
Three-wheelers	30	100
Hydrogen production via electrolysis mandate[b] (% of hydrogen produced that is green)	0	100

Note: All values in the table are percentages. a. EV = electric vehicle. H_2V = hydrogen vehicle. b. With the electricity mix determined by policy settings and other factors.
Source: The authors, based on Swamy et al. (2021b).

Figure 3 | **Projected electricity demand in EPS Reference and LTD scenarios until 2050**



Note: Energy Policy Simulator. LTD = Long-Term Decarbonization. TWh = terawatt-hour.
Source: Authors' analysis using India Energy Policy Simulator, based on Swamy et al. (2021b).

The LTD scenario sees the total electricity demand increase to 5,188 TWh in 2050, approximately 46 percent more than the electricity demand in the Reference scenario in the same year. Over the period 2021–50, electricity demand increased at a CAGR of 4.6 percent in the LTD scenario compared to 3.6 percent in the Reference scenario (see Figure 3). In terms of the sectoral share of electricity demand in the LTD scenario, in 2050, industry accounts for the largest share (42 percent), followed by buildings (25 percent), green hydrogen production (22 percent), and transport (11 percent).

ELECTRICITY-SUPPLY SCENARIOS

Scenario narratives

We use the EPS LTD scenario as the source of electricity demand, given that it accounts for increasing electrification and green hydrogen production across the economy required in line with India's net-zero target. We construct three alternative power supply scenarios through 2050, each with a unique narrative and set of assumptions about the power sector to meet the previously calculated demand. The supply scenarios are described as follows.

Ambitious Policy scenario

The Ambitious Policy (AP) scenario actively pursues power-sector policies with a high potential for emissions reduction after 2030. Policies modeled in this scenario are chosen using two criteria:

- Their alignment[5] with existing power-sector policies and new policy options being considered in India, such as carbon pricing (PIB 2020).
- Their relative effectiveness (relative to other policy options available in the model for the power sector) in contributing to medium-to-long-term GHG emissions abatement.

Key policies assumed in the scenario include mandates specifying a minimum proportion of carbon-free electricity generation and the phased retirement of coal power plants. The former builds upon the existing Renewable Purchase Obligation (RPO)—a de facto generation target—that mandates the share of carbon-free electricity purchased by electricity distribution companies (DISCOMs) and industrial consumers (MNRE 2023). The latter builds upon the announcement by four states—Gujarat, Chhattisgarh, Karnataka, and Maharashtra—that they would add no new coal power (Climate Trends 2021). It assumes a gradual retirement schedule for existing coal capacity which linearly increases over time from 0 MW/year in 2027 to 900 MW/year in 2030 and 7000 MW/year in 2050.

Among pricing policies, we assume a carbon tax on emissions from the power sector that builds on the cess of INR 400 per tonne presently levied on coal production—approximately \$4 per tonne of CO_2 in carbon tax equivalent terms (IISD 2018)—in a phased manner over time. Table 2 summarizes key policies, together with their implementation assumptions. We do not assume any RE subsidies because they have been declining as RE achieves cost parity with fossil fuels, falling by nearly 45 percent between 2017 and 2020 (Viswanathan et al. 2021).

In addition, this scenario assumes policy mechanisms to support the integration of intermittent VRE into the electricity grid, including the addition of grid battery storage and

Table 2 | **Key policies and their implementation assumptions in the Ambitious Policy scenario**

POLICY	DESCRIPTION	ASSUMED SETTING[a]	
		2030	2050
Carbon-free electricity generation mandate (%)[b]	Specifies the minimum proportion of electricity to be generated from non-fossil sources by the target years.	49	75
Retirement of coal-fired power plants (MW)	Annual capacity retirement of coal-based power plants reaches these levels in the target years	900	7,000
Carbon tax	The tax per tonne of CO_2 emissions from electricity generation grows annually to reach these levels in these target years (in 2018 prices).	INR 1,100 ($17)	INR 3,500 ($50)

Note: a. Unless otherwise mentioned, the policy rate of policy implementation is linearly increased between 2030 and 2050 to reach the full policy setting in 2050.

b. Carbon-free sources include solar, wind, hydro, nuclear, and biomass.

Source: Compiled by the authors from the literature review and expert consultations listed in Appendices C and D.

demand response capacity. The full set of policies and the rationale for their implementation assumptions are presented in Appendix C.

No New Policy scenario

The No New Policy (NNP) scenario pursues no additional power-sector policies beyond the existing policies announced as of 2020, which are assumed to continue to operate until the end of their specified period. Capacity expansion is determined by cost considerations alone; that is, the simulator chooses the least-cost technology options to meet the electricity demand. This scenario sees no new coal capacity additions after 2030, and coal capacity remains nearly constant (natural retirements slightly reduce capacity over time) from 2030 to 2050.

The assumptions of this scenario correspond to the assumptions for the electricity sector made in the Reference Scenario of the model, which is discussed in the model's technical note (Swamy et al. 2021a). The key assumptions are summarized as follows:

- Based on actual progress, approximately 60 percent of the 175 GW target of installed RE capacity by 2022 (comprising 100 GW solar, 60 GW wind, 10 GW biomass, and 5 GW small-scale hydro), set by the Ministry of New and Renewable Energy (NITI Aayog 2022), is assumed to be achieved.
- Annual capacity additions for conventional sources and retirement for existing coal and lignite capacity (up to 2027) are based on the CEA's 2018 National Electricity Plan (CEA 2018), accounting for the retirement of approximately 43 GW of coal-based thermal generation capacity between 2018 and 2027.
- Must-run status for RE generation under the Indian Electricity Grid Code (Central Electricity Authority India 2010) is assumed to continue through the model run.
- Availability of 34 and 74 GW of grid battery storage capacity by 2030 and 2050, respectively, is assumed.

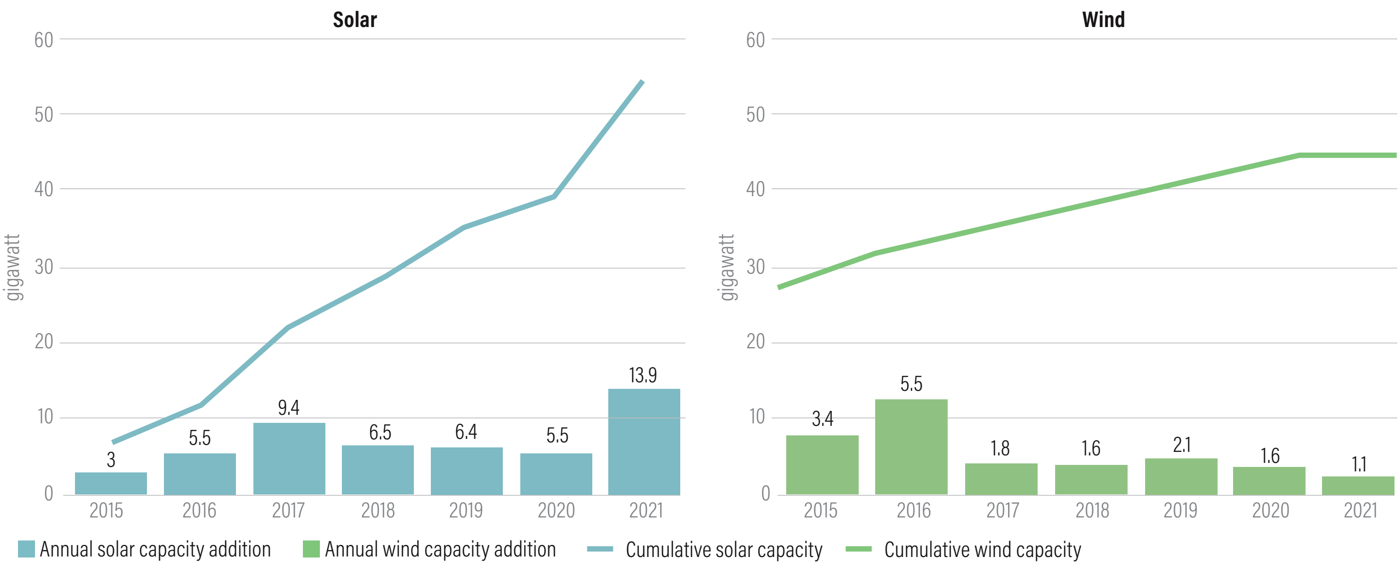
Renewable Energy Bottleneck scenario

Renewable Energy Bottleneck (REB) is a pessimistic scenario that assumes no additional policies. In addition, it assumes that the market-driven growth of solar and wind technologies will be constrained by on-ground implementation challenges. The scenario assumes that the annual capacity additions of solar PV and onshore wind[6] up to 2030 will not exceed their respective historical maxima achieved since 2015 (see Figure 4). For years after 2030, we relax the constraint and limit annual capacity additions to twice the respective historical maxima.

For onshore wind, capacity grew at a CAGR of 8 percent between 2015 and 2022, with the maximum annual capacity addition being achieved in 2016, when 5.5 GW of capacity was added (CEA 2017). This is set to be the maximum permissible annual capacity addition until 2030, after which it is doubled to 11 GW.

Solar PV grew at a CAGR of 47 percent over this period, with the maximum annual capacity addition of 13.9 GW occurring in 2021 (CEA 2022a). Similarly, this defines the upper limit for the permissible annual capacity addition for solar PV until 2030, after which this limit is doubled to 27.8 GW.

Figure 4 | **Historical annual capacity additions for solar and onshore wind power, 2015-2022**



Source: The authors' compilation, based on data from CEA (2023).

Several practical factors that could constrain the market-driven growth of solar and wind technologies have been acknowledged, including technical challenges in increasing the flexibility of the electricity grid to accommodate the growing share of intermittent RE sources, lock-in of DISCOMs to long-term power purchase agreements with thermal power producers, and challenges in land acquisition for land-intensive RE projects (Regy et al. 2021; Gagal 2022).

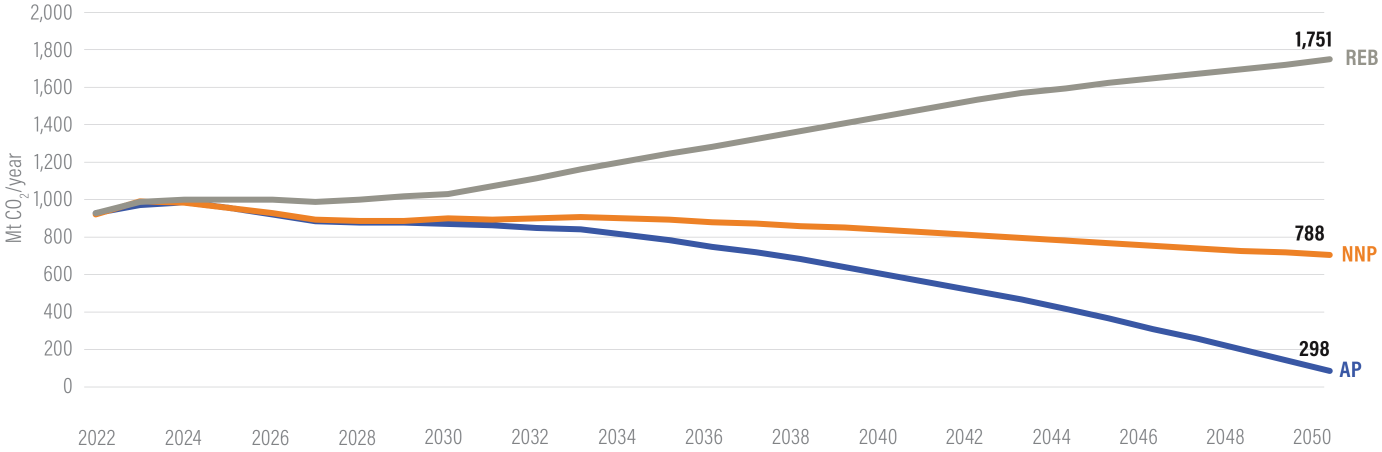
To reflect such potential on-ground implementation challenges in this scenario, the authors have specified an upper limit on the annual deployment of solar and wind capacity by the model using the approach described above. This scenario sees the need for more coal capacity addition after 2030.

Scenario results

GHG emissions

The AP and NNP scenarios both see power-sector emissions peak in 2024 at just over a billion tonnes of CO_2 ($BtCO_2$). Emissions show a similar trend in both scenarios, gradually declining through the early 2030s. The AP scenario sees the rate of decline in emissions pick up after this, with emissions reducing by almost 70 percent from the peak year to about 0.3 billion tonnes of CO_2 ($BtCO_2$) in 2050. The NNP scenario sees emissions stabilize in the long term at about 0.8 $BtCO_2$, which is close to the present level of emissions. The REB

Figure 5 | **Annual power-sector CO_2 emissions in the three scenarios through 2050**

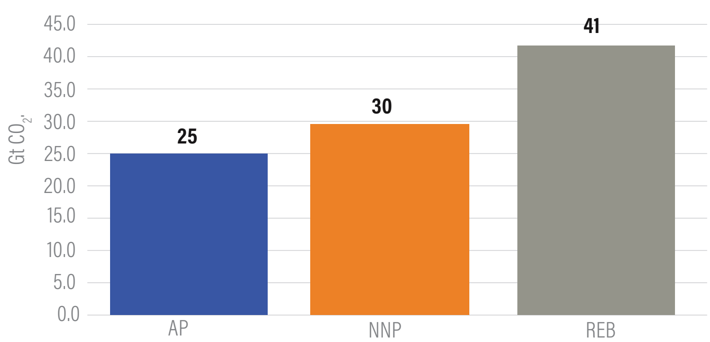


Note: CO_2 = carbon dioxide. AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. Mt = megatonne.
Source: Authors' analysis using India Energy Policy Simulator.

scenario, on the other hand, sees a steady rise in emissions, with emissions approximately doubling from the present level to reach 1.8 $BtCO_2$ by 2050 (see Figure 5).

In cumulative terms (see Figure 6), the AP scenario avoids nearly 5 $BtCO_2$ (62 percent) and 17 $BtCO_2$ (82 percent) over the NNP and REB scenarios, respectively.

Figure 6 | **Cumulative power-sector GHG emissions in the three scenarios through 2050**



Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. GHG = greenhouse gas. Gt = gigatonne.

Source: Authors' analysis using India Energy Policy Simulator.

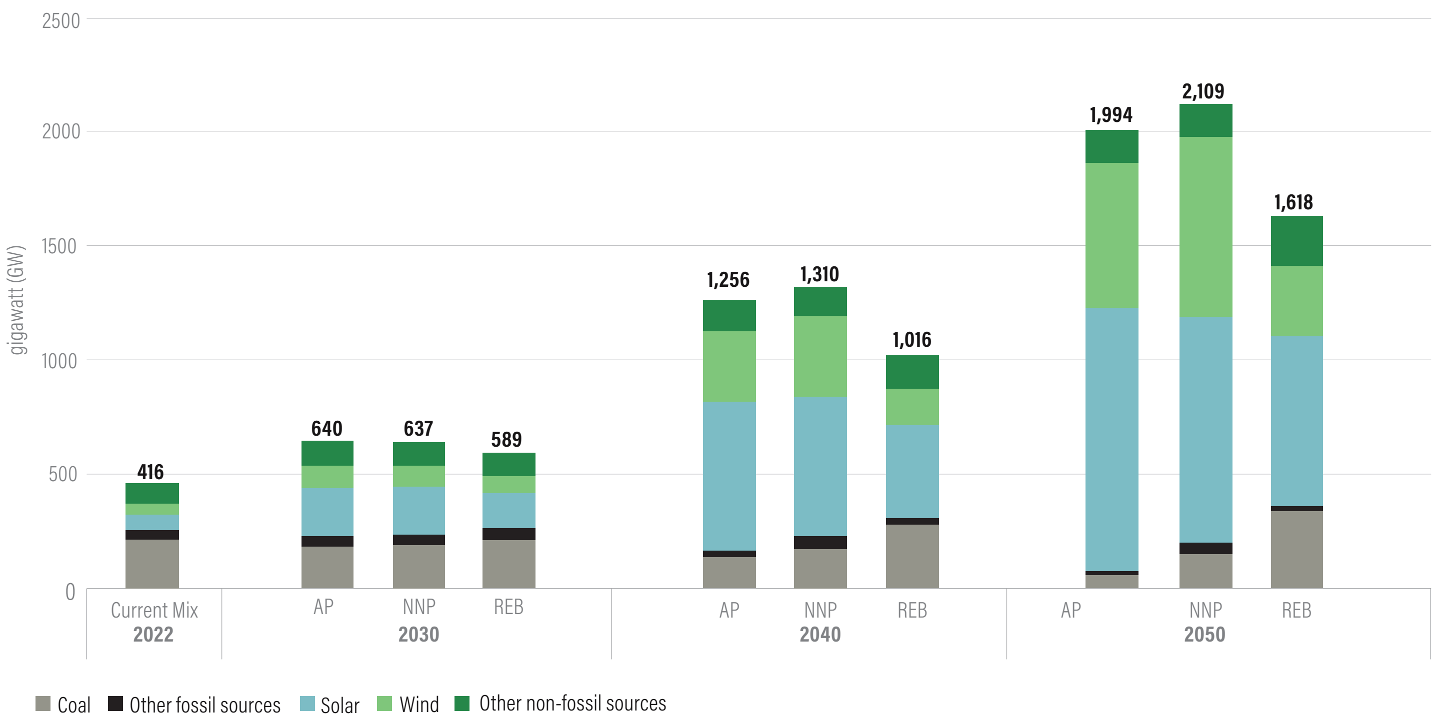
Installed electricity capacity, generation, and grid flexibility

Installed capacity. Coal-fired power plants—212 GW at present—account for the highest share of total installed capacity (51 percent). By 2050, the AP and NNP scenarios have a phase-down in coal-based capacity of 73.5 percent (a reduction of 156 GW) and 29 percent (a reduction of 61 GW), respectively, from the present level.[7] Extrapolating the rate of reduction in coal-based capacity in the AP scenario, the remaining 56 GW (approximately) in 2050 could be phased down by about 2060. In contrast, the REB scenario requires a net addition of another 121 GW of coal-based capacity, taking the total to 334 GW in 2050, 1.5 times greater than the present capacity (see Figure 7).

All scenarios see a significant increase in non-fossil installed electricity capacity over time. This is also true of the REB scenario, which sees a faster rate of increase in non-fossil capacity additions than coal, leading to their growing share in total installed capacity over time. India's NDC target of achieving a 50 percent share of non-fossil capacity by 2030 is achieved in all three scenarios (see Table 3).

Among non-fossil sources, solar PV sees the highest capacity increase among the three scenarios, emerging as the dominant technology in India's future electricity supply. By 2050, all scenarios see an at least 10 times increase in solar capacity

Figure 7 | **Total installed capacity in the three scenarios in 2030, 2040, and 2050 by power plant type**



Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck.

Source: CEA (2023c) for 2023 and authors' analysis using India Energy Policy Simulator for all future years.

Table 3 | **Achieved non-fossil installed capacity in the three scenarios in 2030 and 2050**

SCENARIO	2030		2050	
	CAPACITY (GW)	PERCENTAGE (%)	CAPACITY (GW)	PERCENTAGE (%)
AP	411	64.2	1918	96.2
NNP	403	63.3	1911	90.6
REB	328	55.8	1260	77.9

Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. GW = gigawatt.

Source: The authors' analysis using India Energy Policy Simulator.

from the present capacity of about 66 GW. The AP scenario sees the maximum growth, with an approximately 17-fold capacity increase.

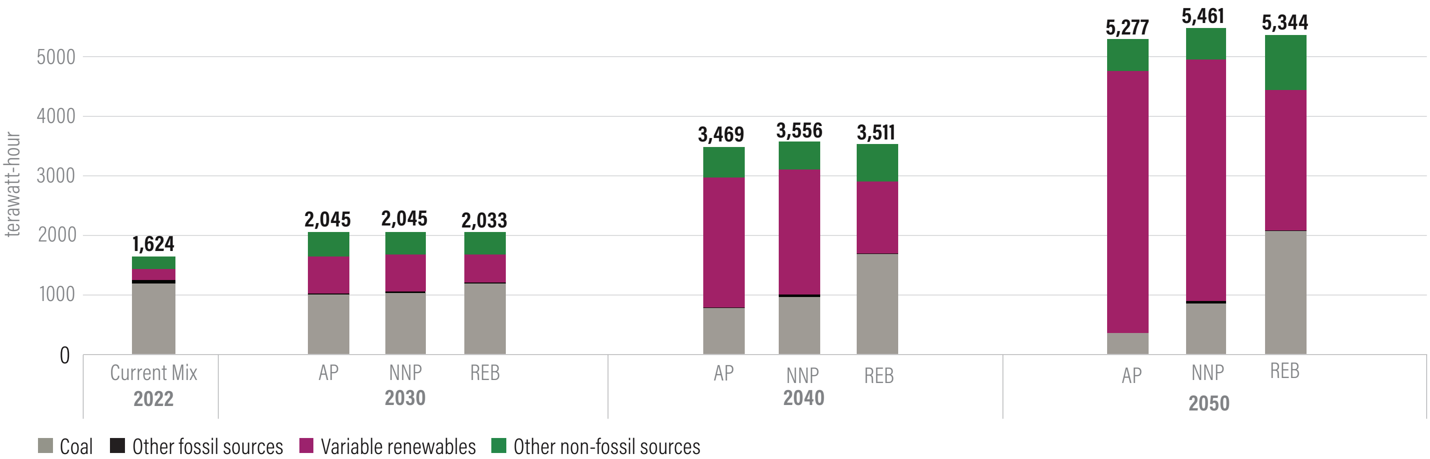
After solar PV, wind sees the next highest increase. By 2050, all scenarios see an at least sevenfold increase in present capacity. However, it is interesting to note that the maximum wind-based capacity is achieved in the NNP (786 GW) and not in the AP (631 GW) scenario. This is because in the absence of any new policies, grid storage capacity emerges as a constraint in the NNP scenario over the long term, resulting in a preference for a more balanced mix of solar and wind capacities—which typically produce energy at different times during the day—as opposed to a solar-dominated mix in the AP scenario (see the run-in heading titled "Grid flexibility" later in the paper).

In the absence of any assumed subsidies, offshore wind sees negligible capacity addition in our scenarios because of its considerably higher capital costs at present, which are approximately 3–4 times higher per unit of capacity than those of solar PV and onshore wind. The recently announced viability gap funding scheme for offshore wind could bring down the cost of offshore wind (PIB 2024). However, the scheme is not considered in our scenarios, and whether offshore wind can compete with onshore wind and solar PV in the long run is unclear as of today.

In terms of other non-fossil fuels, all three scenarios demonstrate a similar increase in large hydro capacity of between 96 GW and 111 GW by 2050, which translates to a multiplier of 2–2.4 times with respect to the presently installed hydro capacity of 47 GW. For nuclear power, the REB scenario, with constraints on solar and wind growth, sees an increase of nine times the 2023 installed capacity of 7.5 GW by 2050 versus an increase of approximately 2.5 times in the other two scenarios.[8]

Generation. Coal maintains a higher share in electricity generation than its corresponding share in installed capacity because of an average capacity utilization factor that is more than double that of solar PV and wind. However, its share in electricity generation declines over time across all scenarios from its present share of 73 percent. By 2050, the share of coal declines considerably to 7 percent and 16 percent in the AP and NNP scenarios, respectively. In the REB scenario, coal still occupies a 39 percent share of the generation mix in 2050 (see Figures 8 and 9).

Figure 8 | **Generation in the three scenarios in 2030, 2040, and 2050 by fuel source**



Note: Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. TWh = terawatt-hour.

Source: CEA (2023c) for 2023 and the authors' analysis using India Energy Policy Simulator for all future years.

Figure 9 | **Share of generation in the three scenarios in 2030, 2040, and 2050 by fuel source**

Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck.

Source: CEA (2023c) for 2022 and the authors' analysis using India Energy Policy Simulator for all future years.

By 2050, the share of VRE in total electricity generation in the AP and NNP scenarios increases to 83 percent and 74 percent, respectively, from a meager 11 percent at present. In the REB scenario, the share of VRE shows a considerably slower growth, contributing to 44 percent of generation in 2050.

It is noteworthy that the share of carbon-free electricity generated in 2050 comfortably exceeds the policy-mandated minimum of 75 percent in the AP scenario. However, the policy is important for driving VRE uptake in the earlier years, which reduces technology costs and in turn accelerates technology adoption in subsequent years (see Appendix E for the unit technology cost trends observed in the model).

Grid flexibility. The increasing share of VRE in the electricity mix over time makes it necessary to build flexibility in the electricity grid to match demand with intermittent supply. [9]The AP scenario, which sees the most significant growth in the VRE share, relies on two main supporting policies to increase grid flexibility to integrate the growing share of VRE (see Appendix C for the details):

- Demand response: Demand response programs to enable a potential shifting of up to 38 GW of peak electricity demand by 2030 and 108 GW by 2050 during periods of excess supply.
- Grid battery storage: Policies to scale grid battery storage capacity to 34 GW by 2030, increasing to 298 GW by 2050 to store energy during periods of excess supply for use during high-demand periods.

In the absence of any supporting policies, the model assumes the availability of a grid battery storage capacity of 34 GW by 2030 and of 74 GW by 2050 (Figure 10). In the REB scenario, flexibility requirements for VRE integration are entirely met by this modest storage capacity together with surplus coal capacity.

The NNP scenario, which sees a higher share of VRE and a lower share of coal in electricity generation than in the REB scenario, presents an interesting case of flexibility constraints due to the lack of supporting policies, which manifests itself in two ways in the scenario to minimize VRE curtailment at the least cost:

- A preference for a more balanced mix of solar PV and wind—which typically differ in the amount of energy they generate at different times during the day and across seasons—thereby reducing the intermittency of overall electricity supply and the need for grid flexibility compared to a solar-dominated mix in the other scenarios.
- Construction of 27 GW of natural gas peaker plant capacity to provide additional flexibility.

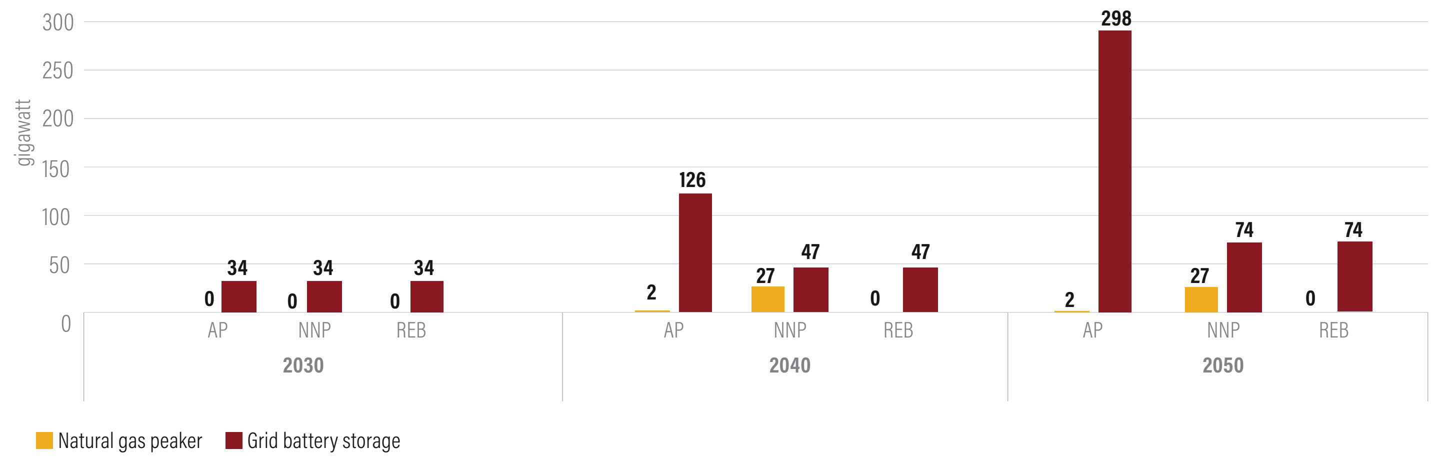
The NNP scenario illustrates that the growth of grid energy storage capacity—negligible at present—is unable to maintain the pace required to integrate the growing VRE capacity in the absence of any new policies, which underscores the importance of grid flexibility as an area of medium-term policy priority.

Moreover, the requirement for grid flexibility would be even greater in a solar-dominated VRE growth trajectory, which is anticipated in India, with solar PV capacity being added at a much faster rate than wind over the last decade and finding greater emphasis in policy targets (MNRE 2023). Targeting a more balanced mix of solar PV and wind in electricity supply in the long term could be a relevant policy consideration to ease storage needs, signaling a potential rethink of long-term policy targets, which presently emphasize solar PV.

Carbon intensity of electricity

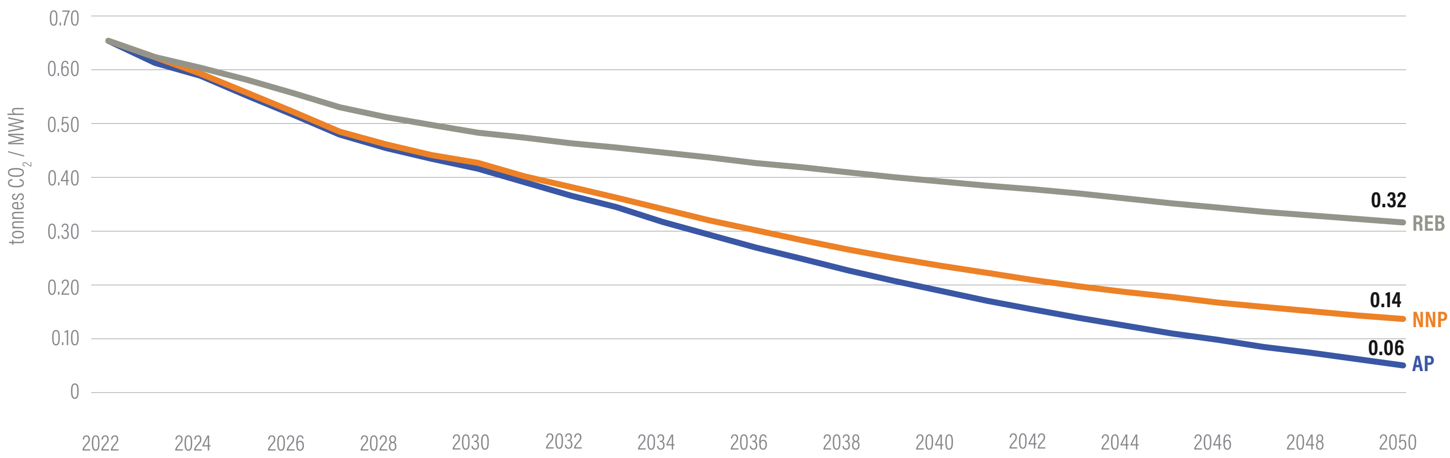
The average carbon intensity[10] of the electricity grid falls over time in all three scenarios, given the increasing share of non-fossil sources in electricity generation. The present carbon intensity of the Indian electricity grid is about 700 gCO_2/kWh, compared with the global average of 475 gCO_2/kWh and the EU average of 225 gCO_2/kWh (IEA 2021a; CEA 2022c). India's grid carbon intensity approaches the present global average in about five years in the AP and NNP scenarios, and in 10 years in the REB scenario (Figure 11).

Figure 10 | **Grid battery storage and peak gas capacity in the three scenarios in 2030, 2040, and 2050**



Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck.
Source: CEA (2023c) for 2022 and the authors' analysis using India Energy Policy Simulator for all future years.

Figure 11 | **Annual carbon intensity of electricity generation through 2050 in the three scenarios**



Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. CO_2 = carbon dioxide. MWh = megawatt-hour.
Source: Authors' analysis using India Energy Policy Simulator.

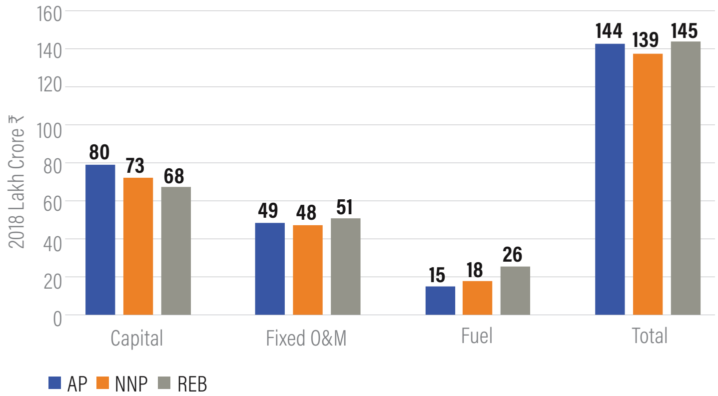
From an emissions mitigation perspective, the full impact of India's ambitious plans of electrifying transport and green hydrogen production depends on the pace of decline in the carbon intensity of the electricity supply. In the REB scenario, even in 2050, India's grid carbon intensity (321 gCO_2/kWh) is comparable to the direct combustion of fossil fuels such as coal (326 gCO_2/kWh) and oil (292 gCO_2/kWh) (Carbon Independent 2023). In the AP and NNP scenarios, India's grid carbon intensity becomes the cleaner alternative to direct fossil fuel combustion. This highlights the importance of continued policy emphasis on power-sector decarbonization as electricity increasingly replaces the use of these fuels across the economy over time.

Electricity-supply expenditure

In this section, we compare the total expenditure—comprising capital cost, fixed operations and maintenance (O&M) cost, and fuel cost—on electricity supply across the three scenarios. The model uses an endogenous learning curve for the capital costs of emerging power-sector technologies, namely, solar PV, wind, and battery storage, which fall with increasing deployment in a scenario to reflect the development of economies of scale. The capital costs of other technologies, O&M, and fuel costs are based on the literature and are assumed to remain fixed over time (see Appendix E). All cost estimates are in constant 2018 prices and assume no discounting of future costs.

The total projected expenditure through 2050 is comparable across the three scenarios and is in the range of INR 139–145 lakh crores[11] ($2,032–2,119 billion) in 2018 prices (Figure 12). Capital expenditure consistently accounts for about half the share of the total expenditure (Figure 13).

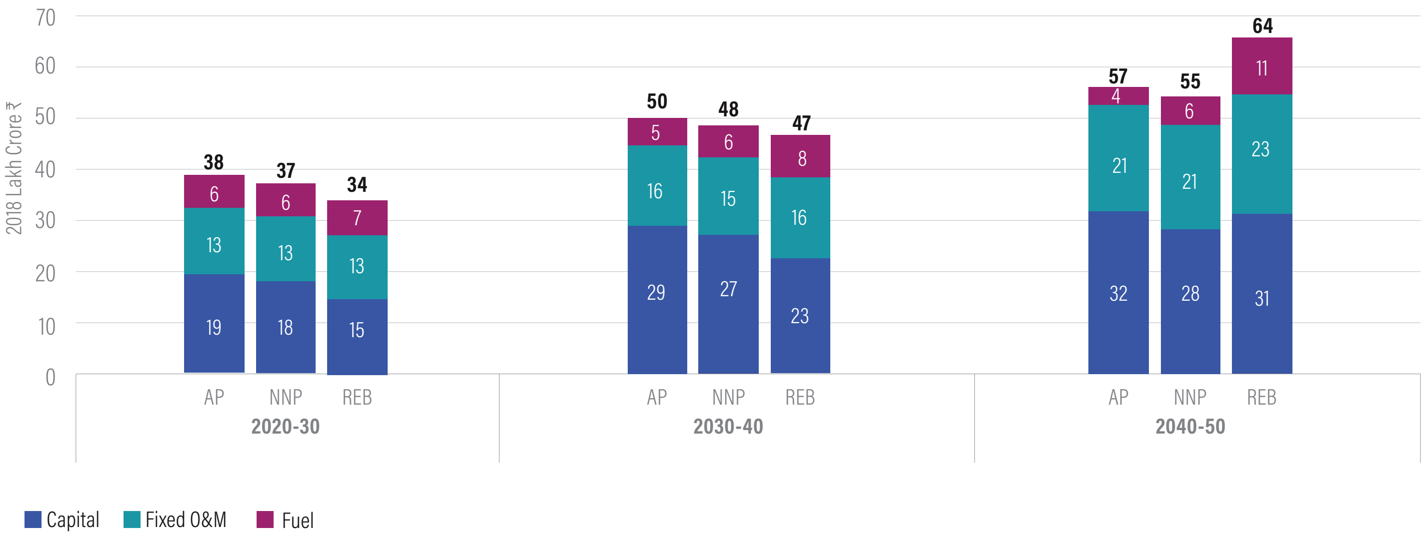
Figure 12 | **Total electricity-supply expenditure through 2050 in the three scenarios**



Note: Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. O&M = operations and maintenance. 1 lakh crore = 1 trillion.

Source: Authors' analysis using India Energy Policy Simulator.

Figure 13 | **Decadal electricity-supply expenditure in the three scenarios: Capital, fixed O&M, fuels, and total**

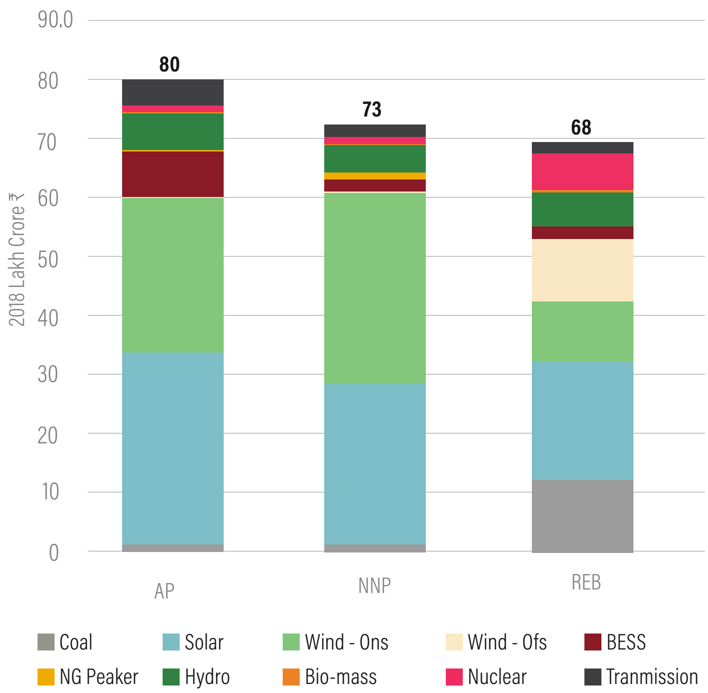


Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. O&M = operations and maintenance. 1 lakh crore = 1 trillion.

Source: Authors' analysis using India Energy Policy Simulator.

The AP scenario sees the highest capital expenditure among the scenarios, driven by investment in VRE and storage technologies, despite accounting for the reduction in unit costs of these technologies with technology diffusion over time.[12] Of the total capital expenditure of INR 80 lakh crores ($1,169 billion)[13] through 2050 in the scenario, investment in solar PV (43 percent) accounts for the largest share, followed by onshore wind (35 percent) and battery storage (11 percent). Together, these account for almost 90 percent of the total investment (see Figure 14).

Figure 14 | **Cumulative capital expenditure through 2050 in the three scenarios**



Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. BESS = battery energy storage system. Ofs = offshore. Ons = onshore. NG = natural gas. 1 lakh crore = 1 trillion.

Source: Authors' analysis using India Energy Policy Simulator.

The storage-constrained NNP scenario sees a higher share of investment in wind (46 percent) than in solar (39 percent). The lower investment in storage in this scenario cuts the total capital expenditure by about 6 percent compared to the AP scenario.

It is noteworthy that even in the REB scenario, investment in non-fossil capacity significantly outweighs that in new coal capacity, which accounts for only 18 percent of the total investment through 2050. The considerably higher share of coal in electricity generation in this scenario reduces the requirement of total installed electricity capacity[14] and cuts the capital expenditure by about 12 percent compared to the AP scenario.

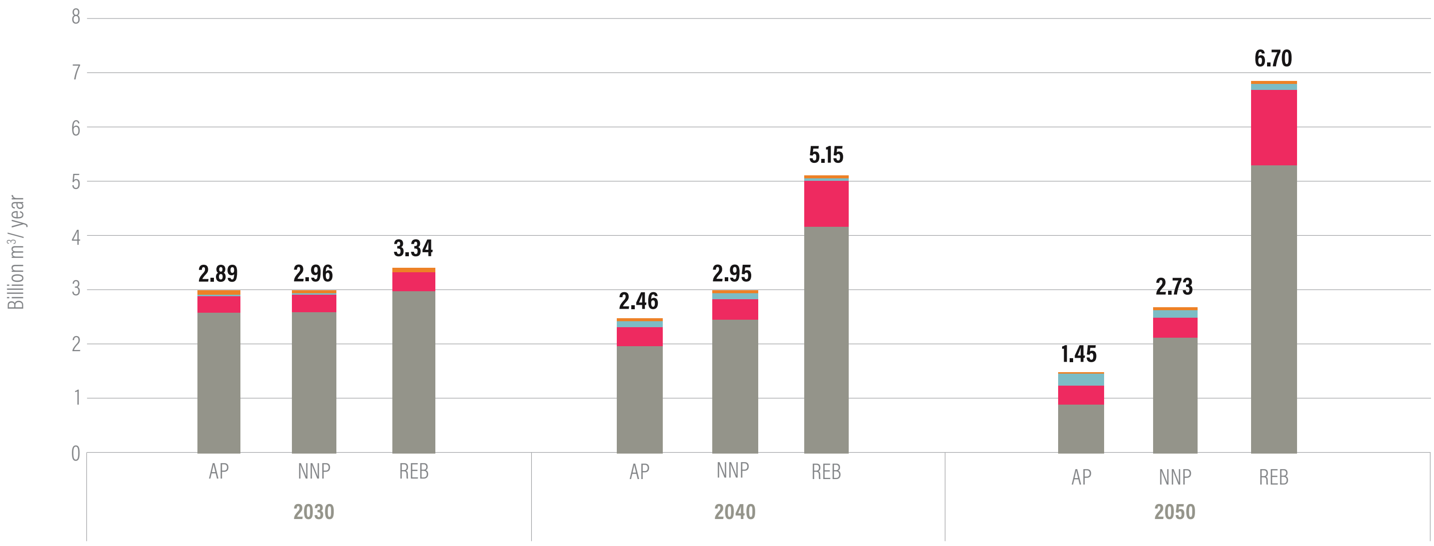
In all three scenarios, the average annual investment over the period 2023–50 in solar PV and onshore wind capacity is at least twice as much as the investment level as of 2021. India was then among the top 10 countries in the world in terms of annual capacity added for both solar and wind power, which together saw a total investment of approximately $10 billion (REN21 2022). However, this represents only about a third of the annual average investment required from 2023 to 2050 in these technologies in the AP and NNP scenarios and about half of the required annual amount in the REB scenario, highlighting that policies to accelerate investment in these technologies will be critical to achieving the scale of the electricity-supply transformation required.

In terms of total expenditure, the REB scenario is still marginally more expensive than the other two scenarios, primarily due to greater fuel expenditure. Between the AP and NNP scenarios, the NNP scenario, interestingly, sees a lower total expenditure because of relative savings on capital expenditure on energy storage. This indicates that an electricity-supply system with a balanced mix of solar PV and wind could potentially be more cost-effective than a solar- or wind-intensive scenario.

Environmental co-benefits: Water use and air quality

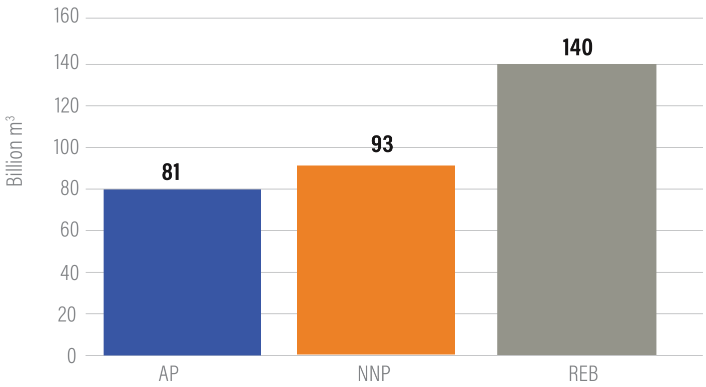
Water use. Coal-based power generation is the most water-intensive form of electricity production (see Appendix F). On comparing the annual water consumption (Figure 15), the REB scenario, which adds 122 GW of coal capacity between 2030 and 2050, sees the annual water consumption in the power sector more than double over this period. In contrast, in the NNP and AP scenarios, water consumption is cut by 10 percent and 50 percent, respectively, by 2050 from 2030 levels. In cumulative terms, the AP scenario saves 12 trillion liters and 60 trillion liters over the NNP and REB scenarios, respectively (see Figure 16).

Figure 15 | **Water consumption by power plant technology in the three scenarios in 2030, 2040, and 2050**



Note: m³ = cubic meter. RE = renewable energy. 1 m³ = 1,000 liters.
Source: Authors' analysis using India Energy Policy Simulator.

Figure 16 | **Cumulative power-sector water consumption through 2050 in the three scenarios**

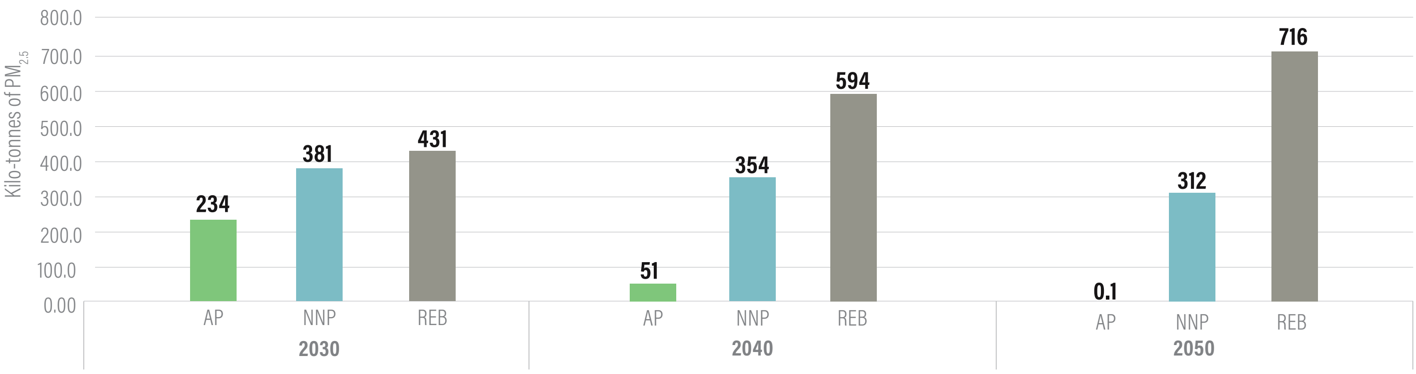


Note: AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck. m³ = cubic meter. 1 m³ = 1,000 liters.

Source: Authors' analysis using India Energy Policy Simulator.

Air pollutants. Increasing particulate matter pollution is a major concern in India. Premature mortality related to air pollution was estimated at 0.67 million in 2017 (Pachouri and Saxena 2020) and rose to 1.6 million in 2019 (Fuller et al. 2022). By 2050, we find that electricity-supply-related PM2.5 emissions in the AP scenario are cut to negligible levels. The NNP scenario sees a marginal decline of 18 percent in PM2.5 emissions by 2050 from 2030 levels, whereas the REB scenario sees an increase of 66 percent over this period (see Figure 17).

Figure 17 | **Particulate matter ($PM_{2.5}$) emission levels for electricity supply in the three scenarios in 2030, 2040, and 2050**



Source: Authors' analysis using India Energy Policy Simulator.

POLICY IMPLICATIONS

Strong growth in electricity demand makes it challenging to bend the GHG emissions curve of India's power sector. We see electricity demand quadruple by 2050 from the present as decarbonization efforts across the economy shift demand from fossil fuels to electricity. Although the 2030 NDC targets are met in all scenarios and the carbon intensity of electricity and the share of coal in electricity generation are each cut to half of their present values by 2050, only the AP scenario witnesses a significant downward bend in its emissions trajectory. This indicates that additional policies are likely to be required for deep, long-term decarbonization of the power sector.

Three key policies can enable deep decarbonization of the power sector. To cut power-sector emissions to a quarter of present levels by 2050, the AP scenario relies on the phased implementation of two key policy mandates—minimum carbon-free electricity generation (linearly increasing over time to reach 75 percent by 2050) and gradual retirement of coal-fired power plants (linearly increasing over time to reach 7 GW/year by 2050)—and a carbon tax in the power sector (linearly increasing over time to reach \$50 per tonne of CO_2 by 2050). All these policies can be implemented by gradually building upon existing policies.

- The carbon-free electricity generation mandate is similar, in effect, to the existing RPO policy that mandates a minimum share of RE in the electricity procured by DISCOMs and industrial consumers. The Ministry of Power (MoP) has already announced the RPO trajectory through 2029–30 (see Table 4). Building upon this in the long term, together with enforcement of RPO obligations, which have been consistently poor in the past, will be key going forward.
- The retirement of coal-fired power plants is a sensitive subject, given the growing demand for base-load power. Four Indian states—Gujarat, Chhattisgarh, Maharashtra, and Karnataka—together with a few leading private power companies have committed to a no-new-coal policy. Collectively, the states and the companies make up 50 percent of India's total installed power-generating capacity (Climate Trends 2021). A plan for retiring inefficient coal power based on efficiency and environmental criteria will be key going forward.[15]
- India introduced a tax assessment (cess) on coal production (subsequently renamed the Goods and Services Tax [GST] compensation cess) in 2010 and increased it three times since then to reach INR 400 per tonne of coal extracted in 2016 from INR 50 per tonne of coal (Garg et al. 2017). In terms of carbon tax equivalent, this translates to \$4 per tonne of carbon dioxide at 2023 exchange rates, levied at the point of production (IISD 2018). A phased carbon pricing policy for the power sector that builds upon this could be a key method of decarbonizing the sector. This can be implemented in the form of a fixed carbon tax or an emissions trading scheme, which India has recently announced. In addition, it could provide a policy signal to spur private-sector green investment and create a stream of new public revenue that could be reinvested to support the transition. Evaluating such a policy, including its potential effects on electricity prices and distributional implications, will be the critical next step.

Supporting policies to increase grid flexibility will be crucial in easing bottlenecks in RE scale-up. The massive scale-up in grid battery storage capacity from negligible levels at present as the share of intermittent VRE in electricity generation grows has been consistently recognized as a challenge. A recent notification by the MoP added an Energy Storage Obligation alongside its RPO obligations (MoP 2022). Scaling demand response program pilots, such as the scheme by Tata Power Delhi that incentivizes consumers to reduce electricity consumption during peak hours (Tata Power-DDL 2022), can be an important tool to mitigate the challenge and ease storage requirements. Additionally, policy targets to support a more balanced growth of solar PV and wind could also reduce supply-side intermittency, thereby reducing the need for energy storage.

Policies to reduce financing costs will be necessary to spur investment in VRE technologies. According to our analysis, investment needs to triple in average annual terms from present levels to achieve the scale of the electricity-supply transformation required. Aside from carbon pricing, which can provide a policy signal to spur private green investment, policies to reduce financing costs will be critical for easing bottlenecks in scaling up investment. Although we do not include financing costs in our capital expenditure estimates, they can add significantly to the cost of capital due to the perceived risk profiles (regulatory, political, currency) of emerging economies. The weighted average cost of capital for

Table 4 | **Long-term Renewable Purchase Obligation trajectory until 2029-2030**

FINANCIAL YEAR	2022-2023	2023-2024	2024-2025	2025-2026	2026-2027	2027-2028	2028-2029	2029-2030
Total RPO (in %)	24.61	27.08	29.91	33.01	35.95	38.81	41.36	43.33

Source: MoP 2022.

green investment in India is estimated at 8.2 percent, almost double that of the United Kingdom and the European Union (Ameli et al. 2021).

Decarbonizing the electricity supply can ease the water shortage in the power sector and improve air quality. More than 80 percent of India's thermal electricity generation relies completely on freshwater for cooling. Further, among all of India's freshwater-cooled thermal utilities, 39 percent of the capacity is installed in high-water-stress regions (Luo et al. 2018). We find that the AP scenario, on average, saves 266 billion liters and 2 trillion liters per year over the NNP and REB scenarios, respectively, between the present and 2050. The latter saving is more than New Delhi's annual water demand of 1.7 trillion liters in 2020 (Rumi 2020). The reduced use of coal-fired power generation also improves air quality. By 2050, annual $PM_{2.5}$ emissions in the AP scenario are cut to negligible levels.

Measures designed to mitigate the trade-offs would ensure a more just and equitable transition away from fossil power generation. Although research shows that the transition from coal to RE is likely to produce a net gain in jobs, the impacts will differ across regions (Swamy and Agarwal 2023). Over 75 percent of domestic coal production takes place in four Indian states: Jharkhand, Chhattisgarh, Orissa, and Madhya Pradesh. Identification of the potential socioeconomic consequences of the transition with an emphasis on such states, together with policies to mitigate these impacts, will be critical.

The availability of land for accelerated uptake of RE is another challenge. The power density of RE is one to two orders of magnitude lower than that of fossil fuels, meaning that it requires at least 10 times more land area per unit of electricity produced (Gross 2020). According to a recent estimate, about 68 percent of the existing solar projects in India are sited on agricultural land and about 19 percent in natural ecosystems, highlighting the potential impacts of RE projects on biodiversity, community livelihoods, and future food security (TNC 2022). This warrants a careful evaluation of land-use impacts and proactive policy measures, such as incentives for rooftop solar or offshore wind, to avoid potential land-related bottlenecks to RE scale-up in the future.

APPENDIX A. SUMMARY OF SELECTED RECENT LITERATURE ON INDIA'S POWER-SECTOR TRANSITION

Table A-1 | **Selected studies on India's power-sector transition**

STUDY NAME	STUDY DESCRIPTION	METHODOLOGY AND COMMENTARY
Chaturvedi and Malyan 2022	The authors examine four transition scenarios that combine different peaking and net-zero years for the Indian economy using the Global Change Analysis Model (GCAM).	The authors use GCAM, an integrated economy-wide model, whose core operating principle is market equilibrium (JGCRI 2023). Economy-wide models such as GCAM model potential interactions between the power sector and the economy at large, but such models are not commonly used to create alternative transition scenarios specific to the power sector. They have limited utility for power-sector outcomes.
Parikh et al. 2021	This study explores the technological options for, and economic implications of, achieving net zero within the power sector in two separate target years, 2050 and 2060, using the power-sector model MESSAGE.	MESSAGE and PLEXOS specialize in modeling the power sector, typically accounting for hourly and seasonal demand profiles. Although these models can be run with various assumptions regarding load growth and changes in peak demand, they are unable to endogenously capture interactions of the power sector with other economic sectors, such as the response of electricity users to a change in electricity costs resulting from policies enacted in the power sector. They are also unable to capture the effects of policies enacted in end-use sectors, such as the impact of electrification or green hydrogen production mandates on electricity demand.
Abhyankar et al. 2023	The authors explore a scenario in which India achieves near-complete energy independence by 2047, covering the power, industry, and transport sectors, which are analyzed using various models. To model the power sector, the study uses the power-sector simulation model PLEXOS.	

APPENDIX B. KEY ECONOMIC ASSUMPTIONS IN THE INDIA EPS

Table B-1 | **Economic assumptions in the India EPS[a]**

YEAR	2017-2022	2022-2027	2027-2032	2032-2037	2037-2042	2042-2047
Annual average GDP growth rate at factor cost, at real prices (%)	6.20	6.40	6.40	6.30	5.20	4.70
Population (million)	1,383.6	1,453.5	1,534.9	1,592.2	1,659.6	1,704.2
Urbanization (%)	36	39	42	45	48	51
Household size	4.6	4.4	4.3	4.1	4	3.8
Urban population (million)	498.1	566.9	644.3	716.5	796.6	869.1
Rural population (million)	885.5	886.6	889.6	875.7	863	835.1
Urban households (million)	108.4	127.7	150.5	173.7	200.8	228.1
Rural households (million)	192.7	199.7	207.8	212.3	217.5	219.2

Note: a. Version 3.1.3.5. GDP = gross domestic product.

Source: India Energy Security Scenarios, NITI Aayog 2015 (low-growth scenario). See NITI Aayog (2023).

APPENDIX C. RATIONALE FOR POLICY SETTINGS IN THE AMBITIOUS POLICY SCENARIO

Table C-1 | **Policy settings in the Ambitious Policy scenario**

POLICY	POLICY SETTING (2050)	RATIONALE FOR POLICY SETTING
Carbon tax	INR 3,500 per tonne of CO_2 ($50 per tonne of CO_2) in 2018 prices.	The chosen tax rate corresponds to the "modest" rate of a coal tax for India assumed by Parry et al. (2017). The study finds that a phased carbon tax reaching approximately INR 1,200 ($17) per tonne of CO_2 by 2030 can have significant health, economic, and environmental benefits. The authors assume that this value of carbon tax continues to increase linearly after 2030 to reach the policy setting value of INR 3,500 ($50) by 2050.
Carbon-free electricity standard	At least 75% of the total electricity generated must originate from carbon-free sources.	Based on The Energy and Resources Institute's (TERI's) report (Spencer et al. 2020).
Demand Response Capacity (DRC)	108 GW	Estimates for the potential growth of demand response in India based on a study by the Climate Policy Initiative (Udetanshu et al. 2020). Fifty percent of the estimated potential is assumed to be met by 2050.
Early retirement of power plants	7,000 MW/year	We assume that coal plants will be gradually retired beginning with 300 MW/year annually in 2027, with the annual retirement rate linearly increasing to 7,000 MW/year by 2050. This ensures that coal capacity will be phased out within the decade 2050–60.
Grid-scale electricity storage	298 GW	Grid battery storage potential based on the IEA's projection (Pavarani 2019). Fifty percent of this potential is assumed to be met.
Increase the transmission capacity of the electricity grid	968,000 circuit-kilometers (ckm)	India's MoP projects that transmission capacity will increase by 65% from 2018 through 2035 (CEA 2016a), which is held constant during 2036–50 in our Reference scenario because the growth rate in years preceding 2036 tapers off. If we assume this growth rate is sustained until 2050, this will increase Reference scenario transmission capacity by 44% in 2050 to 968,000 ckm.
Reduce T&D losses	50%	India currently has T&D losses of about 19% (WB 2018). Developed nations, particularly in Europe, have T&D losses of about 4%. An additional 55% policy lever setting brings down India's losses by 2050 to the current level of these other countries.

Note: CO_2 = carbon dioxide. GW = gigawatt. IEA = International Energy Agency. MW = megawatt. T&D = transmission and distribution.

Source: The authors, based on the available literature.

APPENDIX D. EXPERTS CONSULTED FOR FEEDBACK ON SCENARIO POLICY SETTINGS

Table D-1 | **Experts consulted**

S. NO	NAME	ORGANIZATION
1.	Anoop Singh	Indian Institute of Technology, Kanpur
2.	Raghav Pachouri	The Energy and Resources Institute (TERI)
3.	Rahul Tongia	Centre for Social and Economic Progress
4.	Rangan Banerjee	Indian Institute of Technology, Bombay
5.	Rasika Athawale	Regulatory Assistance Project
6.	Thomas Spencer	TERI
7.	Usha Ramachandra	Administrative Staff College of India

Note: Consultations were held in 2020–21 during scenario creation for our previously published work (Swamy et al. 2021b). Minor updates were made to the policy settings for the Ambitious Policy scenario in this publication to reflect subsequent policy announcements.

Source: The authors.

APPENDIX E. CAPITAL, OPERATIONAL, AND FUEL COST ASSUMPTIONS

Unit costs: Capacity addition (constant prices), fixed O&M, fuel

Table E-1 | **Fixed unit costs**

POWER PLANT TECHNOLOGY	UNIT CAPEX (INR LAKH/MW)	FIXED O&M (INR LAKH/MW)	FUEL COSTS (INR LAKH/GWH)
Coal	856	22	5.54
Gas turbine	400	17.6	11.99
Biomass	924	10	X
Onshore wind	Decreasing costs	6.8	n/a
Offshore wind	2,010	67.4	n/a
Utility PV	Decreasing costs	3.5	n/a
BESS	Decreasing costs	8.3	n/a
Large hydro	1,000	91	n/a
Nuclear	1,000	43	1.45

Note: INR values are in 2018 prices. BESS = battery energy storage system. GWh = gigawatt-hour. MW = megawatt. n/a = not applicable. O&M = operations and management. PV = photovoltaic. X = not included.

Source: National Electricity Plan, Volume 1: Generation (2017 & 2023) (CEA 2018, 2023b) and Indian Technology Catalogue—Generation and Storage (CEA 2022d).

Table E-2 | **Decreasing unit costs**

YEAR	BATTERY (INR LAKH/MWH)	SOLAR PV (INR LAKH/MW)	ONSHORE WIND (INR LAKH/MW)
2020	157.9	564.4	636.7
2025	130.2	452.3	575.0
2030	118.1	344.0	510.2
2035	111.5	314.0	471.7
2040	107.6	292.7	427.9
2045	105.2	278.9	388.3
2050	103.5	269.8	354.0

Note: INR values are in 2018 prices. MW = megawatt. MWh = megawatt-hour.
Source: India Energy Policy Simulator.

Capital expenditure by scenario and plant type

Table E-3 | **Capital expenditure by scenario and plant type, 2020–2050[a]**

PLANT TYPE	2020–2030	2030–2040	2040–2050	TOTAL
Ambitious Policy scenario				
Hard coal	1.21	0.00	0.00	1.21
Utility solar	7.50	12.75	12.17	32.42
Onshore wind	3.27	9.99	12.72	25.99
Offshore wind	0.00	0.01	0.02	0.03
BESS	1.05	2.46	4.35	7.86
Gas: Non-peaker	0.00	0.00	0.00	0.00
Gas: Peaker	0.05	0.00	0.00	0.05
Hydro	2.50	2.20	1.53	6.24
Biomass	0.21	0.00	0.00	0.21
Nuclear	0.95	0.20	0.00	1.15
Transmission expansion cost	2.47	1.04	0.83	4.34

No New Policy scenario				
Hard coal	1.21	0.00	0.00	1.2
Utility solar	7.50	11.51	8.78	27.8
Onshore wind	3.31	12.02	17.03	32.4
Offshore wind	0.01	0.07	0.15	0.24
BESS	1.05	0.36	0.67	2.1
Gas: Non-peaker	0	0	0	0.0
Gas: Peaker	0.00	1.08	0.00	1.1
Hydro	1.68	1.47	1.51	4.7
Biomass	0.21	0.00	0.00	0.2
Nuclear	0.95	0.25	0.00	1.2
Transmission expansion cost	1.77	0.21	0	1.98
Renewable Energy Bottleneck scenario				
Hard coal	1.59	5.58	4.79	11.96
Utility solar	5.12	6.72	7.81	19.66
Onshore wind	2.28	3.36	4.27	9.91
Offshore wind	0.20	1.83	8.27	10.31
BESS	1.05	0.36	0.67	2.09
Gas: Non-peaker	0	0	0	0
Gas: Peaker	0	0	0	0
Hydro	1.36	1.79	2.52	5.68
Biomass	0.21	0.05	0.24	0.50
Nuclear	1.00	2.40	2.50	5.90
Transmission expansion cost	1.77	0.21	0	1.98

Note: a. In INR lakh crores in 2018 prices. BESS = battery energy storage system.

Source: The authors' analysis based on spreadsheets from CEA and DEA (2022).

Table E-4 | **Fixed O&M expenditure by scenario, 2020-2050[a]**

PLANT TYPE	2020-2030	2030-2040	2040-2050	TOTAL
Ambitious Policy scenario				
Hard coal	4.90	3.66	2.28	10.84
Utility solar	0.32	1.26	2.79	4.37
Onshore wind	0.41	0.00	3.05	4.64
Offshore wind	0.00	0.01	0.03	0.04
BESS	0.07	0.58	0.48	2.29
Gas: Non-peaker	0.48	0.42	0.35	1.25
Gas: Peaker	0.01	0.02	0.03	0.06
Hydro	5.98	7.70	9.48	23.16
Biomass	0.12	0.12	0.07	0.31
Nuclear	0.55	0.77	0.79	2.11
No New Policy scenario				
Hard coal	4.93	4.01	3.60	12.54
Utility solar	0.32	1.22	2.48	4.03
Onshore wind	0.41	1.28	3.67	5.36
Offshore wind	0.00	0.01	0.05	0.07
BESS	0.07	0.33	0.48	0.89
Gas: Non-peaker	0.48	0.42	0.37	1.27
Gas: Peaker	0.01	0.27	0.48	0.75
Hydro	5.69	6.64	8.01	20.33
Biomass	0.12	0.12	0.12	0.35
Nuclear	0.55	0.79	0.81	2.14
Renewable Energy Bottleneck scenario				
Hard coal	5.15	5.35	6.84	17.35
Utility solar	0.26	0.77	1.67	2.70
Onshore wind	0.37	0.70	1.33	2.41
Offshore wind	0.02	0.30	1.63	1.95
BESS	0.07	0.33	0.48	0.89
Gas: Non-peaker	0.48	0.43	0.42	1.33
Gas: Peaker	0.01	0.01	0.01	0.02

Hydro	5.59	6.42	8.39	20.39
Biomass	0.12	0.12	0.13	0.37
Nuclear	0.51	1.18	2.24	3.92

Note: a. In INR lakh crores in 2018 prices. BESS = battery energy storage system.

Source: The authors' analysis based on spreadsheets from CEA and DEA (2022).

Fuel expenditure

Table E-5 | **Fuel expenditure by scenario, 2020-2050[a]**

FUEL→ SCENARIO→ YEAR↓	HARD COAL			GAS: NON-PEAKER			GAS: PEAKER			NUCLEAR		
	AP	NNP	REB	AP	NNP	REB	AP	NNP	REB	AP	NNP	REB
2020–30	6.21	6.26	6.56	0.01	0.01	0.01	0.00	0.00	0.00	0.11	0.11	0.10
2030–40	5.11	5.58	7.76	0.02	0.02	0.02	0.01	0.20	0.00	0.17	0.17	0.27
2040–50	3.30	5.04	10.38	0.05	0.06	0.06	0.02	0.37	0.00	0.17	0.18	0.52
Total	14.62	16.89	24.70	0.08	0.09	0.09	0.04	0.58	0.01	0.45	0.46	0.88

Note: a. In INR lakh crores in 2018 prices. AP = Ambitious Policy. NNP = No New Policy. REB = Renewable Energy Bottleneck.

Source: The authors' analysis based on EPS and recent fuel price estimates.

APPENDIX F. OTHER ASSUMPTIONS

Table F-1 | **Water intensity, carbon intensity of, and mean power density of different power generation technologies**

TECHNOLOGY	WATER INTENSITY (M^3/MWH)	CARBON INTENSITY (GCO_2/KWH)	POWER DENSITY[a] MEAN VALUES (W/M^2)
Coal	2.497	326	126
Gas	0.981	203	1283
Oil	1.156	292	179
Utility solar PV	0.08	n/a	10
Wind	0	n/a	1-2
Hydro	0	n/a	0.34
Nuclear	2.994	n/a	289
Biomass	1.994	X	0.13

Note: a. Power density can be interpreted as the inverse of land intensity of electricity generation. gCO_2/kWh = grams of CO_2 per kilowatt-hour of electricity generated. n/a = not applicable. PV = photovoltaic. W/m^2 = watts per square meter. X = not included. m^3/MWh = cubic meters of water consumed per megawatt-hour of electricity generated.

Source: Ferroukhi et al. 2018; van Zalk and Behrens 2018; Gross 2020; Kulkarni et al. 2022; Carbon Independent 2023.

ENDNOTES

1. Other non-fossil plants include biomass, small and large hydro, nuclear, and municipal solid waste. Other fossil-fuel-based plants include distributed diesel generators, natural gas (both peaker and non-peaker), and petroleum plants.
2. The results in the technical note are based on Version 3.1.3.4 of the India EPS. The economic growth assumption was subsequently revised downward to align with more recent estimates and released as model Version 3.1.3.5. The results in this publication are based on India EPS Version 3.1.3.5. The key economic assumptions underlying the present version of the model are presented in Appendix B.
3. This publication is based on EPS version 3.1.3.5. EPS version 4.0, launched for the United States in March 2024, incorporates hourly representation of electricity demand and supply. The India EPS is presently being updated to version 4.0, which is expected to be launched by the end of 2024.
4. Different models typically diverge in estimates of future electricity generation requirement due to differences in assumptions about economic growth, degree of electrification in end-use sectors, and efficiency of electricity use. The EPS projections for electricity generation requirement in 2030 are about 13 percent lower than the CEA estimates.
5. By "alignment," the authors mean similarity to policies that are either already in effect, have been announced and are expected to be implemented soon, or are being actively discussed within the government.
6. Offshore wind is excluded from our analysis because the technology is still at a nascent stage, and there is a lack of institutional support despite the ambitious targets set earlier.
7. Percentages are expressed in terms of installed capacity as of July 31, 2023.
8. The model prioritizes technologies based on cost. However, the costs for each plant type are represented as a normal distribution (a bell curve) in the model to reflect the fact that in the real world, conditions vary from project to project. For example, the cost of coal shipments may depend on the plant location, financing costs may vary depending on project risk factors and borrower creditworthiness, and so on. This is why the scenario sees a mix of coal and nuclear being built although coal plants are, on average, cheaper (see Appendix E for cost assumptions).
9. The EPS uses an abstraction called the "flexibility point" to reconcile its modeled timescale (annual) with that of RE variability (hourly or less). One flexibility point is a quantity of flexibility on the electric grid that is able to support one megawatt (MW) of variable generation. Each storage technology provides a certain number of flexibility points per unit of installed capacity. Solar PV and wind are allowed to share flexibility points due to their differing generation profiles (solar generates during the day and wind primarily at night). In flexibility-constrained scenarios, the availability of flexibility points becomes a determining factor for the VRE mix in our modeled scenarios.
10. Carbon intensities are calculated at the source; that is, there is no effect of CCS or losses in transmission and distribution on the calculated values.
11. The numbering system followed in this working paper is the Indian numbering system. 1 lakh crores = 1 trillion.
12. The authors do not discuss other storage means, such as energy trading and pumped hydro storage, due to methodological constraints. The model does not distinguish between small hydro plants built to meet the base-load/energy demand and those built to meet peak load, which restricts our discussion of pumped storage. Electricity markets are outside the scope of the EPS and at present have limited participation in India.
13. As the timespan of the simulation is 30 years, we have not factored costs associated with solar panel replacement in our capital cost calculations. Additionally, most of the solar capacity additions occur after 2030, whose replacements will occur outside the modeled timespan. Costs associated with replacing the existing capacity of about 65 GW of solar power established until 2030 are assumed to be negligible.
14. Because the capacity utilization factor of coal is higher than that of VRE technologies.
15. Research suggests that several inefficient coal plants in India can be retired purely on economic grounds (Shrimali 2020).

REFERENCES

Abhyankar, N., P. Mohanty, S.M. Deorah, N. Karali, U. Paliwal, J. Kersey, and A.A. Phadke. 2023. *Pathways to Atmanirbhar Bharat: Harnessing India's Renewable Edge for Cost-Effective Energy Independence by 2047.* Berkeley, California, United States: Lawrence Berkeley National Laboratory. https://emp.lbl.gov/publications/pathways-atmanirbhar-bharat.

Ameli, N., O. Dessens, M. Winning, J. Cronin, H. Chenet, P. Drummond, A. Calzadilla, G. Anandarajah, and M. Grubb. 2021. "Higher Cost of Finance Exacerbates a Climate Investment Trap in Developing Economies." *Nature Communications* 12 (1): 1–12. https://doi.org/10.1038/s41467-021-24305-3.

Bhati, P., and S. Ramanathan. 2017. *Using the National Clean Energy Fund to Clean Coal Power Plants.* New Delhi: Centre for Science and Environment. https://www.cseindia.org/policy-brief-using-the-national-clean-energy-fund-to-clean-coal-power-plants-6990.

CAG (Comptroller and Auditor General of India). 2022. "Chapter 7 – Air Pollution due to Thermal Power Plants." In *Audit Report: Air Pollution Control by Government of Gujarat.* New Delhi: CAG. https://cag.gov.in/uploads/icisa_it_reports/Performance-Audit-of-Air-Pollution-Control-by-GoG-Report-No-02-of-2022-0632d8a52067c30-27727299-0664c5f19bab841-29782211.pdf.

Carbon Independent. 2023. "Emissions from Home Energy Use." Carbonindependent.org. https://www.carbonindependent.org/15.html.

Chaturvedi, V., and A. Malyan. 2021. "Implications of a Net-Zero Target for India's Sectoral Energy Transition and Climate Policy." New Delhi: CEEW (Council on Energy, Environment and Water). https://www.ceew.in/publications/implications-of-net-zero-target-for-indias-sectoral-energy-transitions-and-climate-policy.

CEA (Central Electricity Authority). 2010. "Indian Electricity Grid Code." https://cercind.gov.in/Regulations/Signed-IEGC.pdf.

CEA. 2016a. *20-Year (2016-2036) Perspective Transmission Plan Report.* New Delhi: CEA. https://cea.nic.in/old/reports/others/ps/pspa2/ptp.pdf.

CEA. 2016b. "All India Installed Capacity (in MW) of Power Stations - March 2016." https://cea.nic.in/wp-content/uploads/2020/02/installed_capacity-03-1.pdf.

CEA. 2017. "All India Installed Capacity (in MW) of Power Stations." https://cea.nic.in/wp-content/uploads/2020/02/installed_capacity-03-2.pdf.

CEA. 2018. *National Electricity Plan, Volume 1: Generation 2018.* Five-year report. New Delhi: CEA. https://cea.nic.in/wp-content/uploads/2020/04/nep_jan_2018.pdf.

CEA. 2020. *Growth of Electricity Sector in India from 1947-2020.* New Delhi: CEA. https://cea.nic.in/wp-content/uploads/pdm/2020/12/growth_2020.pdf.

CEA. 2022a. "All India Installed Capacity (in MW) of Power Stations." https://cea.nic.in/wp-content/uploads/installed/2022/03/installed_capacity.pdf.

CEA. 2022b. *CEA Annual Report 2021-22.* New Delhi: CEA. https://cea.nic.in/wp-content/uploads/annual_reports/2022/AR_2021_22_dated_03.11.2022.pdf.

CEA. 2022c. "CO_2 Baseline Database for the Indian Power Sector." Version 18.0. User Guide. https://cea.nic.in/wp-content/uploads/baseline/2023/01/Approved_report_emission__2021_22.pdf.

CEA. 2022d. *Indian Technology Catalogue: Generation and Storage of Electricity.* New Delhi: CEA. https://cea.nic.in/wp-content/uploads/irp/2022/02/First_Indian_Technology_Catalogue_Generation_and_Storage_of_Electricity-2.pdf.

CEA. 2023a. *All India Electricity Statistics – General Review 2023.* New Delhi: CEA. https://cea.nic.in/wp-content/uploads/general/2022/GR_Final.pdf.

CEA. 2023b. *National Electricity Plan, Volume 1: Generation.* New Delhi: CEA. https://cea.nic.in/wp-content/uploads/notification/2023/06/NEP_2022_32_FINAL_GAZETTE_English.pdf.

CEA. 2023c. *Report on Optimal Generation Capacity Mix for 2029-30 v2.0.* New Delhi: CEA. https://cea.nic.in/wp-content/uploads/notification/2023/05/Optimal_mix_report__2029_30_Version_2.0__For_Uploading.pdf.

CEA. 2023d. "All India Installed Capacity (in MW) of Power Stations – March." https://cea.nic.in/wp-content/uploads/installed/2023/03/IC_March_2023.pdf.

CEA and DEA (Danish Energy Agency). 2022. *Indian Technology Catalogue: Generation and Storage of Electricity.* New Delhi: CEA and København, Denmark: DEA. https://cea.nic.in/wp-content/uploads/irp/2022/02/First_Indian_Technology_Catalogue_Generation_and_Storage_of_Electricity-2.pdf.

Climate Trends. 2021. "Owners of 50% of India's Energy Fleet Committed to No New Coal Power Generation," April 21. https://climatetrends.in/wp-content/uploads/2021/04/India-no-new-coal-FINAL.pdf.

Durga, S., M. Evans, L. Clarke, and R. Banerjee. 2022. "Developing New Pathways for Energy and Environmental Decision-Making in India: A Review." *Environmental Research Letters* 17 (6): 063004. https://doi.org/10.1088/1748-9326/ac6f13.

Ferroukhi, R., D. Nagpal, V. Ommer, C. Garcia-Banos, T. Luo, D. Krishnan, and A. Thanikonda. 2018. "Water Use in India's Power Generation: Impact of Renewables and Improved Cooling Technologies." WRI and IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENAIndiapowerwater2018pdf.pdf.

Fuller, R., P.J. Landrigan, K. Balakrishnan, G. Bathan, S. Bose-O'Reilly, M. Brauer, J. Caravanos, et al. 2022. "Pollution and Health: A Progress Update." *The Lancet Planetary Health* 6 (6): e535–47. https://doi.org/10.1016/S2542-5196(22)00090-0.

Gagal, V. 2022. "Challenges in Land Acquisition for Solar Projects." *pv magazine India.* March 30. https://www.pv-magazine-india.com/2022/03/30/challenges-in-land-acquisition-for-solar-projects/.

Garg, V., I. Gerasimchuk, C. Beaton, K.R. Bandyopadhyay, S. Whitley, L. Worrall, A. Scott, et al. 2017. *India's Energy Transition: Mapping Subsidies to Fossil Fuels and Clean Energy in India.* Manitoba, Canada: IISD (International Institute for Sustainable Development). https://www.iisd.org/system/files/publications/india-energy-transition.pdf.

Gross, S. 2020. *Renewables, Land Use, and Local Opposition in the United States.* Washington, DC: The Brookings Institution. https://www.brookings.edu/wp-content/uploads/2020/01/FP_20200113_renewables_land_use_local_opposition_gross.pdf#:~:text=Wind%20and%20solar%20generation%20require%20at%20least%2010,disturbed%20to%20produce%20and%20transport%20the%20fossil%20fuels.

Guttikunda, S.K., and P. Jawahar. 2014. "Atmospheric Emissions and Pollution from the Coal-Fired Thermal Power Plants in India." *Atmospheric Environment* 92 (August): 449–60. https://doi.org/10.1016/j.atmosenv.2014.04.057.

IEA (International Energy Agency). 2021a. "Carbon Intensity of Electricity Generation in Selected Countries and Regions, 2000-2020 – Charts – Data & Statistics." IEA. October 28. https://www.iea.org/data-and-statistics/charts/carbon-intensity-of-electricity-generation-in-selected-countries-and-regions-2000-2020.

IEA. 2021b. *India Energy Outlook 2021*. Paris: IEA. https://doi.org/10.1787/ec2fd78d-en.

IISD (International Institute for Sustainable Development). 2018. "The Evolution of the Clean Energy Cess on Coal Production in India." https://www.iisd.org/system/files/publications/stories-g20-india-en.pdf.

JGCRI (Joint Global Change Research Institute). 2023. "The Global Change Analysis Model." Pacific Northwest National Lab, University of Maryland. https://jgcri.github.io/gcam-doc/v5.3/overview.html.

Kulkarni, T., A. Hingne, V. Agarwal, and J.C. Altamirano. 2022. "Sustainable Development Impacts of Renewable Power: Insights from Three Indian States." Working Paper. World Resources Institute. https://doi.org/10.46830/wriwp.20.00109.

Luo, T., D. Krishnan, and S. Sen. 2018. "Parched Power: Water Demands, Risks, and Opportunities for India's Power Sector." Working Paper. World Resources Institute. https://files.wri.org/d8/s3fs-public/parched-power-india-0130.pdf.

MoC (Ministry of Coal). 2022a. "Coal Production and Offtake Data (Last 10 Years)." https://coal.gov.in/sites/default/files/2021-01/productiondata_tenyear.pdf.

MoC. 2022b. "Coal Reserves." Ministry of Coal. https://coal.nic.in/en/major-statistics/coal-reserves.

MoC. 2023. "Coal and Lignite Production." *In Annual Report 2022-23.* New Delhi: Ministry of Coal. https://coal.gov.in/sites/default/files/2023-03/chap9AnnualReport2023en.pdf.

MoEFCC (Ministry of Environment, Forest and Climate Change). 2022. *India's Long-Term Low-Carbon Development Strategy: Submission to the United Nations Framework Convention on Climate Change.* New Delhi: MoEFCC. https://unfccc.int/sites/default/files/resource/India_LTLEDS.pdf.

MoP (Ministry of Power). 2023a. "Power Sector at a Glance All India," June 12. Ministry of Power. https://powermin.gov.in/en/content/power-sector-glance-all-india.

MoP. 2023b. "Generation Overview," June 22. Ministry of Power. https://powermin.gov.in/en/content/overview.

MoP. 2022. "Renewable Purchase Obligation and Energy Storage Obligation Trajectory till 2029-30," July 22. Order. https://powermin.gov.in/sites/default/files/Renewable_Purchase_Obligation_and_Energy_Storage_Obligation_Trajectory_till_2029_30.pdf.

MNRE (Ministry of New and Renewable Energy). 2023. "National Portal for Renewable Purchase Obligation." Ministry of New and Renewable Energy. https://rpo.gov.in/Home/Objective.

NITI Aayog. 2022. "Report of the Expert Group on 175 GW RE by 2022." NITI Aayog Library. https://library.niti.gov.in/cgi-bin/koha/opac-detail.pl?biblionumber=89110.

NITI Aayog. 2023. "India Energy Security Scenarios, 2047." *New Delhi: NITI Aayog*, 2047. http://iess2047.gov.in:80.

Pachouri, R., and A.K. Saxena. 2020. *Emissions Control in Thermal Power Stations: Issues, Challenges and the Way Forward.* New Delhi: TERI (The Energy and Resources Institute). https://www.teriin.org/sites/default/files/2020-02/emissions-control-thermal-power.pdf.

Pai, S. 2021. "Fossil Fuel Phase Outs to Meet Global Climate Targets: Investigating the Spatial and Temporal Dimensions of Just Transitions." Thesis. University of British Columbia. https://open.library.ubc.ca/collections/ubctheses/24/items/1.0398719.

Parikh, K., A. Das, V. Saini, J. Parikh, and P. Ghosh. 2021. *Assessing Potential Carbon Neutrality Target Years for India's Power Sector.* New Delhi: IRADe (Integrated Research and Action for Development). https://irade.org/website/wp-content/uploads/2022/11/Final-Report-Net-Zero.pdf.

Parry, I.W.H., V. Mylonas, and N. Vernon. 2017. "Reforming Energy Policy in India: Assessing the Options." International Monetary Fund (IMF) Working Paper. Washington, DC: IMF. https://www.imf.org/en/Publications/WP/Issues/2017/05/03/Reforming-Energy-Policy-in-India-Assessing-the-Options-44853.

Pavarini, C. 2019. “Battery Storage Is (Almost) Ready to Play the Flexibility Game – Analysis.” International Energy Agency (IEA). https://www.iea.org/commentaries/battery-storage-is-almost-ready-to-play-the-flexibility-game.

PIB (Press Information Bureau). 2020. “Government Constitutes High-Level Ministerial Committee for Implementation of Paris Agreement,” December 2. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1677630.

PIB. 2021a. “G20 Energy and Climate Joint Ministerial Meeting,” July 23. Press Information Bureau, India. https://www.pib.gov.in/pressreleaseiframepage.aspx?prid=1738317.

PIB. 2021b. “NDC Targets,” December 28. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1785808.

PIB. 2022. “India’s Stand at COP-26,” February 3. https://pib.gov.in/PressReleasePage.aspx?PRID=1795071.

PIB. 2024. “Cabinet Approves Viability Gap Funding (VGF) Scheme for Implementation of Offshore Wind Energy Projects,” June 19. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2026700.

Poojary, V., A. Hingne, and U. Narayan. Forthcoming. “More Power to Whom? Insights from India’s 2000 MW Pavagada Solar Park.” WRI India.

Regy, P.V., R. Sarwal, C. Stranger, G. Fitzgerald, J. Ningthoujam, A. Gupta, and N. Singh. 2021. “Turning Around the Power Distribution Sector: Learnings and Best Practices from Reforms.” https://www.niti.gov.in/sites/default/files/2021-08/Electricity-Distribution-Report_030821.pdf.

REN21. 2022. *Renewables 2022: Global Status Report.* Paris: REN21. https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Full_Report.pdf.

Rumi, A. 2000. “Bridging Water Demand and Supply in Delhi: The Potential of Rainwater Harvesting.” Observer Research Foundation. https://www.orfonline.org/research/bridging-water-demand-and-supply-in-delhi.

Schilling, M.A., and M. Esmundo. 2009. “Technology S-Curves in Renewable Energy Alternatives: Analysis and Implications for Industry and Government.” *Energy Policy* 37 (5): 1767–81. https://doi.org/10.1016/j.enpol.2009.01.004.

Shrimali, G. 2020. “Making India’s Power System Clean: Retirement of Expensive Coal Plants.” *Energy Policy* 139 (April): 111305. https://doi.org/10.1016/j.enpol.2020.111305.

Spencer, T., N. Rodrigues, R. Pachouri, S. Thakre, and G. Renjit. 2020. Renewable-Power-Pathways: *Modelling the Integration of Wind and Solar in India by 2030.* New Delhi: TERI (The Energy and Resources Institute). https://www.teriin.org/sites/default/files/2020-07/Renewable-Power-Pathways-Report.pdf.

Swamy, D., and V. Agarwal. 2023. “Macroeconomic Impacts of Long-Term Decarbonization in India: Implications for a Just Transition.” Expert Note. World Resources Institute. https://doi.org/10.46830/wrien.22.00155.

Swamy, D., A. Mitra, V. Agarwal, M. Mahajan, and R. Orvis. 2021a. “A Tool for Designing Policy Packages to Achieve India’s Climate Targets: Methods, Data, and Reference Scenario of the India Energy Policy Simulator.” Technical Note. World Resources Institute. https://www.wri.org/research/tool-designing-policy-packages-indias-climate-targets.

Swamy, D., A. Mitra, V. Agarwal, M. Mahajan, and R. Orvis. 2021b. “Pathways for Decarbonizing India’s Energy Future: Scenario Analysis Using the India Energy Policy Simulator.” Working Paper. World Resources Institute. https://www.wri.org/research/pathways-decarbonizing-indias-energy-future-scenario-analysis-using-india-energy-policy.

Tata Power-DDL. 2022. “Behavioral Demand Response.” *Tata Power Delhi Distribution Ltd.* https://www.tatapower-ddl.com/Behavioral-Demand-Response/Overview.

TNC (The Nature Conservancy). 2022. “Degraded Lands Can Aid Achieve Four Times India’s 2030 Renewable Energy Targets,” August 16. The Nature Conservancy India. https://www.tncindia.in/what-we-do/our-insights/stories-in-india/renewableenergy/.

Udetanshu, S. Khurana, and D. Nelson. 2020. *Developing a Roadmap to a Flexible, Low-carbon Indian Electricity System.* San Francisco: Climate Policy Initiative. https://www.climatepolicyinitiative.org/wp-content/uploads/2020/08/CPI-India-flexibility-25-August-2020-full-report-1.pdf.

UNFCCC (United Nations Framework Convention on Climate Change). 2022. “India’s Updated First Nationally Determined Contribution under Paris Agreement.” Submission to UNFCC. https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf.

Viswanathan, B., A. Viswamohanan, D. Narayanaswamy, A. Geddes, T.B. Sumarno, C. Beaton, S. Goel, et al. 2021. *Mapping India’s Energy Subsidies 2021: Time for Renewed Support to Clean Energy.* Manitoba, Canada: IISD (International Institute for Sustainable Development). https://www.iisd.org/publications/mapping-india-energy-subsidies-2021.

Volcovici, V. 2021. “How a Dispute over Coal Nearly Sank the Glasgow Climate Pact,” November 14. Reuters. https://www.reuters.com/business/cop/how-dispute-over-coal-nearly-sank-glasgow-climate-pact-2021-11-14/.

WB (World Bank). 2018. “Electric Power Transmission and Distribution Losses (% of Output).” World Bank Group. https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=IN.

Zalk, J. van, and P. Behrens. 2018. “The Spatial Extent of Renewable and Non-renewable Power Generation: A Review and Meta-analysis of Power Densities and Their Application in the U.S.” Energy Policy 123: 83–91. doi:https://doi.org/10.1016/j.enpol.2018.08.023.

This Page is intentionally left blank

This Page is intentionally left blank

This Page is intentionally left blank

ACKNOWLEDGMENTS

This Working Paper was produced under a grant by the International Climate Initiative (IKI) of the German Federal Government. We would like to thank WRI colleagues Alex Perera, Ashwini Hingne, Harsha Meenawat, Jennifer Chen, Karl Hausker, Manu Mathai, Neelam Singh, Stephen Naimoli, Wenyi Xi, and Ulka Kelkar, whose insights and suggestions helped improve this paper. A special thank you to our external reviewers: Megan Mahajan (Energy Innovation Policy & Technology), Purva Jain (Institute for Energy Economics and Financial Analysis), and Randika Wijekoon (National Renewable Energy Laboratory) for their valuable feedback. Finally, we would like to express our gratitude to Apoorva R, Steffi Olickal, Emily Matthews, Karthikeyan Shanmugam, Romain Warnault, Bill Dugan, Sara Steidicke, Renee Pineda, Santhosh Matthew Paul, Zebrakross, Apoorva Grover and LSF Editorial for administrative, editorial, and design support.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

Federal Foreign Office

IKI INTERNATIONAL CLIMATE INITIATIVE

on the basis of a decision by the German Bundestag

ABOUT THE AUTHORS

Varun Agarwal is a Program Manager with the Climate, Economics and Finance Program at WRI India.

Subrata Chakrabarty is an Associate Program Director with the Climate, Economics and Finance Program at WRI India.

Devadathan Biju is a Junior Program Associate with the Climate, Economics and Finance Program at WRI India.

Deepthi Swamy is a former Lead with the Climate Program at WRI India.

ABOUT WRI INDIA

WRI India, an independent charity legally registered as the India Resources Trust, provides objective information and practical proposals to foster environmentally sound and socially equitable development. Our work focuses on building sustainable and liveable cities and working towards a low carbon economy. Through research, analysis, and recommendations, WRI India puts ideas into action to build transformative solutions to protect the earth, promote livelihoods, and enhance human well-being. We are inspired by and associated with World Resources Institute (WRI), a global research organization. Know more: www.wri-india.org

Our challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to inform government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.