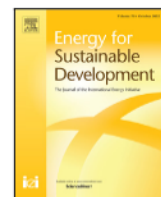




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Highlights

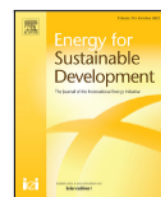
The role of coal plant retrofitting strategies in developing India's net-zero power system: A data-driven sub-national analysis

Yifu Ding ^{*}, Dharik Mallapragada, Robert James Stoner 

- Indian power system planning model incorporates coal plant retrofits through 2035.
- Machine learning approaches capture the heterogeneity of 806 Indian coal plant units.
- Technology scenarios model CCS, biomass co-firing, and renewable integration.
- High renewable integration is cost-effective but leads to uneven capacity investments.

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The role of coal plant retrofitting strategies in developing India's net-zero power system: A data-driven sub-national analysis

Yifu Ding^a,^{*}, Dharik Mallapragada^b, Robert James Stoner^a

^a MIT Energy Initiative, 50 Ames St, Cambridge, 02142, MA, United States

^b Department of Chemical and Biomolecular Engineering, Tandon School of Engineering, New York University, 726 Broadway, New York, 10003, NY, United States

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ABSTRACT

India set Nationally Determined Contribution (NDC) targets toward its net-zero carbon emission goal by 2070, which requires deep decarbonization of India's power generation sector. Yet, coal power generation contributes to more than 60% of the total, and policies still permit further coal fleet expansion and lifetime extensions. In this paper, we investigate the role of retrofitting India's coal plants for carbon capture and storage (CCS) and biomass co-firing in developing the net-zero power system. We model the power generation and transmission network expansions across 30 Indian regions in four representative technology scenarios under progressively tighter carbon emission caps, taking into account sub-national coal price variation and thermal efficiency of individual coal plants. Our analysis indicates that coal plant retrofitting with CCS could achieve gigawatt-scale deployment by 2035 if India reduces its annual carbon emissions from power generation to half of the 2021 level (i.e., 500 million tons of CO₂). Both renewable capacity expansion and coal plant retrofitting with CCS reduce the unabated coal plant capacity, electricity generation costs, and carbon abatement costs. While exploiting renewable energy potential remains the most cost-effective decarbonization strategy, it faces challenges of low coal plant utilization and the uneven geographical distribution of renewable generation investments.

Introduction

India is the third largest carbon emitter globally in 2023 and its energy demand is projected to double or triple by 2040 relative to the level of 2017 (IEA, 2021). Endeavoring to meet the global goal of holding warming well below 2 degrees relative to the pre-industrial level, India has committed to net zero carbon emissions by 2070. It also sets a 500 GW non-fossil-fuel energy generation capacity target by 2030 and plans to reduce its economy-wide emission intensity by up to 45% relative to the 2005 level as the 2030 NDC goal (Ministry of Power, Government of India, 2022).

India's existing power generation is heavily dependent on high-emission coal plants, accounting for more than half in 2021 (IEA, 2022; Metcalf, 2021). The total coal plant capacity reached 205 GW and generated more than 60% of electricity generation in 2022 (Central Electricity Authority, 2022b). The national government has not proposed comprehensive phase-out plans for coal plants to date, and is expected to allow new construction and life extensions of existing coal plants (Ministry of Power, Government of India, 2023a). The decommissioning of unabated coal plants faces socio-economic barriers related to potentially adverse employment impacts in regions with coal

plants and mines (Auger, Trüby, Balcombe, & Staffell, 2021). It also could impact the reliability of the power grid in the short-to-medium term, by reducing the amount of firm capacity even as peak electricity demand continues to grow (Ministry of Power, Government of India, 2023a; Sudarshan & Carman, 2023). These concerns have tended to slow the rate of decommissioning of old plants, especially in low-cost coal regions in the east, thereby perpetuating the carbon emission burden (Oskarsson, Nielsen, Lahiri-Dutt, & Roy, 2021).

Previous studies have assessed India's least-cost power system expansion in the near term until 2030 or 2040 (Abhyankar, Deorah, & Phadke, 2021; Central Electricity Authority, 2023b; Deshmukh, Phadke, & Callaway, 2021; Lu, Sherman, Chen, Chen, Lu, & McElroy, 2020; Rudnick et al., 2022) and long-term until 2050 or beyond (Barbar, Mallapragada, & Stoner, 2023; Rose, Chernyakhovskiy, Palchak, Koebrich, & Joshi, 2020). These studies mainly focus on the role of energy storage, renewable generation, and transmission capacity for carbon emission reductions. All these studies show coal plants will remain a dominant source of energy and reserve through 2030 if no carbon emission and renewable generation constraints are imposed,

^{*} Corresponding author.

E-mail address: yifuding@mit.edu (Y. Ding).

and grid-connected energy storage will start reaching the gigawatts-scale level between 2030 and 2040. (Barbar et al., 2023) investigate the impact of increasing electricity demand on the evolution of power systems from 2020 to 2050 based on a five-zone India power system. They conclude that deep decarbonization of India's power sector will require policy measures targeting the existing coal fleet and accelerating renewable deployment and demand-side reduction. Rose et al. (2020) show that batteries and supercritical coal plants play a crucial role in India's renewable generation integration. A great capacity of supercritical coal plants will be built in the east, which could account for over 90% of the total carbon emissions by 2047. Lu et al. (2020) model India's power generation mix to achieve 80% of renewable penetration by 2040. Such a system requires significant investment in energy storage and network expansion, even while a 200 GW coal plant fleet is retained. Abhyankar et al. (2021) highlight that India's coal consumption for power generation in 2030 will be comparable to coal consumption in 2020, and most coal mining and supply chain jobs will be preserved through 2030.

Another research focus of the prior studies on India's power sector evolution is the role of effective carbon policies and renewable energy targets to decarbonize India's power system. Deshmukh et al. (2021) model India's power system expansion in 2030 under varying renewable generation targets between 200 to 600 GW, with renewable projects selected based on their levelized electricity generation costs. They conclude that achieving high renewable energy targets will not avert the need to build coal plants. The avoided fossil fuel capacity and carbon abatement cost also change greatly with different shares of wind, solar, and renewable resource quality. Rudnick et al. (2022) use a five-zone India's power system model to optimize the power system planning in 2040 under tradable CO₂ emission limits and renewable portfolio standards. Their results show that the tradable CO₂ emission limits result in a lower average CO₂ abatement cost than is achieved under a renewable portfolio standard.

All these studies highlighted the importance of coal power generation in India's power system through 2030, but have not considered the impacts of coal plant retrofits for decarbonization. Retrofitting fossil-fuel power plants to reduce their emissions intensity can enable them to serve the role of firm, low-carbon resources in a future variable renewable energy dominant power grid (Fan et al., 2023; Sepulveda, Jenkins, De Sisternes, & Lester, 2018). Coal plants can be retrofitted in several ways to reduce their carbon intensity, such as by adding CCS or via fuel-switching strategies involving the use of biofuels or carbon-free fuels such as ammonia and hydrogen. Coal plant sites and their existing grid connections could be repurposed for renewable energy generation or converted into synchronous condensers to provide ancillary services. However, these redevelopment strategies eliminate coal power capacity, which could lead to energy security challenges in the short-term (Shrimali & Jindal, 2021). Each coal retrofitting approach has different investment requirements within the plant boundary and distinct supply chain infrastructure needs. For example, CCS retrofits will reduce plant emissions of CO₂ and air pollutants (SO_x, NO_x) but come with substantial capital investment and energy penalties, along with requiring access to CO₂ storage reservoirs. By some estimates, India has abundant carbon storage capacity across the nation (Vishal, Chandra, Singh, & Verma, 2021), with an estimated carbon reduction potential of approximately 715 million tonnes per year through CCS (Lau, 2023).

Using biomass or green ammonia to co-fire with coal to reduce carbon emissions appears technically feasible (Cesaro, Ives, Nayak-Luke, Mason, & Bañares-Alcántara, 2021; Fan et al., 2023), but has substantial cost and supply chain-related constraints. For example, the relatively high cost of green ammonia, estimated as over \$15/MMBtu (Deng et al., 2024), could make its use for power generation challenging in the Indian context. The availability of biomass stock and the extent of co-firing are key constraints limiting wide-scale adoption. Here, we focus on biomass co-firing in light of its favorable present-day economics compared to co-firing with low-carbon ammonia. Biomass

co-firing involves low capital investment costs with only modest plant modification needed for a low mixture of less than 20% biomass (Zhang et al., 2022). India also already mandated part of coal plants to conduct the co-firing of biomass pellets with a minimum of 5% fuel mix percentage (Ministry of Power, Government of India, 2023c).

Globally, there have been a number of pilots and a few commercial projects related to CCS deployments at power plants, firstly on combined power and heat generation units, in many countries including China, U.S., and Japan (Global CCS Institute, 2023). Moreover, CCS deployment in power generation is central to decarbonization plans for regions with large existing coal capacity. For example, Fan et al. (2023) highlight the role for CCS retrofits of coal power plants in 2030 as part of China's plans for decarbonization by mid-century. Other studies evaluating decarbonization plans for India also highlight the role of CCS in the power sector in the coming decades (Amit, Omkar, Saritha, Tirthankar, Udayan, & Vidhee, 2024). A report (Mukherjee & Chatterjee, 2024) published by the Indian government's think tank, NITI Aayog, analyses that compared to some industrial processes such as gasification-based products, carbon capture costs for coal-based power plants are higher due to the lower concentration of CO₂ in their flue gas streams. Nevertheless, given the significant contribution of coal power generation to overall emissions, implementing CCS projects on coal power plants is crucial for CCS to have a meaningful impact on India's decarbonization efforts. One approach to incentivize carbon capture is carbon utilization. During the carbon capture utilization and storage (CCUS) process, the captured CO₂ can enhance gas or oil production, especially in offshore fields (Lau, 2023), or produce synthetic fuels and building materials as components (Mukherjee & Chatterjee, 2024). However, the latter may involve high investment costs for the supply chain and could generate more carbon emissions during the upstream process (e.g., electricity consumption). Additionally, carbon utilization processes may release CO₂ back into the atmosphere. Although utilization could potentially increase profits, this process compromises carbon emission constraints (McLaughlin et al., 2023).

A number of supportive policy measures aimed at reducing carbon emissions and air pollutants from coal power generation have been proposed in India. These include energy efficiency standards for heavy industry, along with a modest tax on coal-based electricity generation (International Institute for Sustainable Development, 2020). The country has also proposed renewable purchase obligations in 2022 (Central Electricity Authority, 2023c) and generation obligations in 2023 (Central Electricity Authority, 2023a). In terms of coal plant emission regulations, Indian coal plants have been ordered to install flue gas desulfurisation units (U.S. International Trade Administration, 2020), but the implementations are far below expectations to date and vary across regions.

Despite the vast difference in coal power plant operating characteristics (Ganesan & Narayanaswamy, 2021), most studies on Indian power system evolution tend to ignore or only modestly account for the heterogeneity in the coal fleet (Abhyankar et al., 2021; Central Electricity Authority, 2023b; Deshmukh et al., 2021; Lu et al., 2020; Rose et al., 2020; Rudnick et al., 2022). With a granular, state-wise power system dispatch model using the empirically derived thermal efficiency curve for coal plants, Sengupta et al. (2022) showed that a substantial national carbon tax would disproportionately increase the cost to the poorer, coal-heavy eastern states. Indian coal plant emission intensity has a wide distribution due to the wide range in the thermal efficiency driven by the heterogeneity of the coal fleet (Mallapragada, Naik, Ganesan, Banerjee, & Laurenzi, 2019), indicating the replacement of subcritical coal plants with high-efficiency supercritical coal power plants and early decommissioning (Maamoun et al., 2022). To the best of our knowledge, no studies have addressed the heterogeneity within the coal fleet when analyzing coal retrofits and early decommissioning in the Indian context, even though the power capacity and thermal efficiency impact the retrofit solution and operation processes.

Here, we undertake a geographically granular analysis of the power sector that considers individual coal plant operating characteristics and retrofit opportunities. Our research uses a power system capacity expansion model (CEM) to investigate the role of coal plant retrofitting strategies in India's power system under various technology and policy scenarios. We develop a 30-region data set for the Indian power system with a reduced representation of inter-state and inter-region transmission and use it with the CEM to study the role of two coal plant retrofitting technologies, CCS and biomass co-firing.

To precisely model sub-national coal plant retrofitting strategies, we leverage a comprehensive coal plant dataset and machine learning clustering techniques to characterize heterogeneous unit-level features of the entire Indian coal fleet. This paper aims to answer several questions: *What is the value of coal plant retrofitting in decarbonizing Indian power system? What are the sub-national impacts of coal plant retrofitting strategies under various technology and policy scenarios and given heterogeneous characteristics of the coal fleet? How does the value of these strategies change under different technology and policy scenarios, such as under different renewable capacity limits and transmission network expansion?*

Methods

Capturing heterogeneous characteristics of coal plant units using machine learning clustering

We model India's coal fleet as 806 coal-fired power units from our prior work (Ding, Wong, et al., 2024). The total coal power capacity is 226 GW, comprising 157 GW from 704 subcritical units and 69 GW from 102 supercritical units as recorded in Global Energy Monitor (2024). The station heat rate (SHR) represents the thermal efficiency of a power plant, which is defined as the ratio of the heat input to a power plant to the electricity generated by this plant. However, SHR performance information is not available for all 806 units. Therefore, we used the operating data for 194 GW of coal plants (541 coal plant power units) in 2020 (Ganesan & Narayanaswamy, 2021) to predict the operating SHR of the entire coal fleet at the unit level, specific to two boiler designs, subcritical and supercritical units.

Predictions indicate that subcritical coal plants will have SHR values ranging from 10.32 to 14.96 MMBtu/MWh (Fig. 1(a)), while supercritical coal plants will range from 9.85 to 11.77 MMBtu/MWh (Fig. 1(b)). The SHR distribution among subcritical coal plants is notably wider compared to supercritical plants, with many subcritical plants exhibiting very high SHR values, indicating lower thermal efficiency.

To facilitate the computationally tractable evaluation of coal fleet evolution via the CEM, we grouped the 704 subcritical coal plants into three clusters based on their SHRs and power capacity using the k-means clustering algorithm, as depicted in Fig. 1(c). Subsequently, we inferred the power capacity of coal plants within each cluster for 30 regions in India. The rest of the 102 supercritical coal plant units were grouped directly by regions, and the representative SHR values are the capacity-weighted average values of each state, as presented in Fig. 3.

We also model spatial heterogeneity in delivered coal prices as per data in Ganesan and Narayanaswamy (2021), as shown in Fig. 1 (d). The coal price ranges from \$1.59/MMBtu to \$3.90/MMBtu, significantly lower than the imported liquefied natural gas price (LNG) in India around \$15/MMBtu in 2022 (India Gas Exchange, 2023). The eastern region has a much lower coal price than the rest of the country since most coal mines are located in these regions; therefore, coal from these regions incurs lower transportation costs.

Capacity expansion considering coal plant retrofitting

The 30-region Indian power system planning model

We built a 30-region India's power system planning model using the open-source CEM, GenX (MIT Energy Initiative and Princeton University ZERO lab, 2024), to co-optimize investment and operation in generation, storage, and transmission systems. This model is a single-stage simulation specifically for the year 2035. As presented in Fig. 2, a brownfield optimization is conducted based on the existing power generation capacity in 2020 to evaluate cost-optimal investments by 2035. We account for power system operation constraints through modeling operations at over seven representative weeks at an hourly resolution. The representative weeks are selected through applying clustering over hourly renewable and projected electricity demand profiles for 2035 (Barbar, Mallapragada, Alsup, & Stoner, 2021), and capture summer and autumn peaks (SI, Section B, Fig. B.2). The 2035 demand scenario accounts for economic-development-driven demand and electricity demand resulting from air conditioning adoption in the building sector (Barbar et al., 2021). To benchmark our models operational performance, we evaluated the model predicted generation shares for each technology to meet the electricity demand in 2020, including coal and non-fossil-fuel power technologies, and the 2020 actual energy generation mix reported by MERIT India (The Centre for Social and Economic Progress, 2023). These results are similar for the model results and actual generation mix, at 74.43% versus 71.73% for coal power generation, 10.28% versus 10.49% for hydropower generations, 3.67% and 2.81% for nuclear power generation, 4.9% versus 4.0% for solar generation, and 6.47% versus 4.4% for onshore wind generation. The detailed breakdown is presented in (SI, Section B, Fig. B.8). A discrepancy is observed in natural gas power generation, as the model used the imported LNG market price of \$15/MMBtu, higher than domestic Indian natural gas prices for power generation around \$7/MMBtu (FertiliserIndia.com, 2024; India Gas Exchange, 2023).

Table 1 summarizes the main data sources. The CEM incorporates renewable energy resources, thermal power plants, and energy storage, all grouped in 30 regions. Renewable energy resources include utility-scale solar PV, hydropower stations, and onshore and offshore wind farms. Thermal power plants include natural gas, subcritical and supercritical coal, biomass, and nuclear power plants. We model thermal power plant operations with linearized unit commitment considering start-up costs and ramping constraints, although we do not differentiate between cold and hot starts depending on different coal power plant operation conditions. The investment costs of power generation capacity and their technical assumptions are based on assumptions in (Central Electricity Authority, 2022b) for India's resource planning. We assume that biomass power plants' capacity will not expand, given its relatively low thermal efficiency as compared to coal. Instead, we consider using biomass co-firing in existing coal power plants. The investments in hydropower and nuclear stations are fixed as per government plans (Central Electricity Authority, 2022b).

Our model includes the existing inter-state AC transmission capacity and inter-regional high-voltage DC (HVDC) transmission lines, as presented in SI, Section B, Fig. B.7. We consider the expansion of inter-state power flows and AC transmission capacity expansion but do not allow for investment in new transmission connections or expanding fixed inter-regional HVDC lines. The relevant data are provided in SI, Section B.

Options for early decommission and retirement of Indian coal plants

The Indian government does not currently mandate coal plant retirements before 2030 (Ministry of Power, Government of India, 2023a). We therefore assume that there are no age-based coal plant retirements. Apart from this, the model considers new investments in supercritical coal plants and three options for retiring or retrofitting existing coal plants: (1) economic retirement — early decommissioning due to economic considerations (i.e., high fuel and carbon prices); (2)

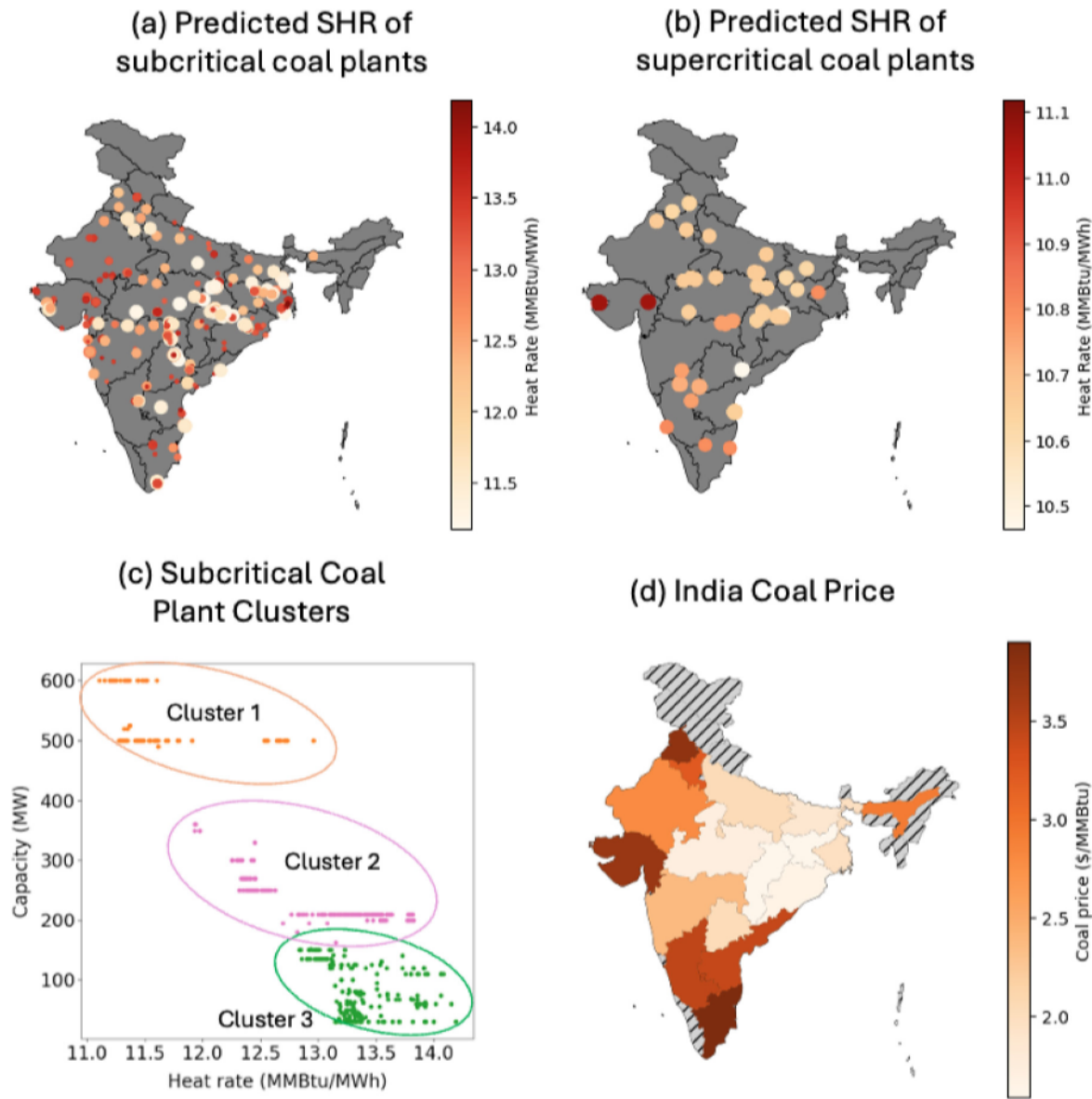


Fig. 1. Spatially resolved characteristics of Indian coal plants considered in the study: (a) the estimated SHR of subcritical coal plants, (b) the estimated SHR of supercritical coal plants, (c) Subcritical coal plant clusters, and (d) Spatial distribution in delivered coal price for each state. The diagonally striped areas show the states that have no coal plants as of 2020. All costs are based on the currency rate of 1 dollar to 84.85 INR unless specified otherwise. SHR = Station Heat Rate.

retrofitting coal power plants with CCS technology through additional investments (SI, Section C, Table C.2); (3) retrofitting to biomass co-firing power plants through additional investments (SI, Section C, Table C.4).

Since India has yet to implement the coal plants equipped with the CCS, we estimate the investment cost of adding CCS to an existing coal power plant based on the case in China (Fan et al., 2023), and then apply a high technological optimism factor of 1.25, which reflects the demonstrated tendency to underestimate actual costs for a first-of-a-kind unit in a country or region (US EIA, 2024). This results in an overnight investment cost of CCS retrofitting for supercritical coal plants of around 0.74 million per MW (SI, Section C, Table C.3). We do not consider CCUS on coal power plants primarily because certain carbon utilization, such as enhanced oil fields, may release the captured CO₂ into the atmosphere, undermining the carbon emission reduction goal (McLaughlin et al., 2023).

CCS retrofits are only considered for supercritical coal plants with a power capacity larger than 500 MW_e (Lau, 2023), and therefore 69 GW

of existing supercritical coal plants is considered for the CCS deployment by 2035. We exclude newly built supercritical CCS plants from consideration, as India's preference for constructing ultra-supercritical coal plants or new subcritical coal plants with CCS remains uncertain due to social acceptance and falls beyond the scope of this research. The decrease in power capacity and the increase in fuel consumption caused by the carbon capture process are represented using penalty factors for power capacity and thermal efficiency (SI, Section C, Table C.1). That is, following retrofitting, the adjusted power capacity and SHR are determined by scaling the original values based on these penalty factors. Fig. 3 shows the comparison of (a) the original capacity-weighted SHR values of supercritical units and (b) estimated SHR values of retrofitted supercritical CCS units based on the SHR penalty factor. We estimated the incurred CO₂ transportation and storage cost in each state, which we represent as an additional fuel cost, ranging from \$0.8 - \$2.4/MMBtu (SI, Section C, Fig. C.5). The detailed mathematical formulations of retrofitting modules are presented in Appendix A.

We allow the maximum of 20% biomass co-firing for all coal power units on the energy basis, which means that 20% of the heat input

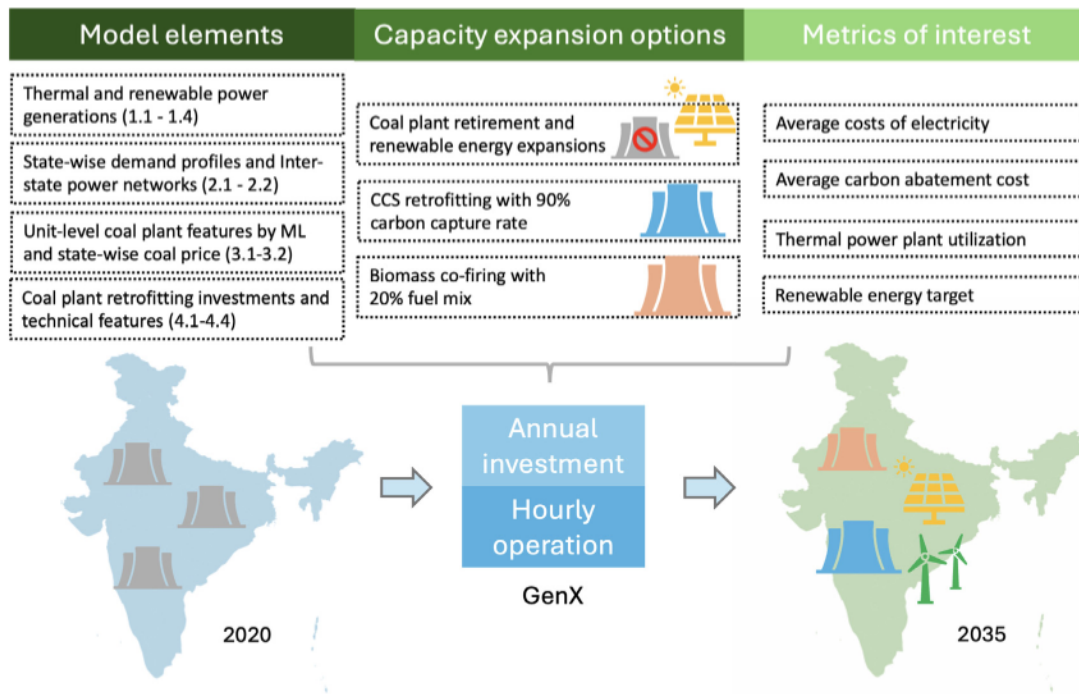


Fig. 2. Model framework including model elements, capacity expansion options, and metrics of interests to examine the role of coal plant retrofitting strategies in achieving India's NDC targets; The number in brackets of the model elements refer to the data sources in Table 1.

energy from coal is replaced by the biomass fuel. We assume the thermal efficiency to be unchanged after retrofitting. In other words, there is zero thermal efficiency and power capacity penalty factor. We set the maximum power capacity limits for the planned biomass co-firing coal plants of each state as the biomass power generation potentials published in Ministry of new and renewable energy (2023) (SI, Section C, Fig. C.6). We use the same biomass feedstock price for all plants, irrespective of their location. Since the co-firing ratio is low, the biomass cost variation has a lesser impact on coal retrofitting decisions than coal price fluctuations. Additionally, biomass costs are highly dependent on local conditions involving high uncertainty that we could not resolve with available datasets. Instead, we perform a sensitivity analysis based on biomass fuel prices, which is discussed in detail in later sections (SI, Section D, Figs. D.4 and D.5).

Renewable generation expansion and coal plant retrofitting scenarios for India's grid decarbonization evolutions

Four technology scenarios for the least-cost power system expansion are evaluated under four different carbon emissions policies, as highlighted in Fig. 4. The carbon intensity of India's power generation in 2005 was approximately 901.7 kg CO₂/MWh (Shearer, Fofrich, & Davis, 2017). We assume a 45% reduction of carbon intensity in the power generation sector in line with NDC targets, and this gives a carbon intensity of 495.9 kg CO₂/MWh and a total carbon emission of power generation of around 1130 Mt CO₂ in 2030, in alignment with estimations in Central Electricity Authority (2023b). The Indian government estimated that this carbon emission will peak from 2035 to 2040 (Amit et al., 2024). We set a 1000 Mt carbon cap scenario to meet the NDC targets, and the 800 and 500 Mt CO₂ cap scenarios represent two more ambitious carbon reduction targets.

Fig. 4 illustrates that the baseline and high renewable capacity scenarios focus on renewable energy capacity expansion for decarbonization. While the renewable energy potentials are decided by resource quality and land use (NREL, 2023b; Von Krauland & Jacobson, 2024), we set 171 GW and 443 GW as the maximum power capacity limits for the onshore wind and solar PV respectively for the baseline.

These limits are based on India's renewable generation targets (Global Energy Wind Council, 2022). The baseline scenario also assumes that India will build at least 5 GW of offshore wind farms in the next ten years (Ministry of Power, Government of India, 2017) with further expansion allowed if deemed economical. To explore the impacts of renewable energy potentials, we create the high renewable capacity scenario with an unlimited solar and wind supply chain, which means there is no limitation on the total onshore wind and solar PV capacity installed. The high renewable capacity scenario also has a more ambitious target to construct at least 30 GW offshore wind capacity by 2035.

Two other coal plant retrofitting scenarios explore another dimension of decarbonizing India's power system. India has yet to equip any coal plant with the CCS, and construction of the CCS facility is uncertain due to the high capital cost and social acceptance. We consider two coal plant retrofitting scenarios with and without the CCS infrastructure. The 'CCS & Biomass co-firing' allows for the option to retrofit supercritical coal plants with CCS and the option that any coal plant can be retrofitted into biomass co-firing power plants with a 20% biomass fuel mix. In contrast, the 'biomass co-firing only' scenario does not allow CCS coal plant retrofitting.

Results

Capacity expansion and power generation outcomes

Fig. 5 shows the projected power generation and transmission capacity by 2035 in four scenarios, under the unconstrained (no cap), 500, 1000 Mt CO₂ emissions constraint scenarios, respectively. Results under 800 Mt CO₂ emissions constraint are presented in SI, Section D, Fig. D.1. Under the baseline scenario without a carbon cap, renewables dominate new capacity additions with onshore wind expanded up to its maximum allowable value of 171 GW, implying that more deployment would be economical. We also see the deployment of 43 GW of new coal capacity in this scenario. Increasing stringency of CO₂ emissions constraints under the baseline technology scenario also drives up renewable generation capacity deployment and also investment in

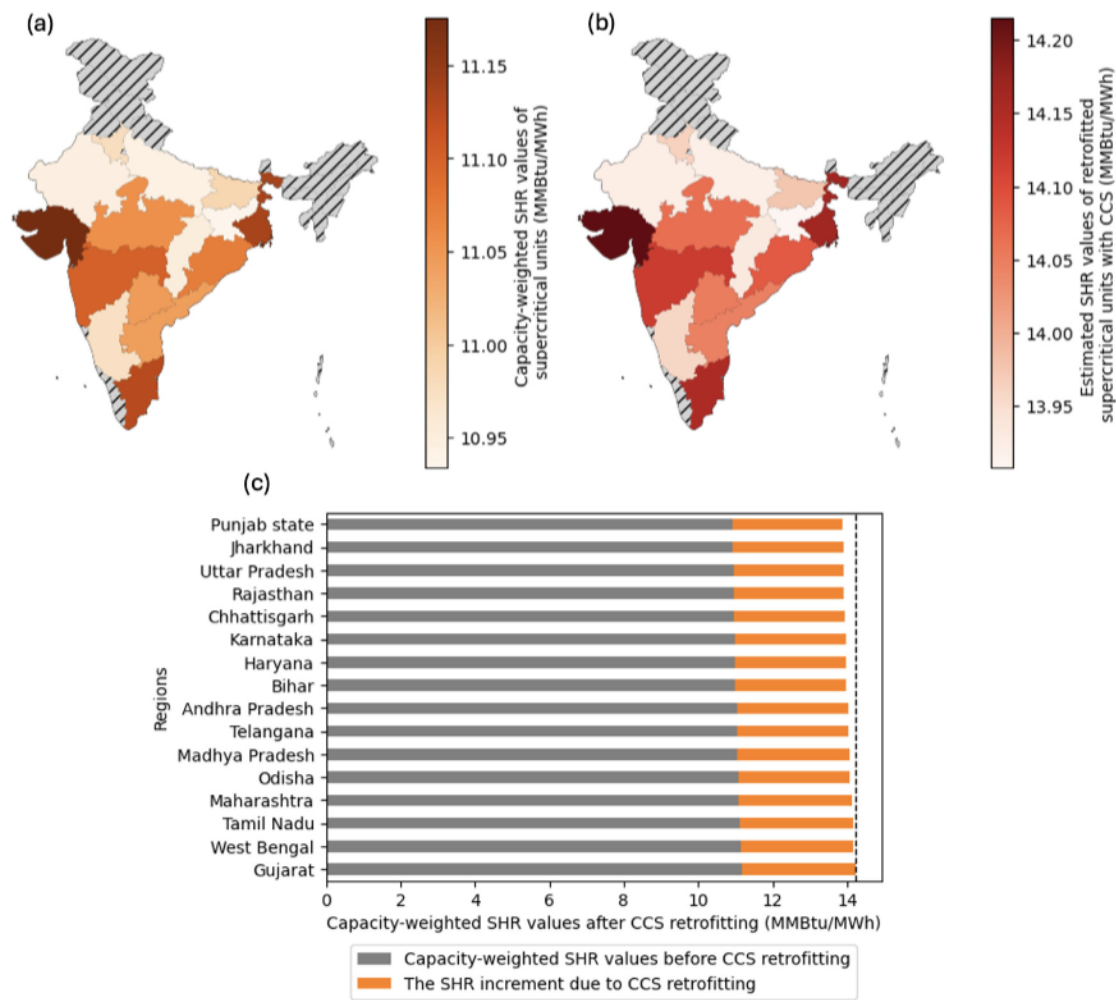


Fig. 3. Comparisons of (a) capacity-weighted SHR values for supercritical units (MMBtu/MWh), (b) estimated SHR values for supercritical units retrofitted with CCS (MMBtu/MWh), and (c) ranked capacity-weighted SHR values by region after CCS retrofitting (MMBtu/MWh).

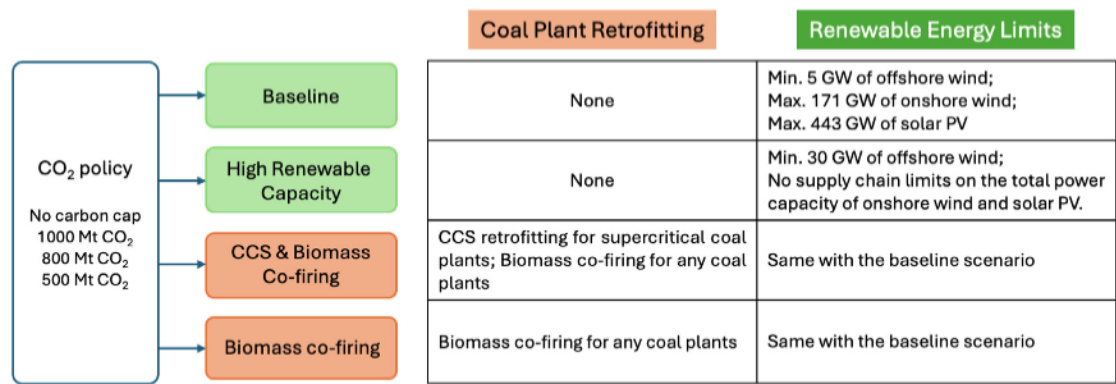


Fig. 4. Scenarios with different technology and emissions constraints evaluated in this study. Technology scenarios differ in their assumptions about available coal power plant retrofit options and renewable energy expansion limits. Unless otherwise stated, network expansion is allowed in all scenarios.

natural gas generators, batteries, and transmission expansion. Notably, solar and wind capacity installation is limited by the supply chain restriction in the baseline scenario, with an annual CO₂ emissions cap of 500 Mt.

In the high renewable capacity scenario without a carbon cap, the total non-fossil-fuel generation capacity (including solar PV, onshore wind, offshore wind, hydro power stations, and biomass power plants) reaches 403 GW as compared to 348 GW in the baseline scenario. The installed non-fossil fuel generation capacity exceeds the national target

of 500 GW when a moderate annual carbon cap of 1000 Mt CO₂ is enforced. Here, we note that the planned onshore wind capacity is far less than the actual wind power potentials published by [Central Electricity Authority \(2022b\)](#) (i.e., 302 GW at the height of 100 meters and 695.5 GW at 120 m).

Early coal plant retirement and retrofitting are only observed under scenarios when annual carbon emissions are constrained below 1000 Mt CO₂. Subcritical coal plants are favored for retirement when the carbon cap is 1000 Mt CO₂ and completely decommissioned when the

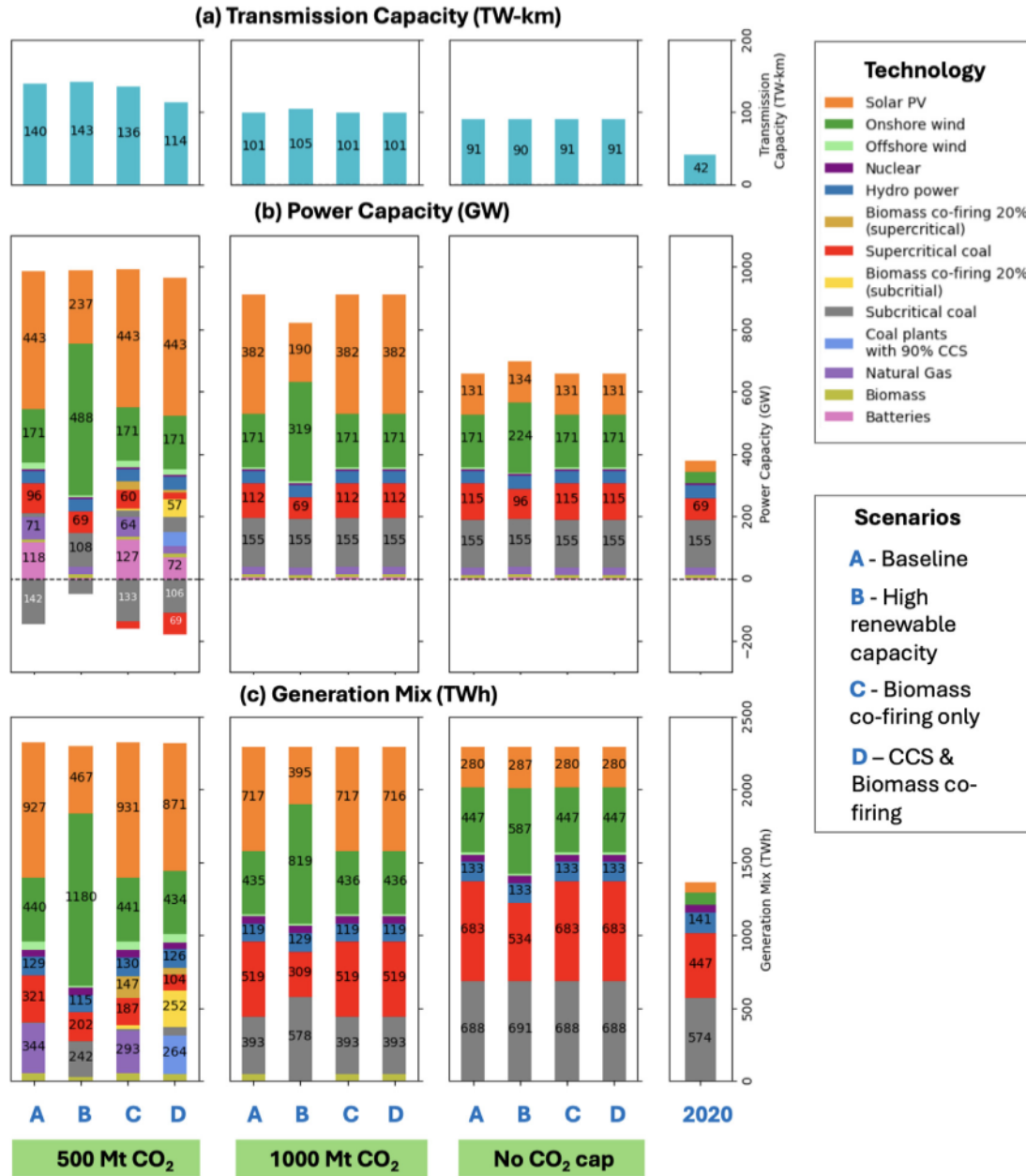


Fig. 5. (a) Transmission capacity, (b) power capacity, and (c) generation mix by 2035 under three CO₂ cap scenarios: 500 Mt, 1000 Mt, and no cap, across four technology scenarios: Baseline, High Renewable Capacity, Biomass Co-firing Only, and CCS & Biomass Co-firing. The three panels, from top to bottom, illustrate India's transmission capacity, power capacity, and generation mix, accounting for retired or retrofitted coal plants. Values are labeled for power capacities exceeding 50 GW and power generation surpassing 100 TWh.

carbon cap reduces to 500 Mt CO₂. Interestingly, under the 500 Mt CO₂ cap, we see fewer coal plant retirements in the high renewable capacity scenario as compared to the baseline scenario, likely due to the increased need for firm and flexible power generation in the former scenario with greater renewable deployment. This is seen in the power dispatch plots of the high renewable capacity vs. baseline scenario in Fig. 7.

In the 'CCS & Biomass co-firing' scenario, 43 GW of supercritical coal plants will be retrofitted with the CCS under the 500 Mt CO₂ emissions scenario, but none of the supercritical coal plants are retrofitted to co-fire biomass. This indicates that biomass co-firing is less cost-effective compared to retrofitting supercritical coal power plants with CCS (Note: CCS retrofits are only allowed for supercritical coal plants). Likewise, the biomass co-firing only scenario without CCS will only

retrofit less than 30 GW of supercritical coal plants under the 500 Mt CO₂ emissions cap. Retrofitting of coal power plants under the 500 Mt CO₂ emissions cap leads to reduced investment in transmission expansion, energy storage, and natural gas capacity, even though it does not impact renewable capacity investment.

Substantial transmission network expansion is required to support power system decarbonization across all scenarios. The capital cost of transmission expansion is influenced by both the rated power capacity and the length of the transmission lines. Accordingly, we define transmission expansion in terms of TW-km, representing the product of the transmission distance (km) and the expanded capacity (TW). India had approximately 42 TW-km of inter-state transmission capacity (including HVDC lines) by the end of 2020 (IEA, 2021, 2022). An additional transmission capacity of 49–102 TW-km is expected to be

Table 1
Summary of the main data sources used in this study.

Thermal and renewable power generations		
No.	Descriptions	Data sources
1.1	Existing renewable energy, thermal power generation and hydropower station capacity in 2020	Central Electricity Authority (2019) and Ministry of new and renewable energy (2022)
1.2	The planned capacity of nuclear power stations and hydropower plants by 2035	Central Electricity Authority (2022b)
1.3	Hourly capacity factor profiles of hydropower station, renewable energy resources, and geospatial renewable potentials	ReEDS - India (Ho et al., 2021); The Centre for Social and Economic Progress (2023)
1.4	Overnight investment costs and technical parameters of thermal power plants	Central Electricity Authority (2022a)
State-wise demand profiles and inter-state power networks		
2.1	Projected electricity demand profiles of 30 Indian states or regions in 2035 considering electric vehicles and air conditioners	Barbar et al. (2021)
2.2	Inter-region and inter-state power network topology and transmission capacity	Ministry of Power, Government of India (2023b), PowerLine (2017), and ReEDS - India (Ho et al., 2021)
Unit-level coal plant features and regional coal price		
3.1	Operational SHR value of 806 India coal-fired power units	Methods in Section 2 (Ding, Wong, et al., 2024)
3.2	30-region delivered coal price	Ganesan and Narayanaswamy (2021)
Coal plant retrofitting investments and technical features		
4.1	Thermal efficiency and power capacity penalty factors for CCS and Biomass co-firing retrofit	NREL (2023a)
4.2	Overnight investment and operational costs for CCS and biomass co-firing coal plant retrofitting	IRENA (2021) and Fan et al. (2023)
4.3	Estimated costs of CO ₂ transportation and storage in the 30 Indian states or regions	Lau (2023) and Vishal et al. (2021)
4.4	Biomass resource availability for power generation (MW) in the 30 Indian states or regions	Ministry of new and renewable energy (2023)

built across all scenarios, and the planned transmission power capacity increases with a more stringent carbon cap.

Coal plant capacity and utilization

Coal plant retrofitting can change the operating regimes of coal plants, for example, whether they supply the base or peak load. Here, we use the plant load factor (PLF), defined as the ratio of the annual electricity output to the output at its full nameplate capacity over a year. A higher PLF means a better thermal plant utilization. Fig. 6(a) – (d) shows the average PLF for subcritical and supercritical coal plants and their power capacity under different carbon constraints in four technology scenarios, respectively.

Without any carbon constraints, India's coal plant capacity will increase around 1.1–1.2 times by 2035 across four technology scenarios, driven by the increasing electricity demand. The total coal capacity reduces as the stringency of the carbon emissions constraint is increased. Under the 500 Mt CO₂, the baseline scenario has the lowest coal plant capacity among the four scenarios since almost all subcritical coal plants are retired. In contrast, the high renewable capacity scenario has the highest coal plant capacity among the four scenarios (Fig. 6(c)). The CCS & Biomass co-firing scenario also retains a majority of the coal plant capacity, though half of the coal plant capacity has been retrofitted.

As shown in Figs. 6(a) – (d), the average PLF of coal plants also decreases as the carbon cap becomes more stringent, primarily due to the reduced utilization of coal plants in response to higher implied carbon emissions costs. More energy efficient supercritical coal plants typically exhibit a higher load factor than subcritical coal plants, often exceeding 50% for the retrofit scenarios. Under the 500 Mt CO₂ cap, in the baseline scenario (d), the average load factor of subcritical coal plants drops to below 10%, which means a number of unabated subcritical coal plants will only operate for a few hours across a year to meet the peak demand. Coal plant retrofitting could increase the load factors of coal plants. For instance, the load factors of subcritical and supercritical coal plants increase from 28.9% to 33.3% and from 52.8% to 62.7% respectively, when the carbon cap reduces from 1000 to 500 Mt in the CCS & Biomass co-firing scenario.

Figs. 7 (a) – (e) show the daily power dispatch for three scenarios, CCS & biomass co-firing, high renewable capacity, and baseline in the months around the peak electricity demand, April and September, under the 500 Mt CO₂ emissions constraint. The daily power dispatch of the biomass co-firing only scenario is similar to the baseline scenario (SI, Section D, Fig. D.2). In the CCS & biomass co-firing and baseline scenarios, batteries and coal plants serve as the primary flexibility resources to support significant ramping requirements of up to 40 GW per hour. In the baseline scenario, subcritical coal plants are completely retired. Batteries and natural gas provide significant flexibility, leading to little renewable curtailment. In the CCS & biomass co-firing scenario, the retrofitted supercritical coal plants with CCS change power outputs less flexibly due to their higher assumed start-up cost compared to the unabated coal power plant (SI, Section C, Table C.1). This leads to renewable generation curtailments during the afternoon ramp-up. In the high renewable capacity scenario, onshore wind power generation complements solar power generation in the spring and summer, which leads to lower renewable curtailments (Fig. 7(c)).

Electricity generation and carbon abatement costs

We calculate the average electricity generation costs as the total system cost (i.e., the annualized investment and operational costs as in Table 2), divided by the total annual energy consumption. Fig. 8(a) shows the average costs of electricity under different carbon emissions constraints under four technology scenarios. In the baseline scenario, the average cost of electricity increases from \$29.26/MWh under no carbon cap to \$63.45/MWh under a 500 Mt CO₂ emissions cap. The option to retrofit with CCS and biomass co-firing results in around 22% reduction of the system cost of electricity under the 500 Mt CO₂ cap, compared to the baseline scenario. This is because of lower investments in transmission, battery storage, and natural gas capacity as well as greater coal retirements (see in Fig. 5). Under the most stringent emissions cap of 500 Mt CO₂, the lowest system cost of electricity is seen for the high renewable capacity scenario without any limits on renewable deployment, corresponding to around 45% reduction vs. the cost of the corresponding baseline scenario.

The average carbon abatement costs of four technology scenarios are compared in Fig. 8(b). These are calculated as the difference in the total system cost of the selected emission cap case and the corresponding no emission cap case, divided by the total carbon abatement amounts. The total system costs without a carbon cap amount to \$66.78 billion for the baseline, CCS with biomass co-firing, and biomass co-firing-only scenarios, while rising to \$71.42 billion in the high renewable capacity scenario. The higher cost in the latter is attributed to the enforcement of a 30 GW offshore wind farm target. In the baseline, the average carbon abatement cost will increase rapidly to \$78.92/tCO₂ under the 500 Mt CO₂. While the CCS and biomass co-firing retrofits could reduce the average carbon abatement cost by 41.51%, biomass co-firing with a low biomass mix below 20% does not reduce the electricity generation and carbon abatement costs.

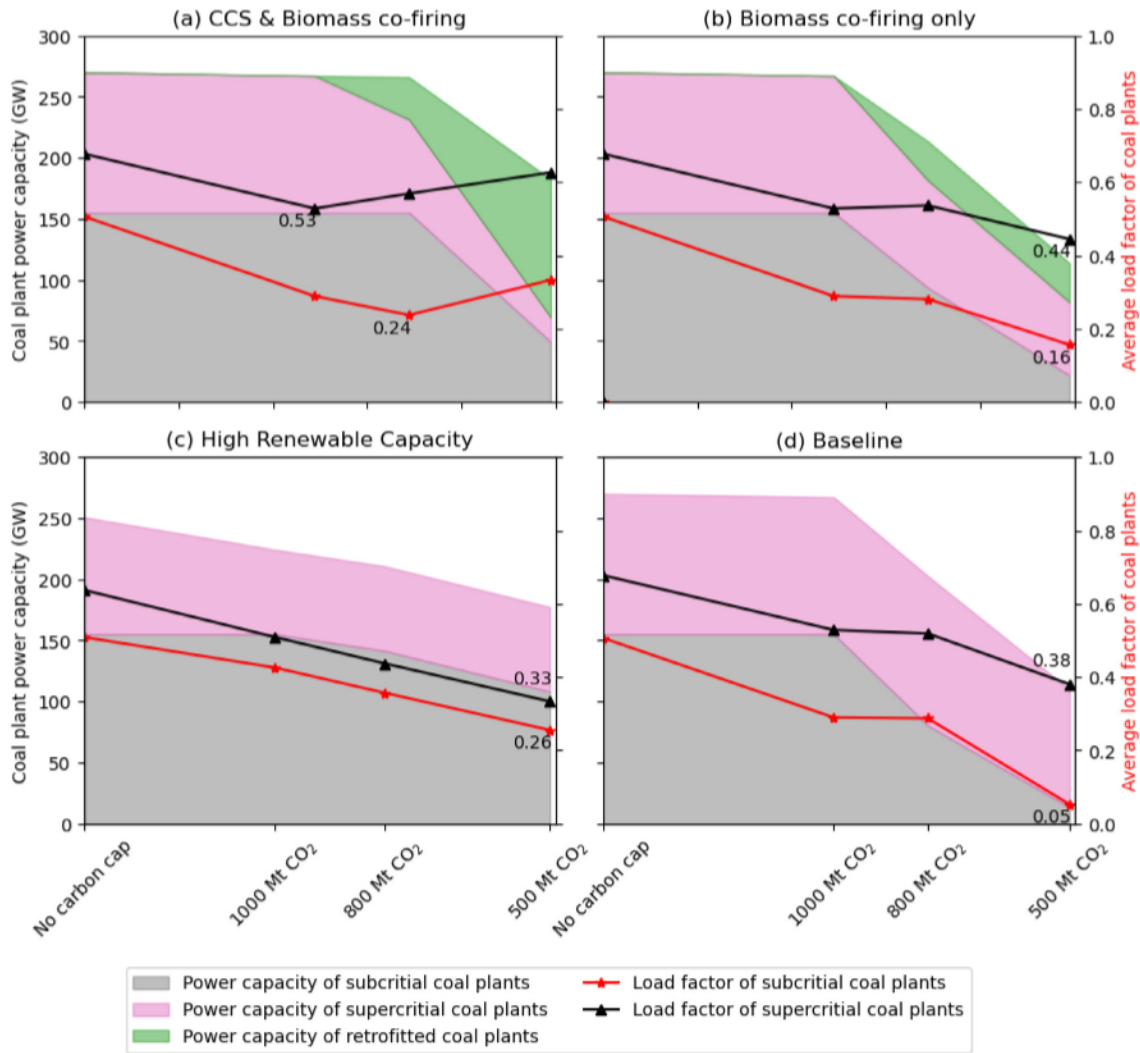


Fig. 6. The power capacity of subcritical, supercritical and retrofitted coal plants, with the average load factors of the unabated subcritical and supercritical coal plants in four technology scenarios; The minimum values of the average load factors of the unabated subcritical and supercritical coal plants are annotated.

We also conduct a sensitivity analysis in terms of the biomass fuel price. We simulate the Indian power system in the CCS & Biomass co-firing scenario at the biomass fuel price of \$3.7/MMBtu and \$7.4/MMBtu, respectively. We found that although a high biomass fuel price results in fewer retrofitted subcritical coal plants and more retired coal capacity, the biomass fuel price variation has little impact on the average electricity generation and carbon abatement costs, as presented in *SI, Section D, Figs. D.5 (a) and D.5 (b)*.

Geographical distributions of renewable power generations, retired and retrofitted coal plants

While system costs are one indicator of interest, another indicator of interest is the distribution of these costs across various regions, reflecting the distributional impacts of power system evolution under various technology and policy scenarios. Fig. 9 depicts the total power capacity and renewable capacity percentage (i.e., Renewable energy includes solar PV, onshore wind farms, offshore wind farms, and hydro power stations) across 30 regions in three technology scenarios under 500 Mt CO₂ cap. The detailed power capacity breakdown in 30 regions is presented in the *SI, Section D, Fig. D.9*. We also compare the sub-national differences in the transmission capacity and annual generation under no carbon cap and 500 Mt CO₂, as presented in the *SI, Section D, Fig. D.7*.

Energy inequality is a historical issue in India's energy system development (Bhattacharyya et al., 2022). India's energy infrastructure is regulated within each state, and most of the renewable generation capacity is found in southern and western India, where wealthier states are located (Sengupta et al., 2022). We found that the high renewable capacity scenario has the biggest spatial differences in the total power capacity and renewable capacity percentage. This is because the onshore and offshore wind farms are mainly concentrated in a few regions, including Rajasthan, Tamil Nadu, and Gujarat, alongside a sharp reduction in thermal power generation in northern and central states. To meet the energy demand, the power network capacity increases substantially to transmit excess renewable generation from the western region to the northern and eastern regions, as presented in *SI, Section D, Fig. D.7 (c)*.

In the CCS and biomass co-firing scenario, renewable generation capacity is more evenly distributed. Batteries and low-carbon power generation, including retrofitted coal power plants, play a crucial role in supporting solar power integration, particularly in states like Uttar Pradesh, Bihar, and Jharkhand. For instance, Uttar Pradesh, highlighted by the red contour in Fig. 9, had the highest number of subcritical coal plant units in 2021. This state shows a notable increase of 4 GW in total power capacity and a 6.4% growth in the renewable capacity percentage, when comparing the CCS & biomass co-firing scenario to the high renewable capacity scenario. The power generation capacity

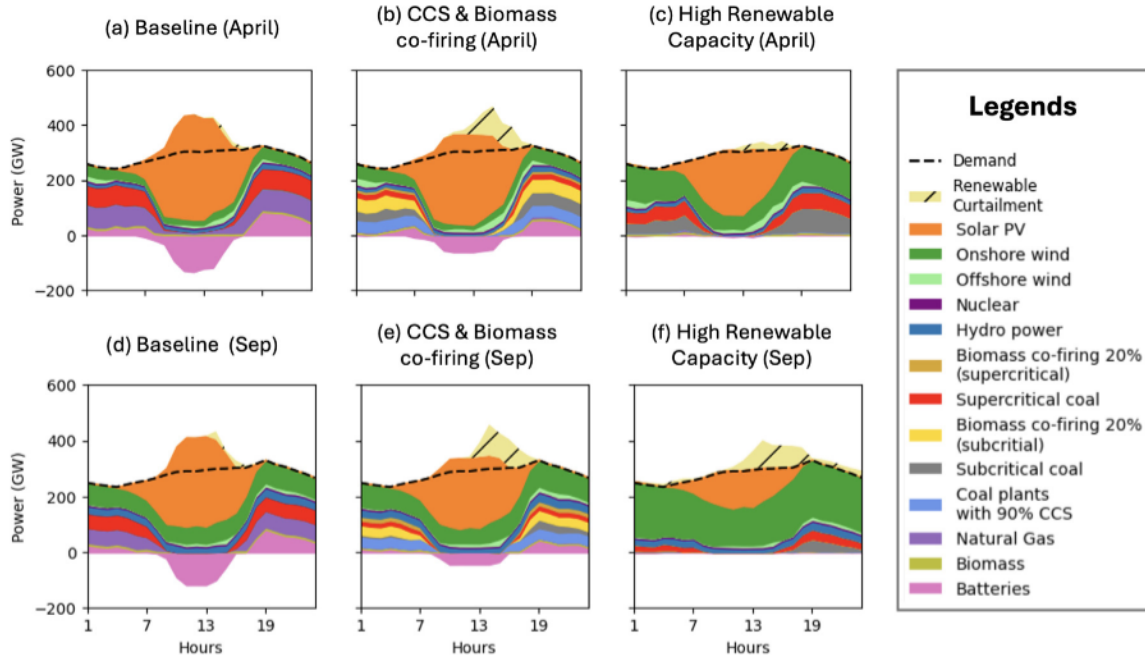


Fig. 7. Daily power dispatch profiles for three scenarios under 500 Mt CO₂: (a) Baseline — April, (b) CCS & Biomass co-firing — April, (c) High renewable capacity — April, (d) Baseline — September, (e) CCS & Biomass co-firing — September, and (f) High renewable capacity — September.

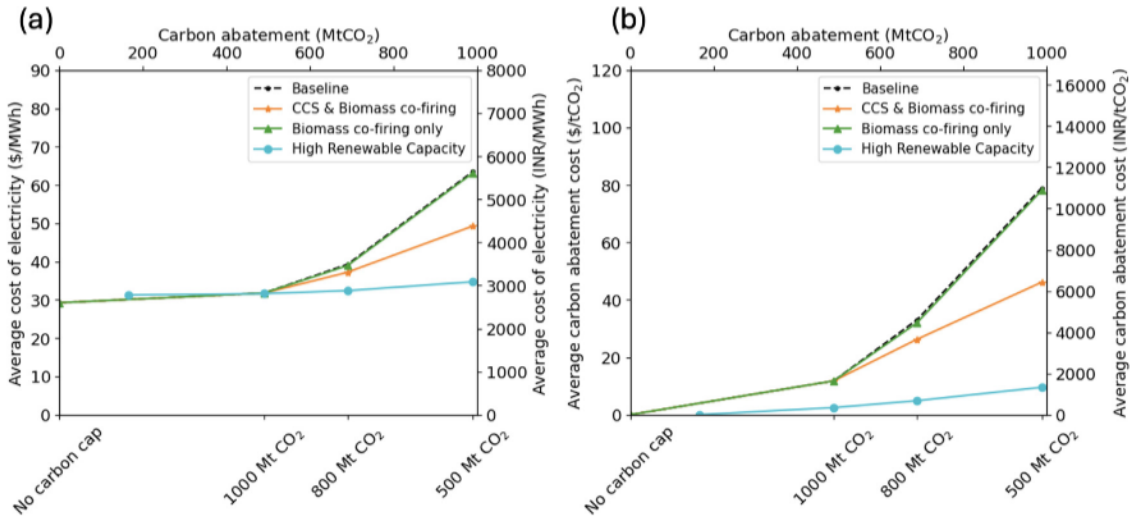


Fig. 8. (a) Average cost of electricity generation and (b) average carbon abatement costs in the baseline, CCS & Biomass co-firing, Biomass co-firing only, and High renewable capacity scenarios under different carbon emissions constraints; The annual carbon emission without carbon cap for baseline, CCS & Biomass co-firing, and Biomass co-firing only scenarios is 1489 Mt CO₂. For the High Renewable Capacity scenario, the annual carbon emissions without a carbon cap is 1324 Mt CO₂, reflecting the enforcement of a 30 GW offshore wind farm target.

for the biomass co-firing only and the baseline scenario has similar distributions. In both scenarios, low-efficiency subcritical coal plants are retired, and natural gas power plants are added to provide the dispatchable power with lower emissions than unabated coal power plants (Fig. 5).

Fig. 10 shows the changes in different types of coal plants, including both unabated and retrofitted coal plants, compared to their original capacity in 2020 for the CCS & biomass co-firing scenario under 500 Mt CO₂ cap. The low-efficiency subcritical coal plants are retired in the Western and Southern regions where coal prices are the highest, while new coal plants or retrofits of existing plants are planned in the Central and Eastern regions with lower coal prices.

Summary and key findings

We explore the role of coal plant retrofits in India's power system evolutions through the development of 30-region Indian power system model and its evaluation across four technology scenarios considering alternative technology scenarios consisting of coal plant retrofitting options and different carbon emission caps. Table 2 summarizes the main model outcomes for these technology scenarios across 1000 and 500 Mt CO₂ emissions constraints.

We note the following key findings: First, without a carbon cap, renewable deployment dominates new capacity installations; however, the increasing electricity demand leads to unabated coal capacity additions between 27–46 GW. Second, carbon emissions constraints drive

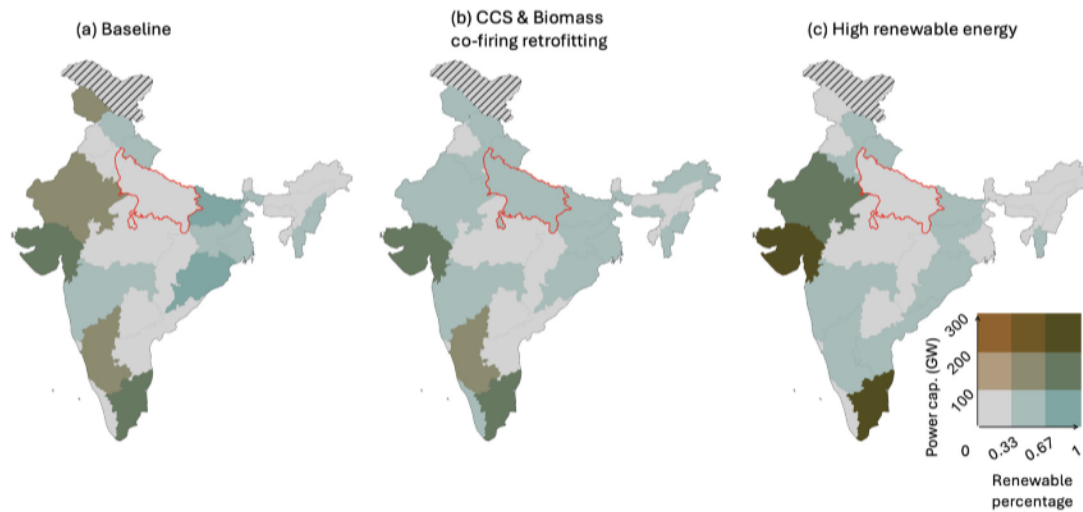


Fig. 9. The total power capacities and renewable capacity percentages across 30 regions in three technology scenarios: (a) Baseline, (b) CCS & Biomass co-firing retrofitting, and (c) High renewable capacity scenarios.

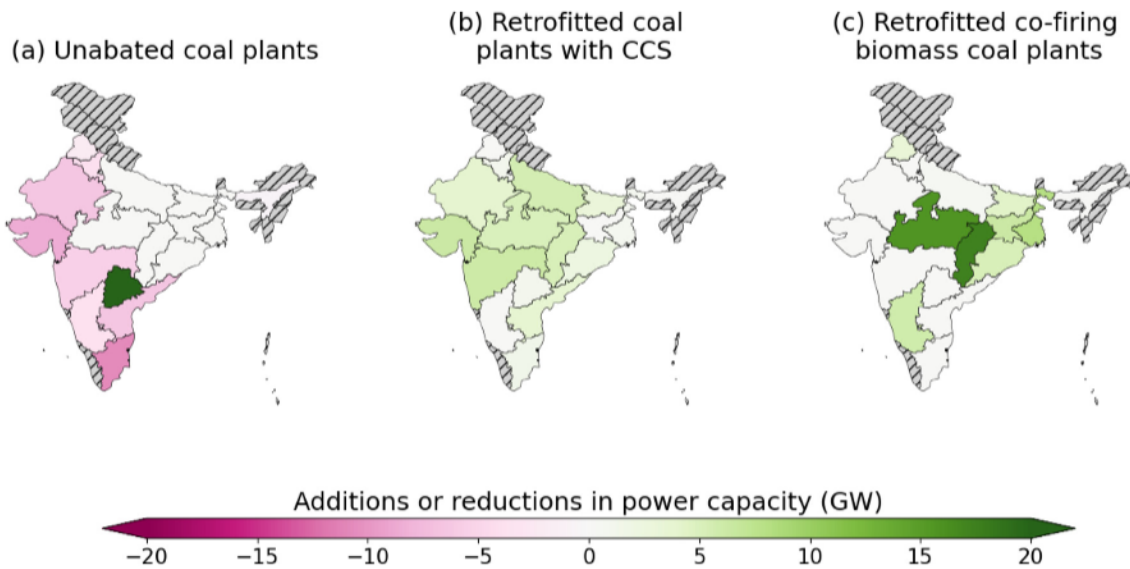


Fig. 10. Changes in the unabated coal plants, retrofitted CCS and biomass co-firing coal plants compared to the starting capacity of 2020 India's power system in the 'CCS & Biomass co-firing' scenario under 500 Mt CO₂ emissions cap; The diagonally striped areas show the regions that currently have no coal plants.

up renewable expansion. If India is able to build onshore wind capacity as needed, this will substantially reduce the average cost of carbon abatement when the annual emissions cap tightens to 500 Mt. Third, coal plant retrofitting, including CCS deployment with supercritical power plants and biomass co-firing of subcritical power plants, offers the second-best alternative in terms of costs for the moderate to deep decarbonization (i.e., 1000–500 Mt CO₂ annual carbon emission cap) of India's power grid by 2035. Coal retrofits improve the total coal plant utilization, reduce the extent of deployment of natural gas plants and transmission expansion, and enable a more geographically even distribution of renewable capacity investments across the country.

Policy implications and model limitations

Our results highlight the potential role for coal retrofits in enabling a just energy transition in the Indian context. Below we highlight a few other policy implications from the analysis.

CCS retrofits in the power sector could scale up under carbon policy support: The retrofit of supercritical power plants by 2035 becomes economically viable only under an annual carbon emission cap of 500

Mt. Under such carbon constraint, the average cost of carbon abatement is \$46 per ton of CO₂, which is 150% higher than the average cost of carbon capture and storage (SI, Section C, Figs. C.3 and C.4). However, the marginal cost of carbon abatement reaches \$120 per ton of CO₂ (SI, Section D, Fig. D.6), indicating a high market carbon price that may pose significant challenges for policy implementation.

Renewable integration should consider energy justice for a just transition: Renewable capacity expansion is the most cost-effective decarbonization strategy for the Indian power sector in the coming decade. However, fully exploiting renewable generation potentials based on the optimal resource locations will concentrate generation capacity in Western and Southern India, where both onshore and offshore wind resources are abundant. Additional measures to distribute renewable generation investments across the regions, like state-level renewable generation targets, could enable a more even distribution of renewable capacity installation.

Significant network expansion is required for the development of India's net-zero power system: Our findings indicate that by 2035, India will need at least around 50 TW-km of additional transmission capacity to facilitate renewable energy integration, excluding HVDC transmission

Table 2

Result summary of four technology scenarios (A: Baseline, B: High renewable capacity, C: Biomass co-firing only, D: CCS & Biomass co-firing) under 1000 and 500 Mt CO₂ emission caps.

	1000 Mt CO ₂				500 Mt CO ₂			
	A	B	C	D	A	B	C	D
Renewable capacity (GW)	599	554	599	599	675	771	675	675
Renewable generation share (%)	39.6	40.3	39.6	39.6	40.5	43.7	40.4	41.0
Unabated coal capacity (GW)	267	224	267	267	110	177	82	70
Subcritical coal plant PLF (%)	28.9	42.6	28.9	28.9	5.3	25.5	15.7	33.3
Supercritical coal plant PLF (%)	52.8	50.9	52.8	52.8	38.0	33.3	44.5	62.7
Total coal plant PLF (%)	38.9	45.1	38.9	38.9	34.0	28.6	36.8	41.8
Total system cost (Billion \$)	72.6	72.2	72.6	72.6	144.8	79.3	144.0	112.4
Avg. cost of electricity (\$/MWh)	31.8	31.6	31.8	31.8	63.5	34.7	63.1	49.3
Avg. cost of carbon abatement (\$/tCO ₂)	11.80	2.49	11.80	11.80	78.92	9.56	78.11	46.16

lines. The expansion plans differ across regions and technology scenarios, implying the need for coordinated efforts between operators in India's five power system regions and renewable energy investors.

The above modeling insights should be interpreted keeping in mind some key model limitations, that can be improved in future work. First, we do not consider biomass transportation and associated carbon emissions across India since we focus on the heterogeneous coal power plant characteristics and coal prices across India. A life cycle analysis and detailed biomass transportation model could be conducted as a separate study for the impact of the biomass supply chain. Secondly, we use the simplified approach for CO₂ storage and transportation cost modeling that does not account for geospatial constraints on CO₂ storage sites and the associated spatial deployment of CO₂ infrastructure. This means the costs of electricity generation and carbon abatement in the CCS & Biomass co-firing scenario could be higher than projected. Given that this is a near-term power system planning analysis, we assume these power plants will continue operating at the same SHR even after 50 years despite the expected reduction over time, and our model does not account for the costs associated with life extension such as component replacement. This will lead to fewer subcritical coal power plants being economically decommissioned than the actual results. Furthermore, the model does not account for technical challenges in the retrofitting processes, such as land use and water stress, which would require a detailed plant-specific assessment. These factors, however, could become increasingly relevant in mid-term power system planning beyond 2035.

CRedit authorship contribution statement

Yifu Ding: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Dharik Mallapragada:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation. **Robert James Stoner:** Writing – review & editing, Validation, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yifu Ding reports financial support was provided by IHI Corporation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Capacity expansion problem formulation for the retrofitted CCS and biomass co-firing coal plants

The coal power plant retrofitting module is built on the single-stage setting specifically for one year using GenX (MIT Energy Initiative and Princeton University ZERO lab, 2024), and an example of re-purposing thermal energy storage can be found in Ding, Mallapragada, Patel, and Stoner (2024). In this paper, we model an India power system with 30 regions $z \in \mathcal{Z}$, including thermal generation $y \in \mathcal{G}$, energy storage $s \in \mathcal{O}$, and transmission lines $l \in \mathcal{L}$. The proposed capacity expansion problem formulation considers the investment, retirement, and retrofitting of thermal power generation and investments in transmission, renewable resources, and energy storage. The objective function encompasses capacity investments in generation and transmission, retrofitting costs, as well as fuel expenses and fixed operation and maintenance costs.

$$\begin{aligned}
 \min \sum_{z \in \mathcal{Z}} \{ & \underbrace{\sum_{y \in \mathcal{G}^h} I_y^{th} \bar{P}_y^{size} \Omega_{y,z}^{inv} + F_y^{th} \bar{P}_y^{size} \Omega_{y,z}^{net}}_{\text{Capital costs of newly-built thermal power plants and fixed O\&M}} \\
 & + \underbrace{\sum_{y \in \mathcal{G}^{coal, biomass, CCS}} I_y^{th} \bar{P}_y^{size} \Omega_{y,z}^{net} + F_y^{th} \bar{P}_y^{size} \Omega_{y,z}^{net}}_{\text{Investments of the retrofitted coal power plants and fixed O\&M}} \\
 & + \underbrace{\sum_{y \in \mathcal{G}^{res}} I_y^{res} \bar{P}_{y,z}^{inv} + F_y^{res} (\bar{P}_{y,z}^{inv} + \bar{P}_{y,z}^{exist})}_{\text{Investments of renewable energy resources and fixed O\&M}} \\
 & + \underbrace{\sum_{l \in \mathcal{L}} (\pi_l^{TCAP} \times \Delta \phi_l^{max})}_{\text{Investments of power transmission lines}} \\
 & + \underbrace{\sum_{s \in \mathcal{O}^{lib}} I_s^{dis} \bar{P}_{s,z}^{dis} + I_s^{en} \bar{E}_{s,z}^{inv} + F_s^{dis} (\bar{P}_{s,z}^{inv} + \bar{P}_{s,z}^{exist})}_{\text{Investments and fixed O\&M for energy storage}} \\
 & + \underbrace{\sum_{y \in \mathcal{G}^h} \sum_{t \in \mathcal{T}} \omega_t (\pi_{y,z}^{vom} + \pi_{y,z}^{fuel}) P_{y,z,t}^{dis}}_{\text{Variable O\&M and fuel costs of thermal power plants}} \\
 & + \underbrace{\sum_{s \in \mathcal{O}^{tes}} \sum_{t \in \mathcal{T}} \omega_t \pi_s^{vom, dis} P_{s,z,t}^{dis}}_{\text{Variable O\&M costs of energy storage}} \\
 & + \underbrace{\sum_{t \in \mathcal{T}} \omega_t \pi_{z,t}^{unmet} P_{z,t}^{unmet}}_{\text{Load shedding costs}} \} \tag{A.1}
 \end{aligned}$$

The power system operation is modeled as the hourly linear unit commitment for $t \in \mathcal{T}$. It has a linear variable Ω to represent the start-up and shut-down status of thermal generation capacity, and the unit size is denoted as $\bar{P}_y^{size}$. The investment cost of generation capacity is denoted as I_y , and the fixed operation and maintenance cost is denoted as F_y . The cycle costs of thermal power plants include the variable operation and maintenance π^{vom} and fuel costs π^{fuel} . The load shedding is based on the value of the lost load π^{unmet} . The power outputs of thermal generations cannot exceed the net operating capacity and should be lower than the minimum stable generation level γ_y .

$$\gamma_y \bar{P}_y^{size} \Omega_{y,z}^{net} \leq P_{y,z,t}^{dis} \leq \bar{P}_y^{size} \Omega_{y,z}^{net} \quad y \in \mathcal{G}^h \tag{A.2}$$

The net operating thermal generation units considering the existing, newly built, retired, and retrofitted units can be expressed as the

following equations. Subcritical coal plants ($y \in \mathcal{G}^{sub}$) can only be early decommissioned or retrofitted, while supercritical coal plants ($y \in \mathcal{G}^{super}$) can be either newly built, early decommissioned, or retrofitted into CCS or biomass co-firing power plants.

$$\Omega_{y,z}^{net} := \Omega_{y,z}^{exist} - \Omega_{y,z}^{retire} - \Omega_{y',z}^{retro} \quad y \in \mathcal{G}^{sub} \quad y' \in \mathcal{G}^{biomass} \quad (A.3)$$

$$\Omega_{y,z}^{net} := \Omega_{y,z}^{exist} + \Omega_{y,z}^{inv} - \Omega_{y,z}^{retire} - \Omega_{y',z}^{retro} - \Omega_{y'',z}^{retro} \quad y \in \mathcal{G}^{super} \quad y' \in \mathcal{G}^{biomass} \quad y'' \in \mathcal{G}^{ccs} \quad (A.4)$$

The net operating thermal generation units of CCS and biomass co-firing power plants depend on the number of coal-fired power units being retrofitted.

$$\Omega_{y',z}^{net} := \Omega_{y',z}^{retro} \quad y' \in \mathcal{G}^{biomass,CCS} \quad (A.5)$$

For the retrofitted coal plants with CCS, the decrease in power capacity and the increase in fuel consumption caused by the carbon capture process are represented using penalty factors for power capacity and thermal efficiency (SI , Section C, Table C.1). These penalty factors are applied to the original values to obtain the adjusted power capacity and SHR. This adjustment is made for each region or coal plant cluster, and therefore the retrofit preferences are determined based on the least-cost criterion, considering heterogeneous coal prices and SHR.

$$\overline{P}_{y',z}^{size} := \overline{P}_{y,z}^{size} \times (1 + \Delta \overline{P}_{y',z}^{size}) \quad y \in \mathcal{G}^{super} \quad y' \in \mathcal{G}^{ccs} \quad (A.6)$$

$$h_{y',z} := h_{y,z} \times (1 + \Delta h_{y',z}) \quad y \in \mathcal{G}^{super} \quad y' \in \mathcal{G}^{ccs} \quad (A.7)$$

At the regional coal prices p_z^{coal} (\$/MMBtu), the fuel cost of retrofitted coal power plants with CCS (\$/MWh) is given by,

$$\pi_{y,z}^{fuel} := h_{y',z} \times p_z^{coal} \quad y' \in \mathcal{G}^{ccs} \quad (A.8)$$

Biomass co-firing retrofitting can be conducted on any coal power unit, and its thermal efficiency is unchanged after retrofitting; in other words, zero thermal efficiency and power capacity penalty factors. This capacity expansion problem formulation incorporates ramp-up and ramp-down constraints of thermal power plants and whole-system power balance, power, and energy balance of energy storage. These constraints are detailed in the GenX (MIT Energy Initiative and Princeton University ZERO lab, 2024).

Appendix B. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.esd.2025.101687>.

The model is built based on GenX version v0.3.6., and the model inputs and original results can be found in <https://doi.org/10.5281/zenodo.12684827>.

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