

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

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1 Table of Contents

1. Section A - Data-driven Prediction and Clustering of Indian Coal Power Plants	2
1.1. India Coal Power Plant Databases.....	2
2. Section B - The 30-region Indian Capacity Expansion Model.....	2
2.1. Projected Electricity Demands in India.....	3
2.2. Existing generation capacity in India.....	3
2.3. Costs and Technical Assumptions of Green-field Thermal Power Plants and Renewable Generations.....	4
2.4. Capital Cost of Energy Storage	5
2.5. Renewable Energy Resource Distributions in India	5
2.6. Power Networks in Current and Future Scenarios.....	7
2.7. Model Validation.....	8
3. Section C - Coal Power Plant Retrofitting	10
3.1. Modeling the CCS and Biomass Co-firing Retrofitting.....	10
3.2. Costs and Technical Assumptions of CCS and Biomass Co-firing Retrofitting	10
3.3. Carbon storage and transportation cost in India	12
4. Section D: Supplementary Figures.....	14

1. Section A - Data-driven Prediction and Clustering of Indian Coal Power Plants

1.1. India Coal Power Plant Databases

India currently has around 840 coal power generation units, and the total power capacity of coal and lignite power plants reaches 211.8 GW [1][2]. We leverage two databases for India's coal power plants. The first database is from the Global Energy Monitor (GEM) [1], which records 840 coal generation units in India in operation. This database also includes the location, the age of power plants, boiler types of each coal generation, and calculated station heat rates (SHR).

The second database is from the Council of Energy, Environment, and Water (CEEW) [3]. This database includes the operating SHR of nearly 194 GW of coal-based generation capacity over 30 months before the COVID-19 pandemic in India. The database recorded many technical features of coal power plants, including boiler design, age since 2020, power capacity, and power plant ownership. Still, the exact location of each coal power plant is not presented. Figure A.1 shows the locations of all coal power plants operating in India from the GEM database [1]. Figure A.2 shows four feature distributions from the CEEW database, including plant age, power capacity, daily power generation, and heat rates [3]. In our prior work [4], we used the operating SHR measurements for 194 GW of coal plants in the CEEW database to predict the SHR of 806 India's coal plants specific to two boiler designs, subcritical and supercritical. The detailed data can be downloaded from our visualization platform [5].

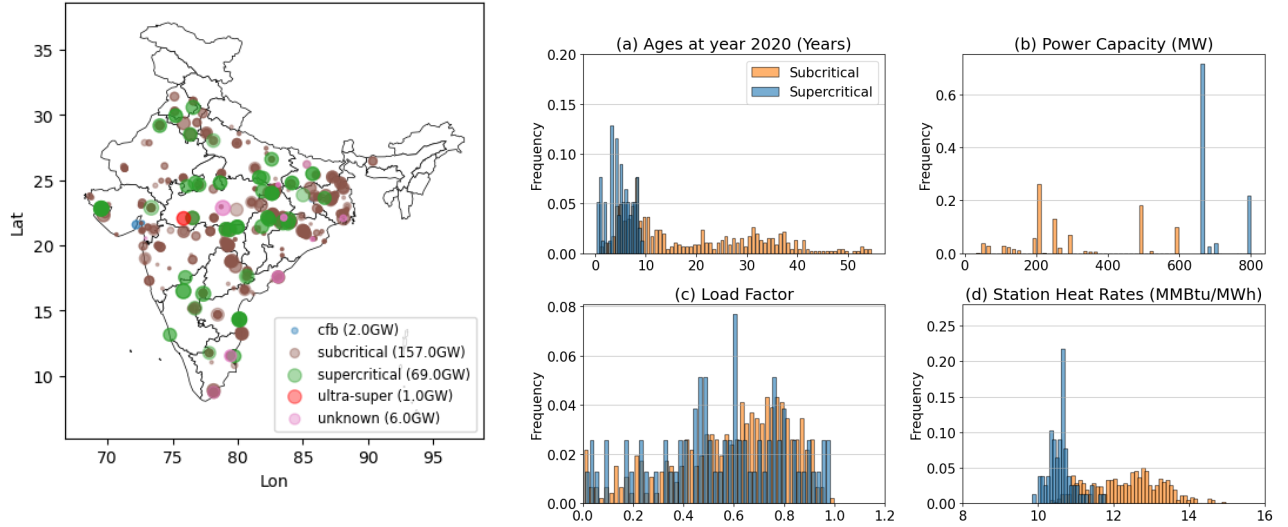


Figure A.1 Locations of current operating coal power plants [4]

Figure A.2 Distributions of coal power plants characteristics (a) plants age since year 2020 (b) power plant capacity (MW) (c) average daily power generation (GWh) and (d) power plant heat rate (MMBtu/MWh) [4]

2. Section B - The 30-region Indian Capacity Expansion Model

We develop a 30-region Indian power system model that co-optimizes generation and transmission systems. The brownfield optimization is conducted based on the existing generations as of 2020 and plans for the power system in 2035.

2.1. Projected Electricity Demands in India

The projected electricity demands for 2035 of 30 Indian regions are from [6], considering the adoption of EVs and air conditioners and a modest GDP growth rate. India's peak electricity demand is 462 GW in 2035, and the total annual electricity demand is 2,282 TWh under this projection.

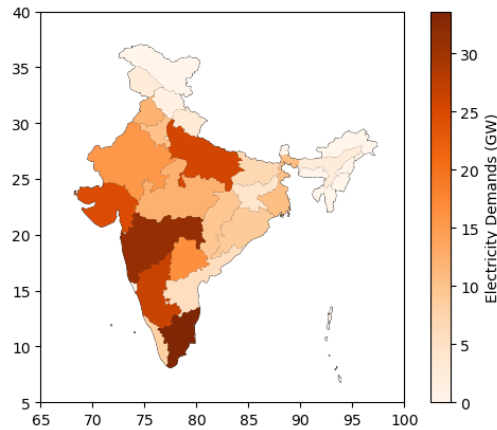


Figure B.1 The projected electricity demand in the during afternoon peak hour by states in 2035

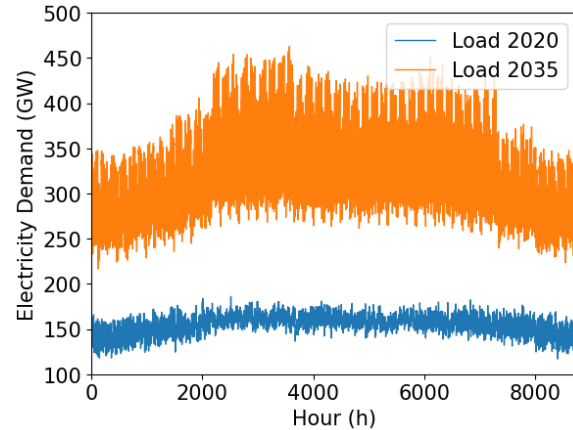


Figure B.2 The total load profile across the whole year in 2035 compared with the load profile in 2020

2.2. Existing generation capacity in India

Figure B.3 shows the 30-region power capacity in India as of 2020 based on the Central Energy Authority [2] and the Ministry of New and Renewable Energy [7]. The installed capacity in the isolated regions (Andaman & Nicobar Islands, Lakshadweep, and other territories) is not considered. The total power capacity of India in 2020 reached 368.79 GW, of which coal power plants accounted for 198.5 GW, hydro 45.5 GW (including 3 GW pumped-hydro storage [8]), onshore wind 37.5 GW, gas 24.9 GW, solar 33.7GW, biomass 10 GW and nuclear 6.78 GW.

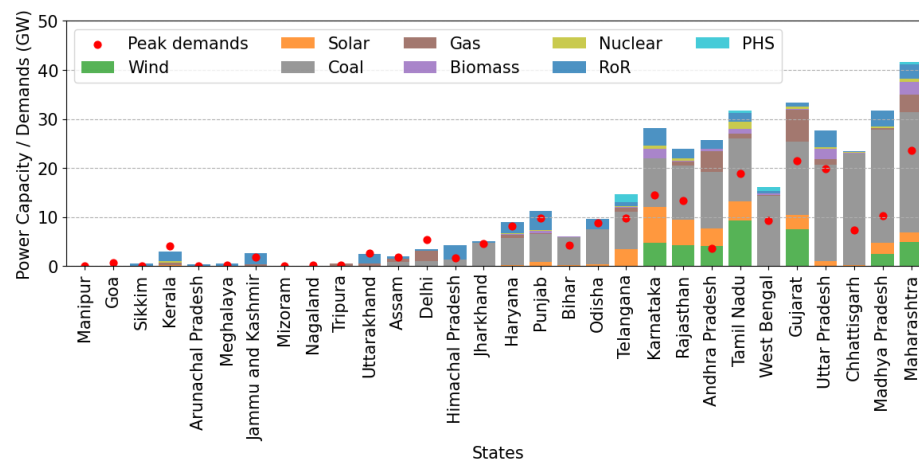


Figure B.3 India's 30-region power capacity and demands in 2020 (ROR: run-of-river; PHS: pumped-hydro storage)

We assume biomass power plants' capacity will not expand due to biomass fuel availability and low plant efficiency. Hydro and nuclear power investments are not decided by economics but by the government plan. As shown in Table B.1, the installed capacities of ROR hydropower, pumped-hydro storage, and nuclear power plants are based on the capacity under construction during 2021-2031 in the Central Electricity Authority report [9].

Table B.1 The installed capacities of ROR hydropower, pumped-hydro storage, and nuclear power plants during 2021-2031 based on the Central Electricity Authority report [9].

	Units	ROR hydropower	Pumped-hydro storage	Nuclear power plants
Existing capacity in 2020	(GW)	40.52	3.30	5.75
Additional capacity during 2021-2031	(GW)	10.99	1.58	15.7
Total capacity in 2031	(GW)	51.51	4.88	21.45

2.3. Costs and Technical Assumptions of Green-field Thermal Power Plants and Renewable Generations
The capital costs and non-fuel fixed and variable O&M costs of dispatchable, renewable generation technologies are based on the Central Electricity Authority [10]. Table B.2 lists the economic assumptions of power generation technologies in 2030 for the planning horizon of 2035. The overnight investment costs are discounted into the annual investment (k\$/MW-year) using the capital return factor (CRF). We assume the investment period of different technologies as in Table A.2 and an interest rate of 0.09.

Table B.2 Economic assumptions of all power generation technologies [10]

	Unit	Coal (Sub.)	Coal (Super.)	Gas (CCGT)	Wind (Onshore)	Wind (Offshore)	Solar PV
Overnight costs	(million/MW)	1.12	1.01	0.42	0.78	2.24	0.43
Annual CAPEX	(k\$/MW-year)	114	102	41	80	218	47
Fixed O&M	(k\$/MW-year)	32	25	35	8	82	4
Variable O&M	(k\$/MWh)	0.03	0.026	0.03	0	0	0
Investment period	(years)	25	25	30	30	30	20

For thermal power plants, we consider their ramp-up and ramp-down limits (%/h) and minimum stable generation (%), as listed in Table B.3.

Table B.3 Technical and fuel assumptions of five types of thermal power plants [10][11]

	Unit	Coal (Sub.)	Coal (Super.)	Biomass	Gas (CCGT)	Nuclear
Ramp-up or down rate	(%/h)	60	60	60	100	-
Minimum stable generation	(%)	55	55	40	55	70
CO ₂ content	(tCO ₂ /MMBtu)	0.1	0.1	0	0.05	0.05
Start-up cost	(\$/MW/startup)	0.19	0.17	0.04	0.09	-
Start-up fuel consumption	(MMBtu/MW)	3.97	3.97	17.87	6.95	-
Start-up time	(h)	4	4	1	1	-
Shut-down time	(h)	1	1	1	1	-
Heat rates	(MMBtu/MWh)	Figure 1 (a)	Figure 1 (b)	15	7.76	10.15

Table B.4 lists the fuel costs for different thermal power plants. The fuel costs are calculated as the multiplication of the heat rate (MMBtu/MWh) and fuel cost per unit (\$/MMBtu). The price of coal depends

on the state, as discussed in the ***data-driven analysis and screening of Indian coal power plants*** section. The gas price is taken from the Indian natural gas spot market [12], and the biomass and uranium prices are taken from the Central Electricity Authority [9] and ref [13].

Table B.4 Technical and fuel assumptions of five types of thermal power plants

	Unit	Coal	Biomass	Natural Gas ¹	Uranium
Fuel cost	\$/MMBtu	Figure 1 (d)	3.7	15	1
Emission factor	ton CO ₂ /MMBtu	0.096	0 ²	0.05	0

2.4. Capital Cost of Energy Storage

The battery cost (i.e., a 4-h Li-ion battery) consists of two parts: the power (\$/kW) and energy components (\$/kWh). These costs are based on the Central Electricity Authority [10], and we use the value in 2030 for the planning horizon of 2035. The annualized power and energy costs (discounted by a capital recovery factor of 0.156 (assuming an investment period of 10 years) are **\$73/kW** and **\$26/kWh**, and the fixed O&M cost is **\$7/kW-year**.

Table B.5 The cost components of 4-h Li-ion batteries in current and future scenarios

	Unit	2020	2030	2040
Overnight energy cost	(\$/kWh)	289	167	145
Overnight power cost	(\$/kW)	818	471	411
Energy cost	(\$/kWh-year)	45	26	23
Power cost	(\$/kW-year)	128	73	64
Fixed O&M	(\$/kW-year)	10	7	5

2.5. Renewable Energy Resource Distributions in India

We consider four kinds of renewable energy resources in India: utility-scale solar PV, onshore wind, offshore wind, and hydropower. We model their spatial and temporal variability by India's hourly capacity factors and renewable energy supply chain limits.

2.5.1. Renewable Energy Capacity Factor

These renewable power outputs are simulated using hourly capacity factors from the National Renewable Energy Laboratory (NREL)'s ReEDS India model repository [14]. State-wise capacity factors are compiled and aggregated from 147 resource regions across India, where each region's weather, natural resources, and land use are considered. Figures A.4 and A.5 show the average capacity factor of utility-scale solar power plants and onshore wind in 30 regions. Run-of-river (RoR) hydro plant output is also simulated using the hourly capacity factor, scaled from actual measurements of hydropower outputs in 2020 [15].

¹ Natural gas price is based on the imported liquefied natural gas price.

² We do not consider the upstream emissions to produce and deliver the biomass.

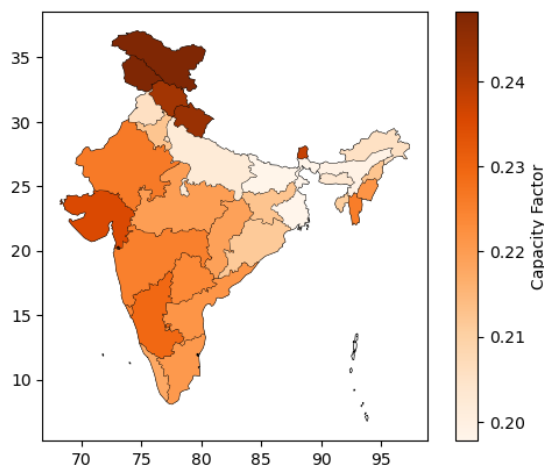


Figure B.4 Annual average capacity factor of utility-scale solar PV power plant in India

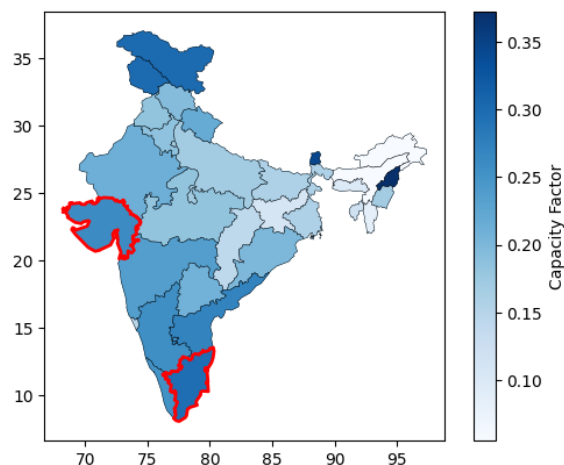


Figure B.5 Average capacity factor of onshore wind in India (Red contours show states plan to invest in offshore wind)

The Indian government has pinpointed 15 offshore wind zones near Tamil Nadu and Gujarat (shown in red contours in Figure B.5). The report [16] shows India is expected to achieve at least 5 GW of offshore capacity by 2032 in these two states. Their power outputs were simulated using the site-level wind level data using the National Renewable Energy Laboratory Wind Integration National Dataset Toolkit for India [17] and power curve data based on the Siemens SWT4.0-130 [18].

Table B.6 The ranges of capacity factors for four renewable generation technologies

Generation Technology	Utility-scale solar PV	Onshore wind farm	Offshore wind farm	Hydro power
Annual Average Capacity Factor Range across 30 regions	0.20 - 0.25	0.06 - 0.37	0.34	0.39

2.5.2. Potentials and Adoption of Renewable Energy Resources

Constructing renewable energy projects depends on land use and supply chain materials. We model the solar and wind potentials of 30 regions using the data from the NREL ReEDS - India model [14]. Figure B.6 shows the utility-scale solar and wind potentials against the existing capacities as of 2020 in 30 regions. India has 4,485 GW of solar power potential and 6,236 GW of wind power potential. For instance, Some Indian states have high renewable capacity but no wind potential due to construction difficulty, such as Jammu and Kashmir in the mountainous region.

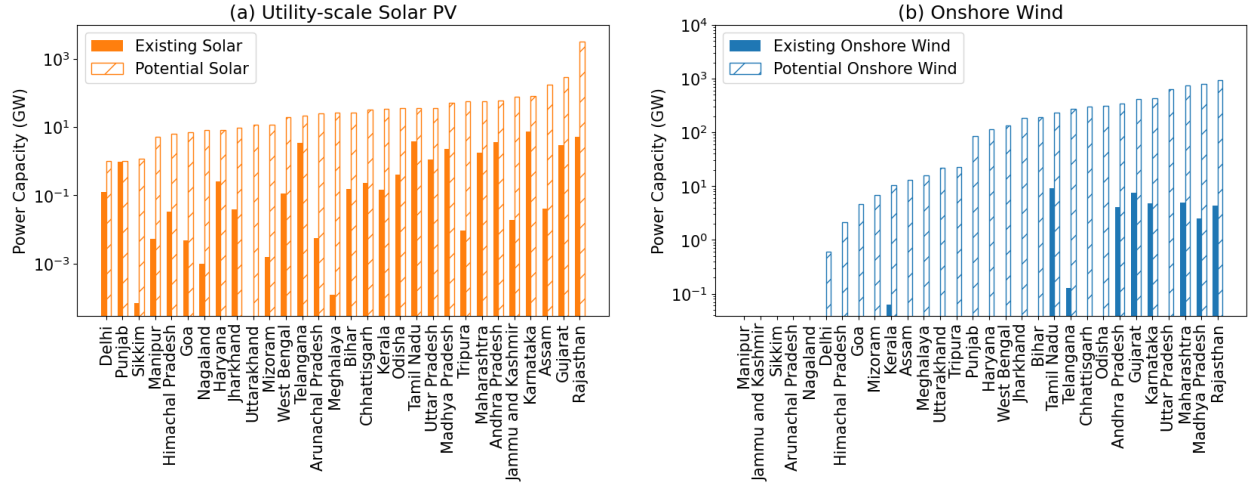


Figure B. Renewable energy potentials of 30 regions: (a) utility-scale solar PV and (b) Onshore wind farms

Additionally, we model the supply chain material limit in the renewable project constructions, which are 171 GW for onshore wind and 443 GW for utility-scale solar PV, according to India's national renewable target [19] and renewable adoption curves [20].

2.6. Power Networks in Current and Future Scenarios

The power network across 30 regions in India is characterized by high-voltage alternative current (HVAC) and direct current (HVDC) lines. India's inter-regional AC transmission capacity reached 112.25 GW by the end of 2022 [21]. The capacity expansion model co-optimizes the generation and transmission capacity across India. We assume the AC network expansion cost is \$219.18/MW-km [11] across India, irrespective of their locations.

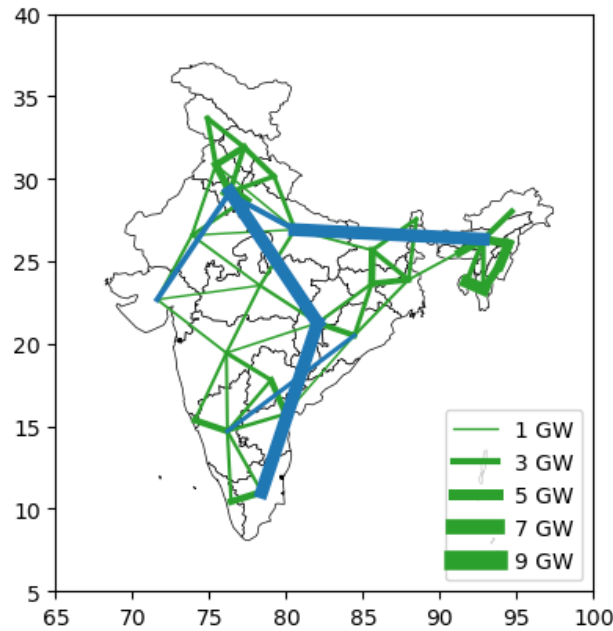


Figure B.7 The 30-region India power network; The green lines are HVAC, and the blue lines are HVDC

In our model, HVAC lines connect the neighboring states, and the total transmission capacity is 118 GW as of 2020. Figure B.7 shows their topologies are plotted in green lines. In addition, six major HVDC projects with transmission capacities of each greater than 2GW [22] (details in Table B.7) are plotted in blue lines. The model assumes there will be no expansion on HVDC lines.

Table B.7 Selected HVDC projects in India with transmission capacities greater than 2 GW [10]

From	To	Name	Commissioning year	Capacity (MW)
Haryana	Gujarat	Mundra-Mahendragarh bipole	2010	2,500
Haryana	Chhattisgarh	Champa-Kurukshetra bipole	2017	6,000
Delhi	Upper Pradesh	Balia-Bhiwadi bipole	2010	2,500
Upper Pradesh	Assam	North-East Agra UHVDC link	2017	6,000
Chhattisgarh	Tamil Nādu	Raigarh-Pugalur UHVDC link	2019	6,000
Odisha	Karnataka	Talcher-Kolar bipole	2003	2,000

2.7. Model Validation

As shown in Figure B.8, we validated our capacity expansion model by comparing the 2020 India power system model outcomes with India's actual power dispatch results from the ref [15]. Since we do not account for power transmission losses at the distribution level and imperfect economic dispatch, we compare the percentage share of different fuels instead of the absolute value. Figure B.9 shows the detailed breakdown of Modeled India 30-region power generation capacity (GW) in 2020.

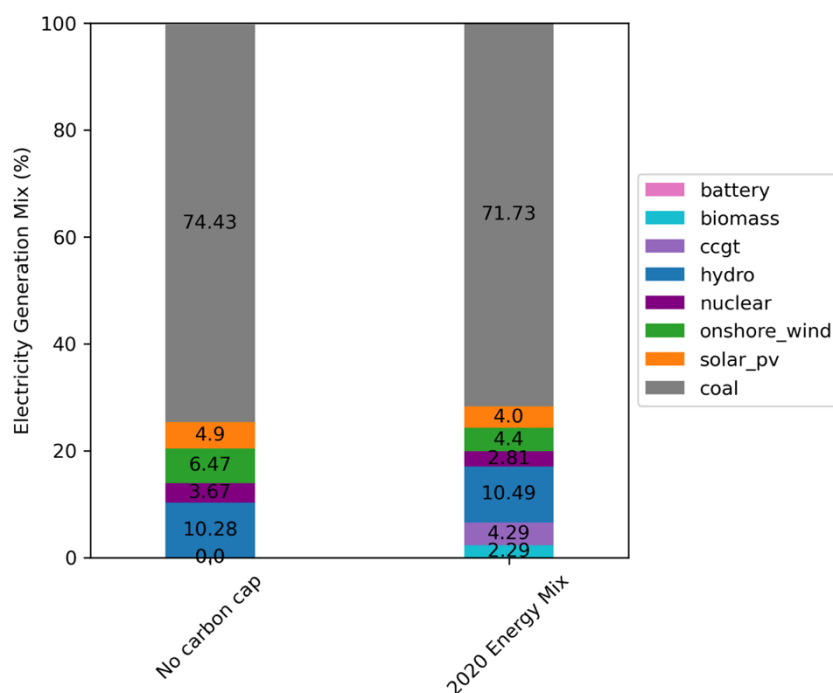


Figure B.8 Comparison of the modelled and actual power dispatch results in the baseline scenario 2020

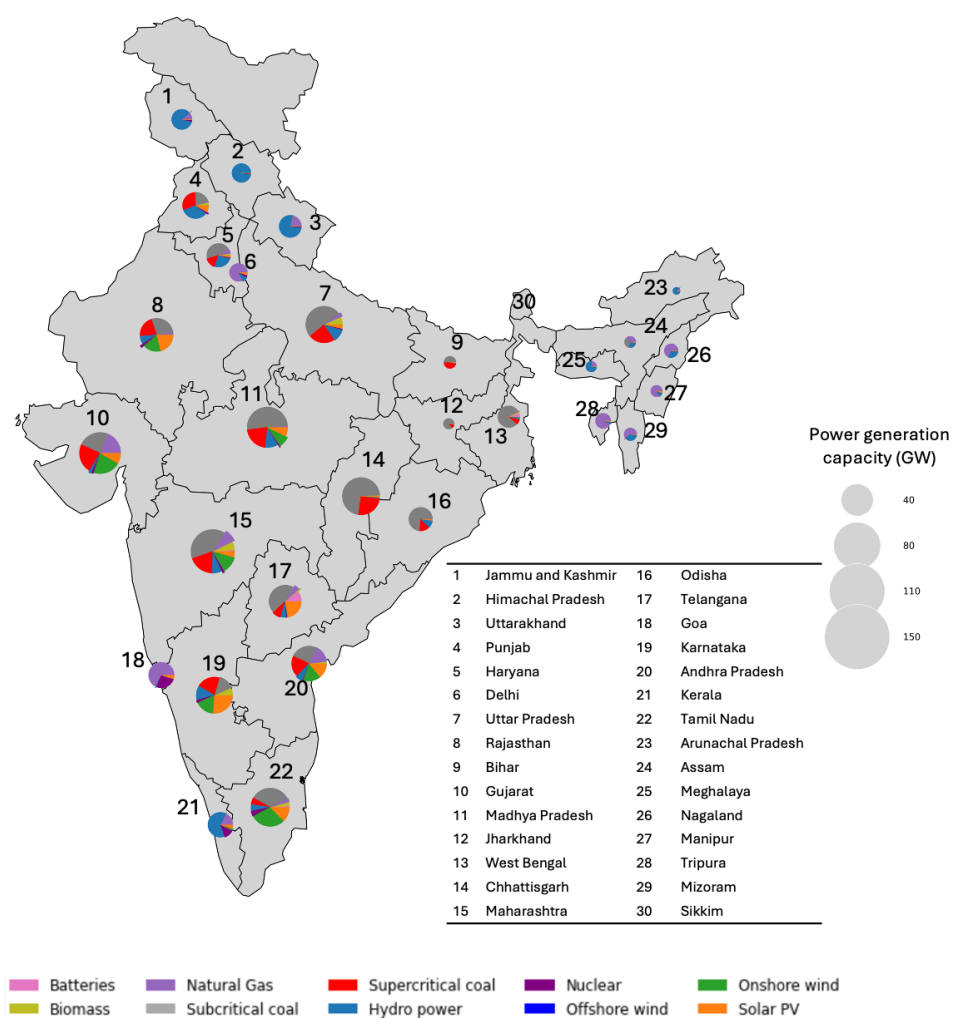


Figure B.8 Modeled India 30-region power generation capacity in 2020; The pie chart in each state shows the breakdown of different generation mix. India currently has 28 states and 8 union territories, and we select 30 regions as the entities in the capacity expansion model as listed in the right-corner table.

3. Section C - Coal Power Plant Retrofitting

3.1. Modeling the CCS and Biomass Co-firing Retrofitting

We create a new retrofitting module in the GenX [23] to model coal power plants' CCS and Biomass Co-firing Retrofitting, and the math formulation can be found in Appendix A. Figures C.1. and C.2. show the diagrams of coal-CCS and biomass co-firing retrofitting power plants, respectively. For the CCS coal retrofitting, apart from the power consumption due to the carbon capture process, the additional cost resulting from carbon transportation and storage per tonne of carbon emission is also modeled and presented in the later sections, **Appendix B**, costs of carbon storage and transportation. These carbon transportation and storage costs (\$/MWh) are modeled as a cost adder to the variable O&M costs of retrofitted coal power plants.

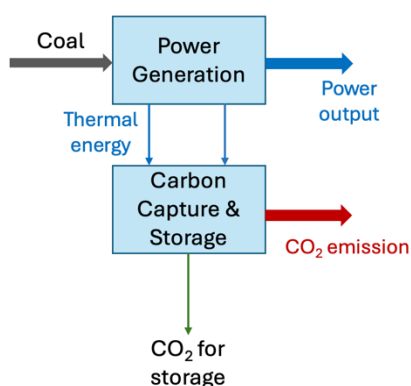


Figure C.1. Diagram for coal-CCS power plant retrofitting

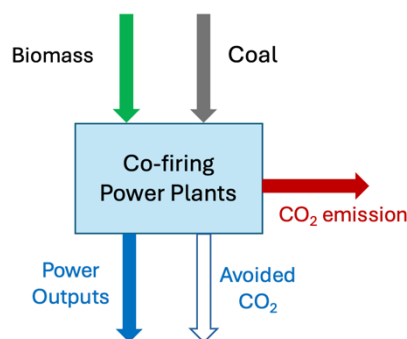


Figure C.2. Diagram for biomass co-firing coal power plant retrofitting

3.2. Costs and Technical Assumptions of CCS and Biomass Co-firing Retrofitting

3.2.1. Penalty on power capacity and heat rates due to the retrofitting

The CCS module consumes some thermal power from coal power plants. These power consumptions are modeled as net capacity losses and heat rate increments on the retrofitted power plants. These technical parameters are shown in Table C.1 based on the US supercritical coal power plants with CCS in the US NREL 2023 Annual Technology Baseline [24]. We assume the coal retrofits keep the boiler design for the biomass co-firing the same. Heat and power plant flexibility (i.e., ramp-up and down rates, start-up, and -downtime) remain unchanged before and after retrofitting.

Table C.1. Technical parameters of Coal-CCS with the 90% carbon capture rate and biomass co-firing with 20% fuel mix

Technical parameters	Units	CCS with a 90% capture [24]	Biomass co-firing with 20% fuel mix
Net Capacity Losses ($\Delta\%$ from pre-retrofit)	%	-24.00	-0.0
Heat rate increment ($\Delta\%$ from pre-retrofit)	%	+27.20	+0.0
Start-up fuel increment ($\Delta\%$ from pre-retrofit)	%	+27.20	+0.0
CO ₂ content after retrofit	tCO ₂ /MMBtu	0.01	0.08

3.2.2. Capital Costs of CCS Retrofitting in India

Since India has yet to implement the coal plants equipped with the CCS, we estimate the investment cost of the retrofitted coal-CCS power plants based on the case in China [25]. We also apply the high technological optimism factor to the first four units of a new, unproven design (i.e., first-of-a-kind unit) [26]. Table C.3 compares the retrofitting investment costs for CCS-equipped supercritical coal power plants in our study and other sources. We assume the lifetime of the CCS-equipped supercritical coal power plants is 25 years, resulting in an annualized investment of \$75.18 /kW-year.

Based on the NREL 2023 ATB data [24], the fixed O&M costs for an ultra-supercritical coal power plant without and with a 95% capture rate are \$61.60/kW-year and \$86.70 /kW-year, respectively. Given that the fixed O&M of India's supercritical coal power plant is \$24.64/kW-year, we estimate that the Indian supercritical coal power plant with CCS has a fixed O&M of \$34.68 /kW-year.

Table C.2 Capital and Operating Costs of CCS with 90% Capture Rate

Cost	Units	CCS with a 90% carbon capture
Retrofitting overnight	million/MW ³	0.74
Annualized investment	\$k/MW-year	75.18
Fixed O&M	\$k/MW-year	34.68

Table C.3 The retrofitting investment costs for CCS-equipped supercritical coal power plants in our study

References	Regions (time)	The technological optimism factor for first-of-a-kind technology	Overnight cost for retrofitting CCS-equipped supercritical coal power plants
[25] (SI, Table 15)	China (2020)	-	0.6
[25] (SI, Table 15)	China (2020)	1.1-1.25	0.66-0.74
Our study	India (2030)	-	0.74

3.2.3. Capital Costs of Biomass Co-firing Retrofitting in India

Table C.4 lists the fixed O&M, overnight, and annualized investment costs for biomass co-firing coal retrofits for unabated coal power plants [27]. The retrofitting overnight investment cost is assumed to be 50% of the capital cost of new biomass power plants. The fuel costs of co-firing coal power plants are calculated based on the share of Biomass and region-wise coal prices.

Table C.4 Capital and Operating Costs of biomass co-firing power plants in two different boiler designs

	Units	20% Biomass + 80% Coal (Sub. Coal)	20% Biomass + 80% Coal (Super. Coal)
Retrofitting overnight	million/MW	0.50	0.50
Annualized investment	\$k/MW-year	50.90	50.90
Fixed O&M	\$k/MW-year	32.36	24.64

³ The power capacity is the pre-retrofitted power capacity of the power plant.

3.3. Carbon storage and transportation cost in India

We consider CO₂ transportation and storage as cost components added to the variable O&M cost of coal power plants. The total cost of CCS consists of three parts: the cost of carbon capture, the cost of CO₂ transportation, and the cost of CO₂ storage. The cost of CCS, excluding carbon capture (\$/MMBtu), is calculated below.

Carbon transportation and storage cost (\$/MMBtu)

$$= (\text{cost of CO}_2 \text{ transportation (\$/ton CO}_2\text{)} + \text{cost of CO}_2 \text{ storage (\$/ton CO}_2\text{)}) * \text{CO}_2 \text{ content (ton CO}_2\text{/MMBtu)} * \text{CO}_2 \text{ capture rate (\%)} * \text{station heat rate (MMBtu/MWh)}$$

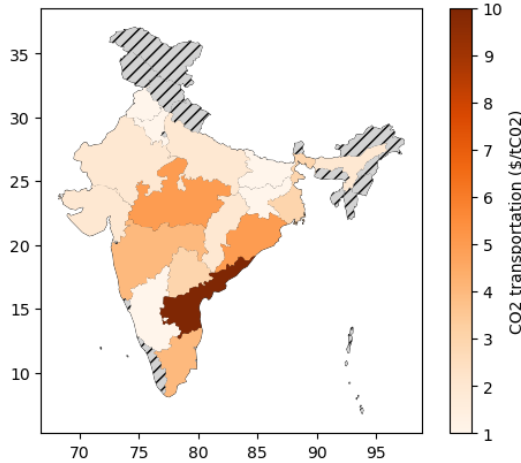


Figure C.3 Costs of carbon transportation across 30 regions (\$/tCO₂)

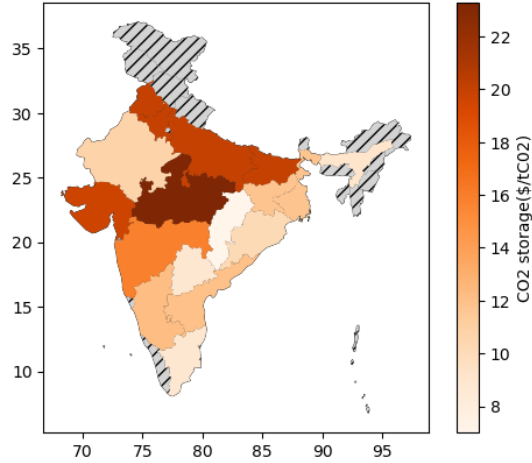


Figure C.4 Costs of carbon storage across 30 regions (\$/tCO₂)

To calculate the CO₂ transportation costs, we use the distance from each state to the nearest carbon storage reservoir [28]. Then, we multiply it by the per unit distance of the cost of carbon transportation at \$0.01/tons-km [29]. This map of the costs of carbon transportation across 30 regions is shown in Figure C.3.

To calculate the CO₂ storage costs, we estimate the cost of carbon storage using the different parameters of the CO₂ reservoir by the Integrated Environmental Control Model [29]. The costs range from \$9–20/tCO₂, as shown in Figure C.4. Importantly, our study focuses solely on saline aquifers for carbon capture and storage. We exclude enhanced oil or gas fields as a carbon utilization method, as their processes could release a portion of the captured CO₂ into the atmosphere, reducing the overall effectiveness of carbon reduction.

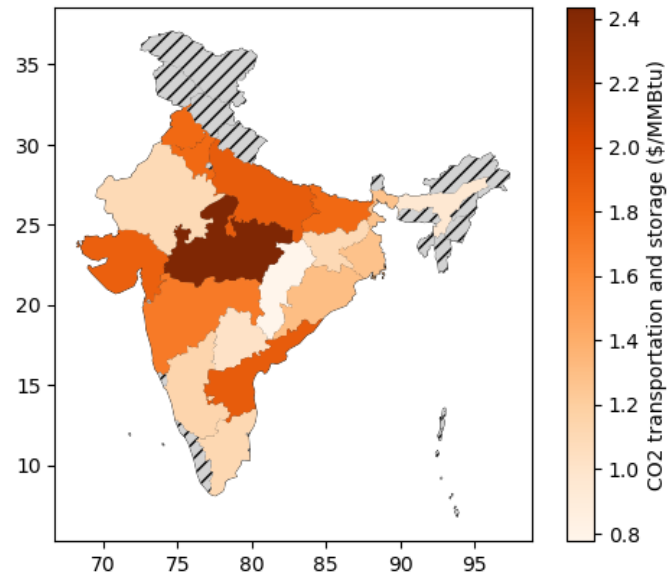


Figure C.5 Carbon transportation and storage cost (\$/MMBtu) across India

Figure C.5 shows India's average carbon transportation and storage cost per ton is between \$0.8 and \$2.4/MMBtu.

3.4. Biomass power generation potentials

Based on the National Biomass Atlas of India, we set the maximum power capacity for the planned biomass co-firing power generation in 30 Indian regions[30], as shown in Figure C.6.

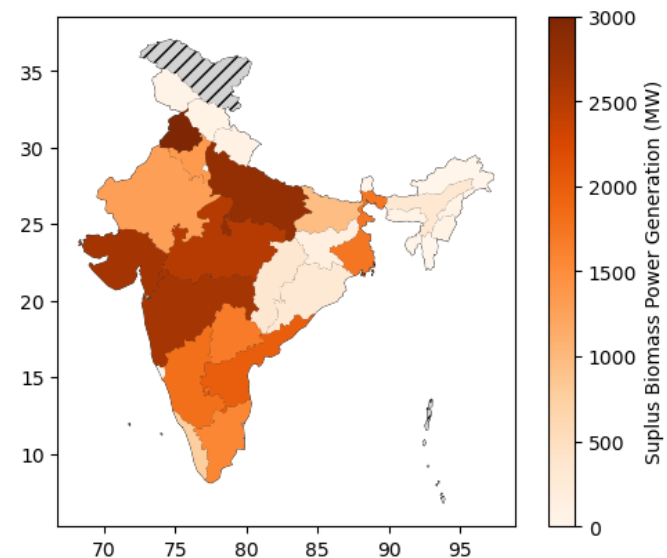


Figure C.6 The maximum surplus biomass power potentials in India (MW) (adopted from ref. [30])

4. Section D: Supplementary Figures

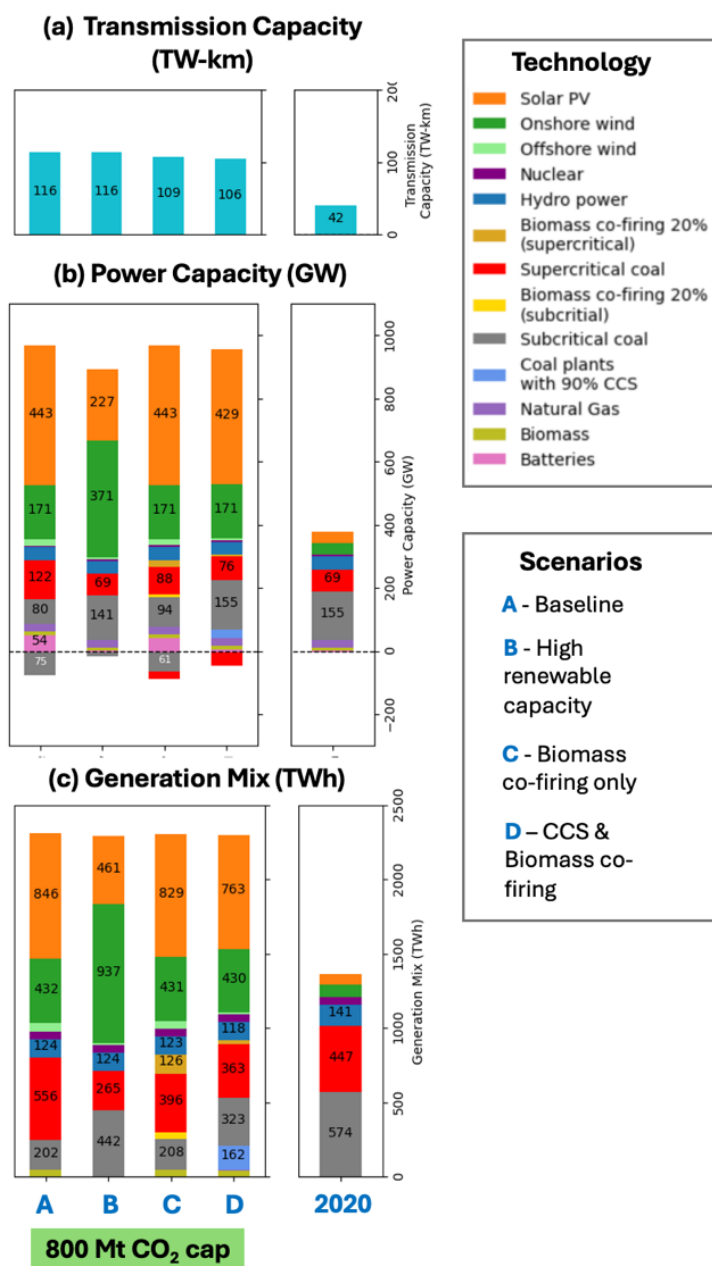


Figure D.1 (a) Transmission capacity, (b) power capacity, and (c) generation mix by 2035 under 800 Mt CO₂ cap across four technology scenarios: Baseline, High Renewable Capacity, Biomass Co-firing Only, and CCS & Biomass Co-firing. The three panels, from top to bottom, illustrate India's transmission 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

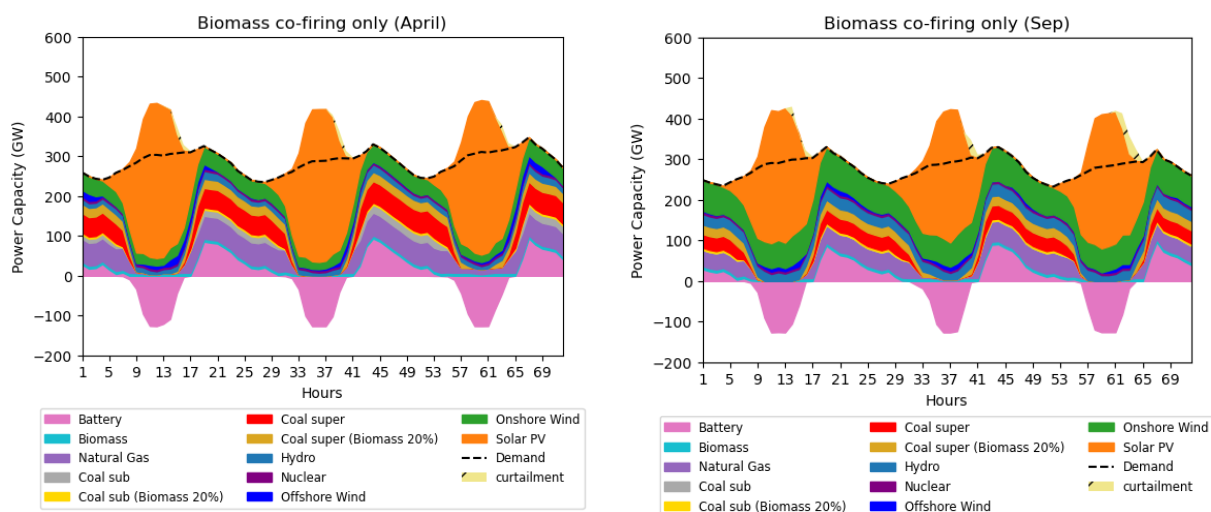


Figure D.2 Daily power dispatch results for the biomass co-firing only scenario (a) in April and (b) in September

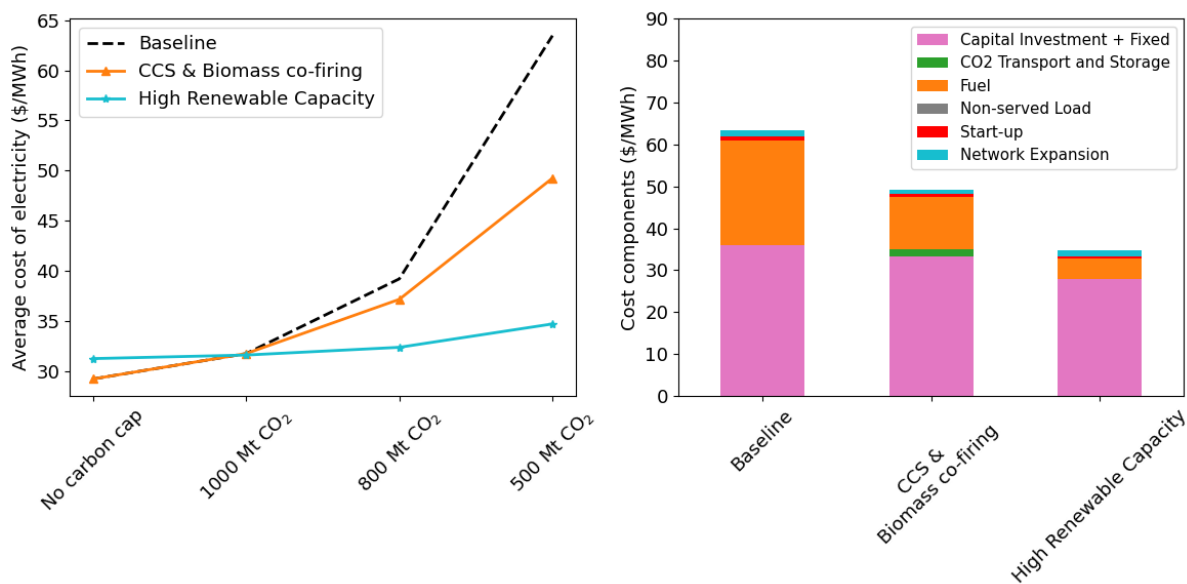


Figure D.3 (a) Average cost of electricity and (b) cost break-down in three scenarios: Baseline, CCS & Biomass co-firing, and High Renewable capacity

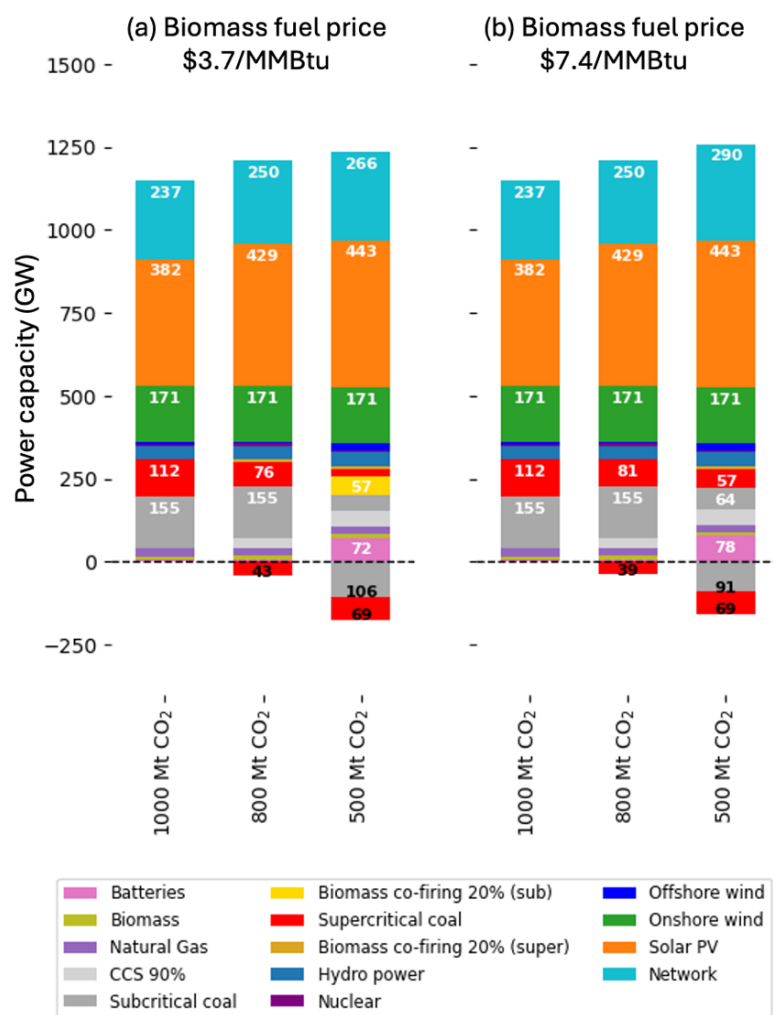


Figure D.34 Power generation capacity under different carbon caps when increasing the biomass fuel cost from \$3.7/MMBtu to \$7.4/MMBtu

Supporting Information

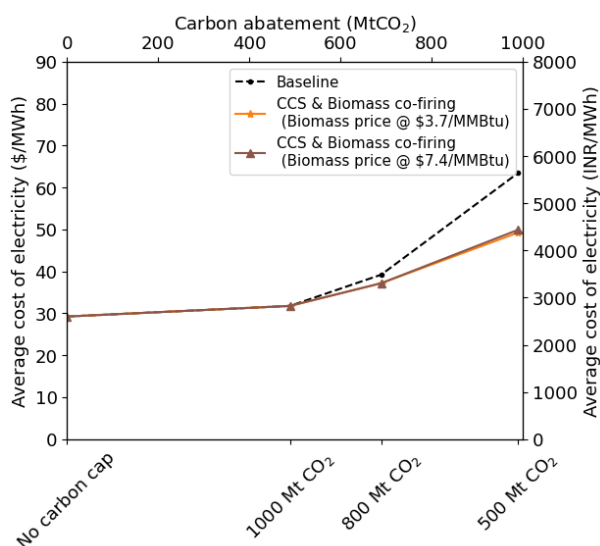


Figure D.5 (a) Average cost of electricity in the CCS & Biomass co-firing when the biomass price is \$3.7/MMBtu and \$7.4/MMBtu respectively.

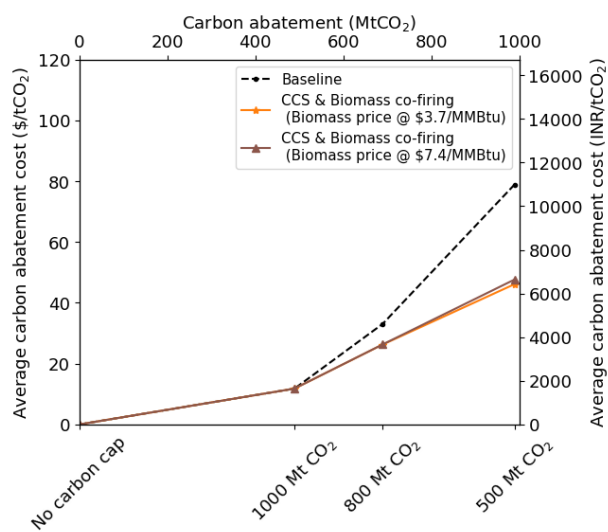


Figure D.5 (b) Average cost of carbon abatement in the CCS & Biomass co-firing when the biomass price is \$3.7/MMBtu and \$7.4/MMBtu respectively.

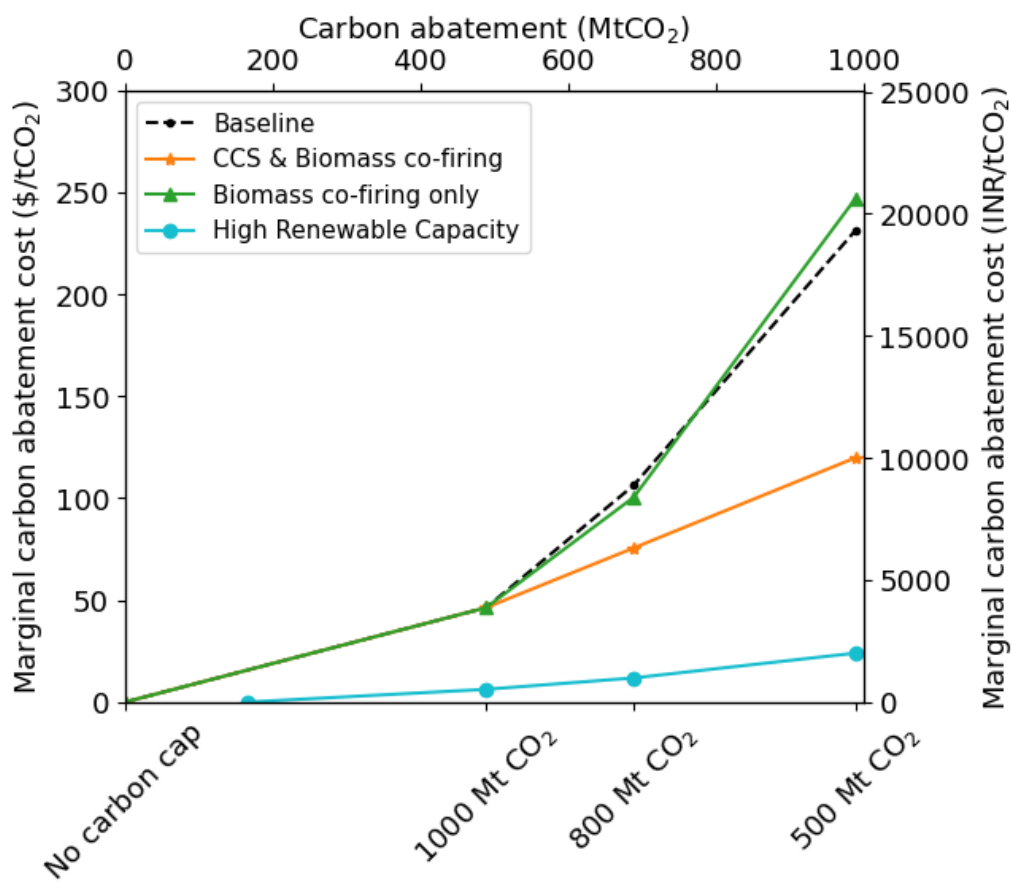


Figure D.6 Marginal carbon abatement cost of four technology scenarios

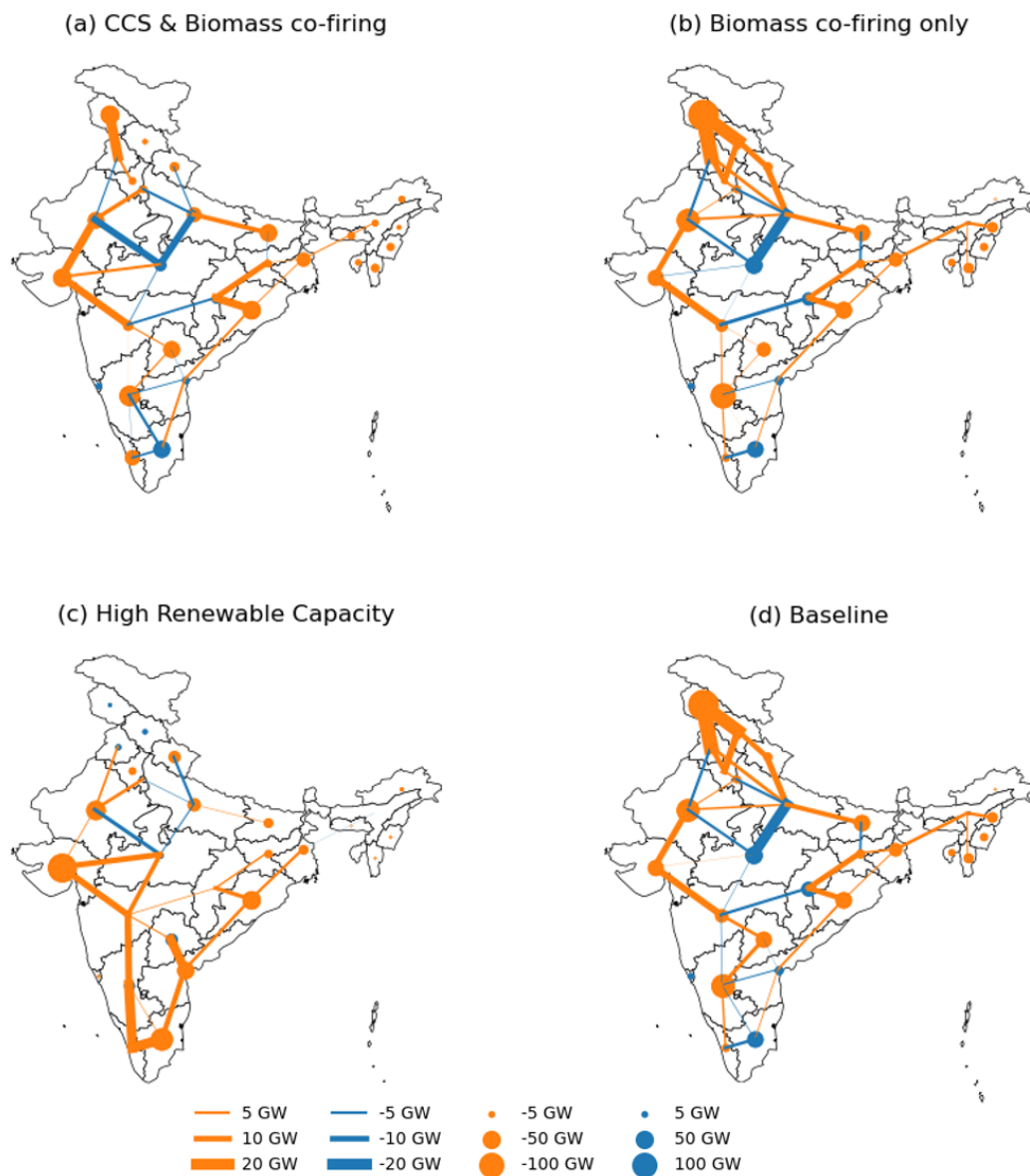
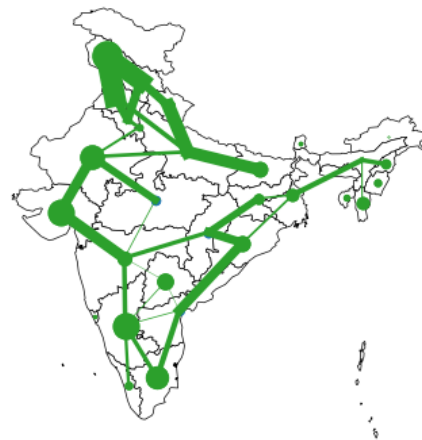


Figure D.7 Differences in the power generation and transmission capacity under no carbon cap and under 500 Mt CO₂ cap in four scenarios; The orange lines or dots represent reduced power generation and network capacity, and the blue lines or dots represent the increased power generation and network capacity.

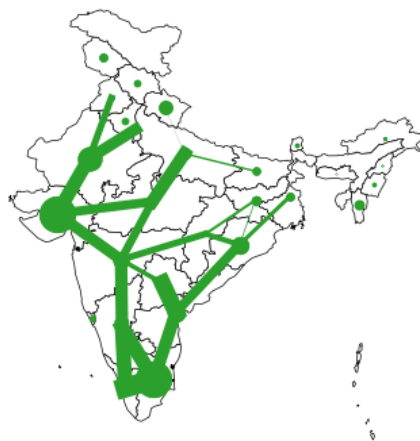
(a) CCS & Biomass co-firing 72.0 TW-km



(b) Biomass co-firing only 94.0 TW-km



(c) High Renewable Capacity 101.0 TW-km



(d) Baseline 98.0 TW-km

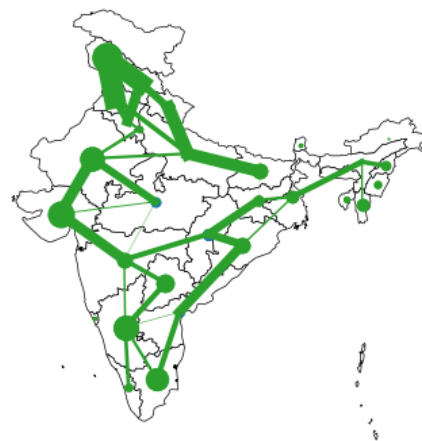


Figure D.8 Network expansion for four technology scenarios under 500 Mt CO₂ cap

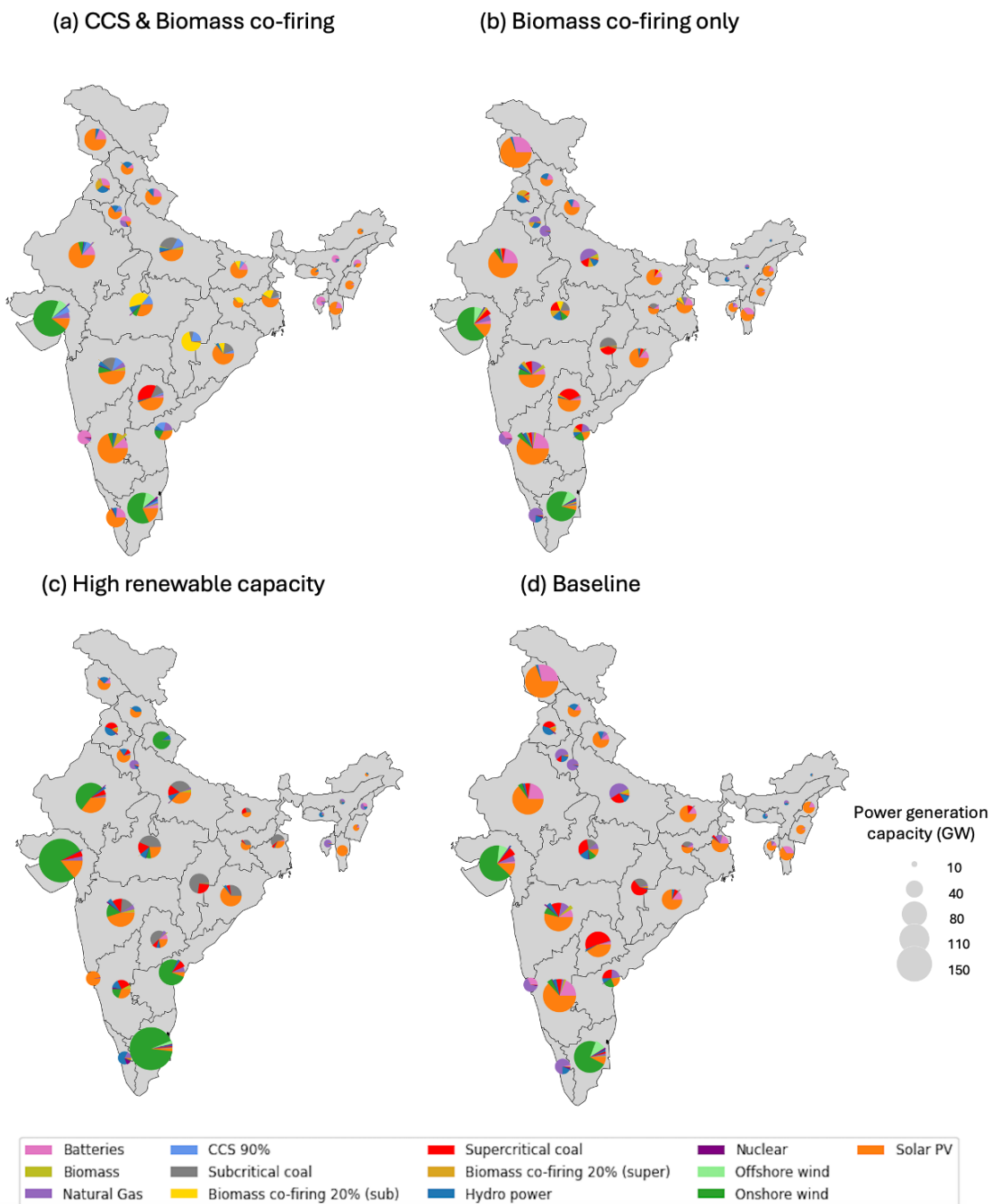


Figure D.9 India's 30-region power generation capacity by 2035 under the 500 Mt CO₂ cap in four technology scenarios: (a) CCS & Biomass co-firing; (b) Biomass co-firing only; (c) High renewable capacity; and (d) Baseline scenarios

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