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# Barriers to CCUS Deployment in India's Coal Power Sector and a Proposed Energy Pathway: A Review

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# Barriers to CCUS Deployment in India's Coal Power Sector and a Proposed Energy Pathway: A Review

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## Abstract

India's ambition to become a developed economy by 2047 and achieve net-zero emissions by 2070 creates a structural tension between growth and decarbonization. Coal supplies 60–70% of electricity, contributes roughly half of national $CO_2$ emissions, and underpins regional economies, making rapid phase-out politically and economically challenging. This PRISMA-based systematic review of 185 peer-reviewed studies identifies four mutually reinforcing barriers to CCUS deployment in India's coal power sector: high capture costs ($4.00–45.00 per tonne) and absent carbon pricing; regulatory gaps in storage liability and permitting; political resistance in coal-dependent states; and social concerns including low awareness and NIMBY attitudes. These constraints have limited progress to a single pilot project despite global expansion. Evidence from international experience supports a four-pillar pathway for India: accelerated deployment of renewable energy; strategic retrofitting of young supercritical plants; robust policy frameworks, including carbon pricing and subsidies; and just transition measures for coal regions.

Keywords: CCUS; India coal power; energy transition barriers; carbon capture; systematic review; just transition

## Introduction

India's pursuit of achieving developed-economy status by 2047 requires a sustainable economic growth rate of 8–10%. This will lead to a sharp rise in electricity demand. India's power sector relies heavily on coal.[1]It currently meets 60 to 70% of national electricity demand. This dependence creates a dilemma: coal is essential for energy security and economic growth, but it contributes 50% of the nation's CO2 emissions.[2]. This constraint follows India's environmental commitments at the 26th Conference of the Parties (COP)[3]meeting held at Glasgow: -

- Reduce total projected carbon emissions by one billion tonnes from now to 2030[4]
- Reduce the carbon intensity of the economy by 45% by 2030, over 2005 levels
- Achieve net -zero emissions by 2070.

This is a daunting task for a carbon-intensive economy like India to restructure itself to achieve net-zero carbon emissions by 2070. Research consistently frames carbon capture, utilization, and storage (CCUS) as a pragmatic "middle path" to decarbonize this sector. Several studies argue that the net-zero goal is unachievable without large-scale adoption of carbon capture, utilization, and storage (CCUS) technology in the power sector and other hard-to-abate industries [5]. The major barriers are that Coal-CCS is more expensive than unabated coal and less competitive than renewables, even with carbon pricing [6]. It has a very high-water footprint compared to renewables. Despite the geological storage potential of 359–416 Gt $CO_2$, sufficient to store centuries of current emissions [7], there are currently only pilots and small

demonstrations, with no large commercial CCS power projects in India [6]. India needs synergy between energy and industrial policy, with a forward-looking strategy, to achieve this long-term objective [7,8]. The policy responses remained fragmented. Multiple reviews call for a comprehensive CCUS framework that combines mandatory mechanisms, such as standards and caps, with voluntary instruments, such as carbon markets and credits [9,10]. Carbon pricing via a coal cess could help fund R&D and closed-loop strategies that utilize captured $CO_2$ to produce fuels, fertilizers, and building materials. It could link CCUS to industrial growth and jobs [11]. Various models analyzing India's net-zero path reinforce that CCS will play an important role in India's future energy mix alongside renewable, nuclear, and energy storage options [12–15]. Considering that coal is expected to play an important role due to its large reserves and transition needs [15,16]

This study proposes a "Third Pathway" as a compromise between a phase-out and unabated coal, advocating retrofitting existing coal-fired plants with carbon capture technology to reduce the carbon footprint and avoid social disruption from an abrupt phase-out.[17]. This will bridge the gap from a carbon-intensive to a net-zero economy.[18–22].

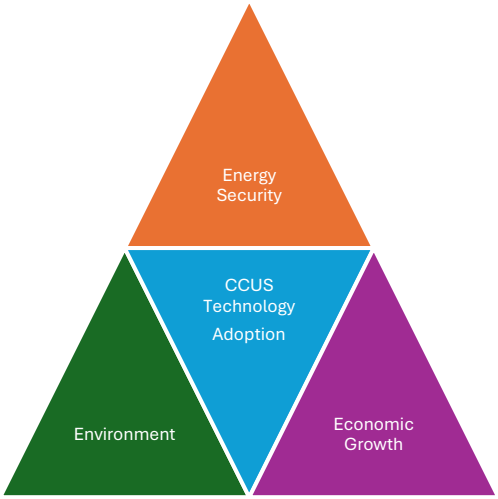


Figure 1: CCUS as a Third Pathway to balance India's energy Trilemma

Despite these benefits, the slow diffusion of this technology in India necessitates further investigation into the barriers and the identification of remedial actions to alleviate the issue.[7,23]. Against this backdrop, the study has been structured on two objectives: first, to identify the financial, policy, regulatory, political, social, and market barriers that are resulting in slow diffusion of CCUS in India's coal-fired power sector; and second, to propose a viable energy pathway for India that balances coal dependence, energy security, and climate commitments.[24,25] Through a CCUS strategy – hence addressing the critical gap between the technology potential and the benefits that can be acquired through its implementation in the Indian context.[26,27]. The proposed solution is in line with the guiding principles of just transition promulgated by the United Nations Economic Commission (UNEC)[28] and will help in meeting the Sustainable Development Goal (SDG) requirements 7, 8, and 13 by providing clean energy, environment, and employment [29]

## 2. Methodology and Literature Review

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility. The Scopus and Web of Science databases were systematically searched using the following keyword combinations with Boolean operators (AND, OR): "CCUS" OR "carbon capture" OR "carbon capture and storage" OR "carbon capture utilization and storage" AND "India" OR "Indian power sector" AND "coal" AND "barriers" OR "challenges" OR "policy" OR "regulation" OR "social acceptance" OR "just transition."

The search was limited to peer-reviewed articles, conference papers, and review papers published between 2010 and 2025. Duplicates were removed. Titles and abstracts were screened for relevance to the two research objectives (barriers and energy pathway). Full texts of potentially relevant articles were retrieved and assessed against inclusion criteria: (a) direct relevance to India or comparable coal-dependent economies (China, Indonesia, South Africa), (b) explicit discussion of CCUS in the power sector, and (c) publication in English.

Reference lists of included articles were hand-searched (snowballing) to identify additional relevant studies. A total of 395 papers were shortlisted after two stages of literature review. The first phase yielded 950 papers; the flow diagrams for both phases are shown in Figures 2 and 3.

Phase 1: Literature review

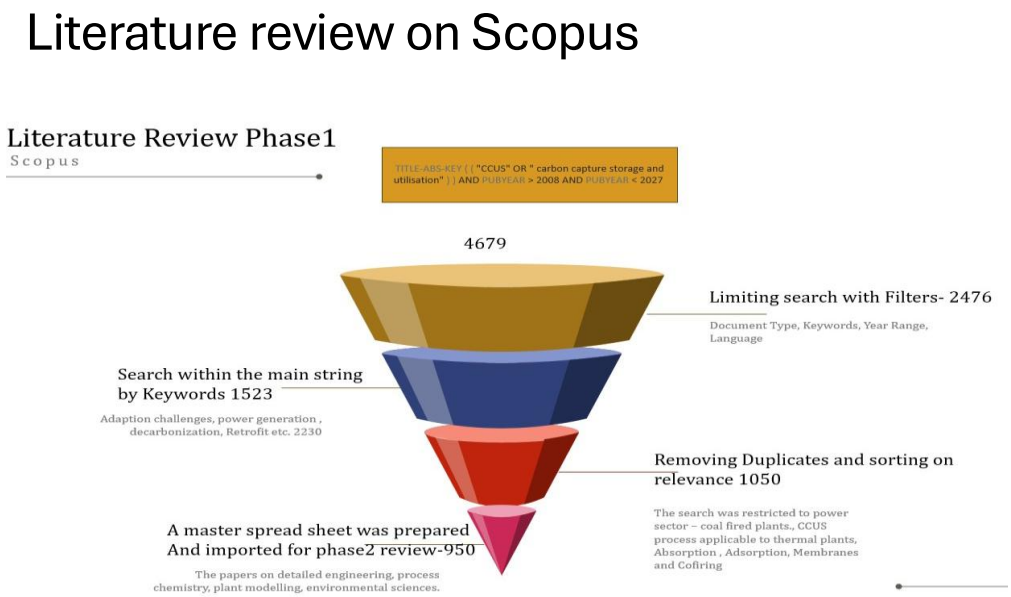


Figure2: Literature review on Scopus with keywords and Boolean combinations

Phase2: Literature Review

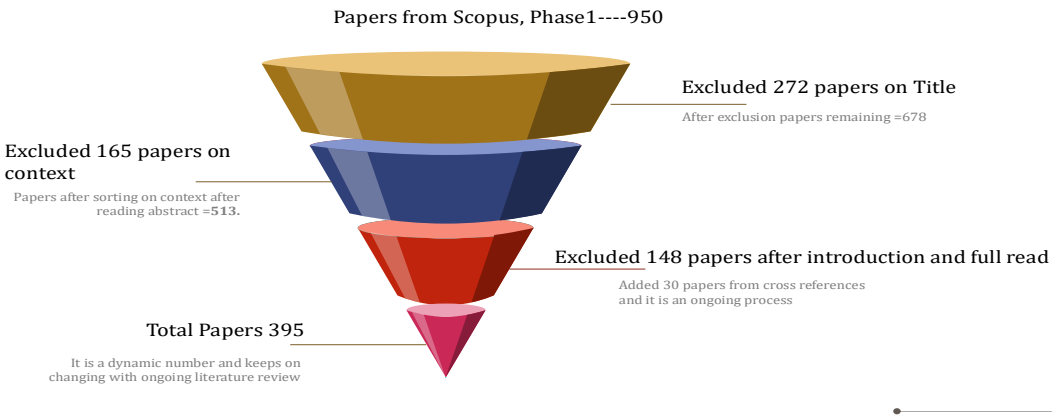


Figure3: Final Literature Review Output

## 2.1 Barriers to CCUS Deployment in India

Indian power sector review indicates that the power sector is highly coal-dependent[1],[30] supported by large coal reserves[31] [2]. The other key feature of the Indian power sector is the dual control of the state and the central governments. [32] . The pattern of past decisions, an indicator of the government's energy strategy, has been to reduce the power deficit by constructing more coal-based thermal plants.[33][34] and its detrimental effects on the environment were ignored[35] Partially due to a lack of scientific evidence and lack of consensus between the nations before the Paris Agreement in 2015[36,37]India has fulfilled its NDC commitments made under the Paris Agreement by expanding its renewable energy portfolio and increasing its forest cover. The long-term goal of net-zero carbon by 2070 can only be achieved by either phasing out coal or adopting carbon capture along with biofuel cofiring. [38]

The paper highlights that phasing out coal is not a feasible solution in the Indian context because of high dependence on coal and the large number of coal-fired plants still operating to meet the country's electricity demand.[39][40–42]. The power generation, economic growth, CO2 emissions, climate change, and societal impacts are all correlated.[43–45]. This makes the energy transition policy an interdisciplinary problem, with an added complexity due to politics at both national and international levels. [46]and pervasive impact across diverse sectors[47–50]. CCUS has been proposed as a viable solution by various international agencies like the IEA and IPCC[19,51,52]. The USA, Canada, and China have adopted carbon capture technology. [53] and other carbon-intensive economies [51][54–56].

The deployment of CCUS in India faces significant financial, regulatory, political, and social barriers. Financially, high capital and operating costs, combined with insufficient infrastructure and weak carbon pricing mechanisms, hinder large-scale adoption [5,57,58]. Regulatory challenges include underdeveloped frameworks for $CO_2$ storage, unclear liability rules, and fragmented permitting processes [59]. Politically, entrenched interests in coal-dependent

regions and the risk of job losses create resistance to transition policies[60–62]. Socially, public skepticism about CCUS safety and efficacy, as well as concerns over local impacts ("Not in My Backyard," or NIMBY), further complicate deployment [63,64]. The following subsections examine each barrier category in detail based on the available literature.

### 2.1.1 Financial Barriers

High capital (CAPEX) and operating (OPEX) costs are the most cited hurdles in CCUS adoption, along with the absence of Return on investment (ROI) due to the lack of downstream utilization markets and robust carbon pricing. Capture costs range from $ 4.00 to 45.00 /tonne) with additional expenses for transport and storage infrastructure[5,58] . The absence of government subsidies makes projects financially unattractive compared to renewables or business-as-usual operations. [5,57] Perceived investment risk and the absence of de-risking instruments, coupled with constraints on private-sector profitability, are the main causes of the lack of private investment and participation. [65–77]

### 2.1.2Regulatory Barriers

India lacks a comprehensive regulatory framework for CCUS, including long-term storage liability, $CO_2$ monitoring requirements, permitting regulations for $CO_2$ pipelines and carbon storage, and clear rules on ownership of geological storage space. [78]. Non-alignment between fragmented CCUS[9] and environmental or ambiguous regulations increases project risk. International experience shows that clear legislation on $CO_2$ injection, storage, and transportation is essential, and monitoring is crucial for scaling up CCUS.[22,78] An incomplete CCUS legal framework, which results in unclear roles among the agencies involved, coupled with the absence of CCUS plant integrity standards, impedes CCUS implementation in India. [48,79,80]

### 2.1.3 Political Barriers

Weak political will, fragmented governance, and competing development priorities—resulting in political resistance to CCUS and the broader coal transition in India—stem from the deep entrenchment of coal in regional economies—particularly in eastern Indian states—and from the influence of vested interests, such as industry conglomerates and labor unions.[60–62,81] . The political resistance is further augmented by economic, employment, and infrastructure deficiencies, and by a lack of public awareness of environmental consequences; these are the main causes of political inertia.

2.1.3.1 Economic dependence of coal-rich states

Coal reserves are concentrated in eight states, with Odisha, Jharkhand, Chhattisgarh, West Bengal, and Madhya Pradesh together holding 97.4% of India's total coal reserves. These five states account for 21% of India's population but have below-average GDP, making them heavily dependent on coal revenue (Ministry of Statistics, Performance and Implementation, 2024). In 2023, Coal India Limited (CIL) generated $59.17 billion in revenue from these states. India is continuously ramping up coal production from mines through mining reforms and efficiency improvements, indicating that coal is likely to remain a key energy source in the coming decades and maintain its status as the number one primary energy source for power

generation. Table 1 summarizes the annual revenue, population, and GDP status of these five coal-bearing states.

Table 1: (Source: Ministry of Statistics, Performance and Implementation, 2023]

| State | Annual Revenue from coal mining, 2023 (billions $) | Population in millions | GDP status relative to average national level |
|---|---|---|---|
| Odisha | 14.40 | 46.00 | Below average |
| Jharkhand | 15.59 | 39.00 | Below average |
| Chhattisgarh | 12.54 | 30.00 | Below average |
| West Bengal | 4.02 | 99.00 | Below average |
| MP | 12.59 | 86.00 | Below average |

2.1.3.2 Employment dependence

The coal sector employs approximately 1 million people directly in mining and power generation, representing 1% of India's national labor force. The sector contributes 2.5% to national GDP (Ministry of Performance, Statistics and Implementation, 2020–21). Beyond direct employment, the coal value chain supports hundreds of thousands of indirect jobs in transportation, equipment supply, and ancillary services.

2.1.3.3 Infrastructure dependence

Indian Railways is another major beneficiary of coal dependence. In 2023–24, railways earned $72.80 billion from coal freight, accounting for 47% of their total freight earnings (Ministry of Railways, 2024). A rapid reduction in coal transportation would therefore create a significant revenue gap for the national railway network, affecting its ability to cross-subsidize passenger services.

2.1.3.4 Political consequences

Concerns about employment loss and revenue decline among coal workers and coal-dependent states create strong opposition to rapid decarbonization or large-scale CCUS adoption without parallel just transition policies[61,82]. Local politicians in coal-producing states have strong incentives to resist policies that threaten state revenue, employment, and their constituents' livelihoods, leading to opposition from trade unions and regional political parties. [62]. This political economy constraint explains why India has consistently endorsed "coal phase-down" rather than "coal phase-out" in international climate negotiations.

**2.1.4 Social Barriers**

Public acceptance is highly variable (40–60% approval rates from available surveys) but generally hampered by low awareness of CCUS technologies, skepticism about safety (e.g., leakage risks), fears of continued fossil fuel dependence (“greenwashing”), NIMBY attitudes toward local storage sites and infrastructure development, and lack of trust in government or

project developers[58,63,64]. Transparent communication between stakeholders and community engagement are essential for effective policy formulation but are often lacking.[83–86]

### 2.1.5 Technological Barriers

The CCUS technological landscape is evolving rapidly; various variants of the technology are available, and a few are at different technology readiness levels. These can be retrofitted and integrated with the existing system at different levels. Since technology is in an evolving stage and there is a lack of information on actual field results and implementation costs, coupled with high capital requirements and the irreversibility of decisions, the selection is difficult. The literature highlights post-combustion carbon capture technology, which has been used in power generation plants. India is dependent on technology transfer due to a lack of in-house innovation. A phased adoption of CCUS will be the preferred option, and the risk can be minimized through institutional and government support by scaling up pilot projects. [9,10,87–92]

### 2.1.6 **Interplay and Synthesis of the barriers**

The literature identifies high costs, regulatory uncertainty, political inertia, and social scepticism as the core barriers to CCUS deployment in India's coal-fired power sector.[5,22,57,58]. These constraints are mutually reinforcing unclear liability rules deter investment and keep costs high, while political resistance weakens policy signals and leaves social concerns unresolved.

Despite growing global evidence of technical feasibility, India lags due to limited policy support and the absence of large-scale demonstration projects.[6,93] Studies show that even substantial public funding cannot compensate for weak regulatory and market conditions. [22]International experience underscores the need for credible policy signals**,** targeted early-stage subsidies**,** clear legal frameworks **for** storage and monitoring, and active community engagement.[94] These barriers interact in a non-linear, self-reinforcing cycle that keeps CCUS at pilot scale in India. **Table 2** summarises each barrier and its manifestations. In contrast, Table 3 maps the cross-cutting pathways through which they amplify one another—highlighting why isolated interventions are insufficient and why coordinated, multi-dimensional policy reforms are essential.

Table 2: Relevant papers on barriers resulting in low diffusion of CC in India

| Barriers | Emphasis | Reference Papers |
|---|---|---|
| Technological | Technological uncertainty, technology readiness, infrastructure, high energy penalties, lack of innovation, scaling up of technology, retrofit integration, high cost of capture, absorption capability, Institutional support, policy support | [5,9,10,14,22,38,74,87–91,95–97] |
| Societal | Socioeconomic impact,<br>Public approval, stakeholder trust and acceptance, public perception on CCS, acceptance of CCS, public awareness, | [83–86]<br>[98,99] |

| | | |
|---|---|---|
| | just transition, public resistance, institutional trust deficit, risk intolerance, Policy | |
| Political | Weak political will, fragmented governance, policy misalignment, competing development priorities, perception of coal lock-in, institutional inertia, dependence on international technology and finance | [100–112] |
| Financial and economic | High capital and operating costs, Absence of downstream market, robust carbon pricing and revenue stream, perceived investment risk and absence of de-risking investment risk mechanism and instruments, sector profitability constraints, absence of private investments and participation | [65–68,70–77,113,114] |
| Regulatory and environmental | Incomplete CCUS legal framework, unclear roles of agencies, lack of standards on plant integrity, limited alignment between environmental and CCUS regulations, public awareness on the impact of environmental degradation, Lack of monitoring regulations | [48,79,80]<br>[5]<br>[9] |

**Table 3: Cross-Cutting Interplay Among Barriers**

| Reinforcing Pathway | Mechanism | Consequence | Illustrative Evidence |
|---|---|---|---|
| Regulatory → Financial | Unclear liability rules increase investor risk perception | Higher cost of capital; fewer private investments | **[22,57]** |
| Financial → Technical | Lack of funding prevents large-scale demonstrations | No learning-by-doing; costs remain high; no performance data | **[6,58]** |
| Political → Regulatory | Coal-dependent regions resist strong decarbonization policies | Weak or delayed CCUS-specific regulations; low carbon pricing | **[60,81]** |

| | | | |
|---|---|---|---|
| Political → Social | Job loss fears amplified by lack of just transition planning | Community opposition; NIMBY attitudes; rejection of projects | **[61,62]** |
| Social → Political | Public skepticism reduces political will for CCUS support | Governments hesitate to commit funds or pass enabling laws | **[58,63]** |
| All four together | Self-reinforcing cycle of inaction | Persistent status quo; CCUS remains at pilot scale; net-zero targets at risk | [22] |

### 2.2 CCUS as an Energy Pathway for Coal-Dependent Economies

The literature proposes various energy pathways in the Indian context.[115,116] But the common features across all proposed energy pathways include a mixed portfolio of assets, with proportions varying depending on the modeling techniques and analytical approaches used.[117,118]. Coal-fired power generation with CC in varying proportions is one of the economically viable mixes. Some authors refute the idea of any new coal-fired power plants, contrary to the recent government sanctions on new coal-fired plants.[119]. The proposed energy pathways must be analyzed from an implementation perspective. CC retrofit depends on the available space; depending on the plant layout, it will reduce the existing plant's generation capacity and increase water consumption. The newer plants aged between ten and fifteen years, with higher thermal efficiency and supercritical boilers, are an ideal choice for a retrofit.[38].

Table4: Energy pathway with CCUS

| Emphasis | Reference papers |
|---|---|
| Deployment pathway through enhanced oil recovery and utilization of carbon dioxide by increasing economic feasibility | [120–123]<br>[124] |
| Project evaluation and better cost estimation methods by including monetary and non-monetary benefits | [125–129] |
| Pathways to net-zero carbon for Indian long-term objective | [130–144] |

| | |
|---|---|
| Strategies for energy transitions | [15,145–148] |

## 2.3 **Carbon capture processes**

At the heart of the CCUS supply chain is the carbon capture process; the chain begins with it. The storage, transportation, and utilization complete the CCUS chain. The carbon capture process is the most cost-intensive part of the CCUS.[72]. Carbon capture technology has different variants and can be integrated into existing processes at various stages of combustion. The literature on the different CC technologies is tabulated below.

Table 5: Literature review on CCUS process

| CO2 Capture/Reduction | Technology | Advantages | Disadvantages | Technology Readiness Level | References |
|---|---|---|---|---|---|
| Precombustion | Coal Gasification | CO2 is captured in an independent plant, after conversion of CO produced during reduced combustion, and H2 is used for combustion | It requires H2 storage to provide flexibility and Reliability. 2. It is a costly option to integrate existing coal plants 3. It is an energy-intensive process. | TRL9, IGGC plants are in operation | [87–91] |
| Combustion | Cofiring | Oxy Fuel, Biomass, Methanol, H2 combustion | The cofiring requires modifications of the combustion equipment and the boiler. | Biomass TRL9 Oxy fuel and H2 combustion are at the technology Demonstration | [92–95] |
| Post Combustion | Absorption, Adsorption, Cryogenic, Hybrid Options | Absorption is a chemical process, Adsorption uses membranes, | Suitable for retrofit on existing plants | TRL for Absorption and Cryogenic | [37,96–107] [108] |

| | | | | | |
|---|---|---|---|---|---|
| | | and the cryogenic process | | | |

2.4: Project evaluation techniques limitations

The existing literature on CCUS feasibility relies predominantly on traditional techno-commercial evaluation tools. [149]such as net present value (NPV) and internal rate of return (IRR)[21,38,150,151]. While these methods estimate lifecycle costs and the present value of investment returns, they are highly sensitive to the discount rate, which is inherently ambiguous for long-horizon, policy-dependent technologies like CCUS. Moreover, NPV and IRR frameworks systematically exclude non-market benefits, including improvements in public health from reduced $CO_2$ emissions, employment generation in emerging CCUS value chains, and the macroeconomic advantages of extending the operational life of existing coal-fired power stations.

India's power system remains structurally dependent on coal; consequently, despite sustained pressure from COP member nations, India has refrained from endorsing the global **"**coal phase-out**"** pledge and instead maintains a more flexible "coal phase-down" position. As the third-largest emitter globally**,** after China and the United States, India faces increasing scrutiny over its decarbonization trajectory. Notably, both China and the United States have positioned CCUS as a central mitigation option for their coal-based power fleets. Other coal-reliant economies—such as Indonesia and Japan—have similarly incorporated CCUS retrofitting into their long-term energy strategies.[51,152].

Globally, more than 135 CCUS projects in the power sector are in various stages of development, and the successful commissioning **of** SaskPower's 115-MW Boundary Dam Unit 3 in 2014 demonstrated the technical feasibility of post-combustion capture on commercial coal units.[53]. Against this backdrop, CCUS adoption in India's coal-fired power plants appears to be a technically viable and strategically aligned pathway**.** CCUS diffusion has been markedly slower in India **t**han in other carbon-intensive economies. Section 3 of the paper reinforces the need for coal-fired assets in the energy mix; the remainder of this paper examines how to alleviate some of the barriers constraining CCUS diffusion and proposes a practical pathway for CCUS in the Indian power sector**.**

## 3.0 A Viable Energy Pathway Balancing Coal Dependence, Energy Security, and Climate Commitments

India's ambition to achieve developed-economy status by 2047 while meeting COP26 net-zero goals presents a complex energy trilemma: electricity demand is projected to rise sharply, yet coal remains the backbone of the power sector and heavy industry. Research consistently identifies carbon capture, utilization, and storage (CCUS) as a pragmatic "middle path" that can decarbonize coal-dependent sectors without abrupt disruption [4,6,9,153–155]. CCUS is especially critical for hard-to-abate sectors—power, steel, cement, and chemicals—which together account for 60–80% of India's $CO_2$ emissions[9,153,156,157]. The large-scale CCUS deployment faces economic, technical, and social hurdles. The literature suggests that a

balanced pathway must combine rapid expansion of renewable energy with targeted CCUS retrofits in coal power and industry, supported by strong policy incentives and just transition measures [4,153,155,158]. This section synthesizes recent research on how such an integrated strategy can deliver both energy security and climate resilience for India.

### 3.1Coal Dependence and Energy Security Constraints

Coal currently supplies over 60% of India's electricity, and its role is projected to remain significant through at least 2040–2050 due to abundant domestic reserves, low-cost generation, and developmental needs. [4,62,159,160].

3.1.1 Scale of coal reserves:

India holds 378.21 billion tonnes of coal reserves, sufficient to support current consumption rates for approximately 300 years (Ministry of Coal and Mines, 2024). The country ranks 5th globally in coal reserves, accounting for roughly 10% of the world's total. Table 4 provides a comparative snapshot of India's primary energy reserves, highlighting the overwhelming dominance of coal relative to oil and natural gas.

Table 6: India's Primary Energy Reserves and Consumption (2023–24)

| Primary Energy | Unit | Reserves | Consumption/year | Import | Export |
|---|---|---|---|---|---|
| Coal | Billion tonnes | 378.21 | 1.00 | 0.21 | .001 |
| Oil | Million tonnes | 671.60 | 233.00 | 242.00 | 0.00 |
| Natural Gas | Billion cubic meters | 1094.30 | 68.76 | 36.00 | 0.00 |

As Table 4 shows, the ratio of oil and gas reserves to consumption is extremely low compared with that of coal. India imports approximately 85% of its crude oil requirements and a significant portion of its natural gas. Coal, by contrast, is largely domestically sourced, making it a strategic asset for energy security.

3.1.2 Transition cost to renewables.

India's power generation capacity comprises 50% coal-based assets, with rapid additions over the last two decades. Phasing out coal-fired plants and replacing them with renewable energy

is neither economically viable nor feasible, as 70% of electricity generation still comes from coal-fired plants. The decommissioning and building new capacity are time-dependent processes. They will put India into a spiral of power shortages during the transition, thereby affecting the economic growth trajectory and requiring a huge capital outlay of Rs 164,300 crores/annum for the next 20 years, with an immediate closure option [7] [65]. The phase-out of these plants needs to be stretched over the years, depending on the rate of renewable power addition. The breakdown of these costs is given in the tables below. Table 7 shows the switching-over cost range, including decommissioning and replacement, which depends on plant specifications, layout, and renewable energy preference. Tables 8 to 10 give a breakdown of decommissioning, renewable changeover, and CCUS retrofit costs.

Table7: Switch-over cost from fossil to Renewables (Data Source IEA and Gov UK)

| Capacity GW | Capex cost/GW (US billion Dollars) | Cost (US billion dollars) | Assumptions | References |
|---|---|---|---|---|
| 212 | 3.2- 6.7 | 678.4- 1420 | New plant capital cost includes planning and pre-project costs | [66][67] |
| | | | Construction costs vary between the countries. The plant's size and technical specifications can affect the cost. | [68,69] |

The breakdown of decommissioning cost and replacement by renewables is highlighted in Tables 8 and 9

3.1.2.1 Decommissioning Cost

The thermal power stations are hazardous sites with chemicals, volatile substances, large structures, excavated ash pits, water sources, and electricity generation and transmission equipment. This cannot be left unattended and must be demolished to make the site safe for further utilization.

Table8: Decommissioning Cost of Existing Coal-Fired Plants

| Capacity GW | Decommissioning Cost/GW in billion USD | Cost in billion USD | Assumptions | References |
|---|---|---|---|---|
| 212 | .051-.466 | 10.82-165.48 | The decommissioning cost will vary according to the law of the land. Environmental regulations for hazardous material disposal and the location of the plant | [65] |

3.1.2.2 Replacement Cost

The retired fossil assets need to be replaced with renewables before phasing out the retiring capacity, assuming the retired capacity is replaced with an equal split between wind and solar. The seasonality of renewable energy needs to be accounted for. The system can be balanced only by building double the capacity of each GW of coal power generation capacity being retired. Therefore, renewable generating capacity required to replace the existing 212 GW of coal will be 424 GW. This will match the generation capacity, but another important factor that directly affects grid stability is the rate at which the power is supplied to the grid; coal-fired plants can be ramped up or ramped down to follow the demand requirements, while renewables do not have that option because of their dependence on the input of solar and wind energy, which are natural processes and uncontrollable. This raises energy storage issues; several storage options are available, including chemical, hydro, and mechanical. The most popular option is battery storage, which entails disposal and replacement costs due to the limited battery lifespan; all these factors need to be factored in when making a switchover decision from coal to renewables.

Table9: Replacement cost of renewables

| Capacity in GW | Capital Cost/ GW with battery storage in billion USD | Cost in billion USD | Assumptions | References |
|---|---|---|---|---|
| 212 GW- Solar<br>212 GW - onshore Wind Battery Storage Cost | 1.075-1.6(Solar)<br>1.375- 2.250(Wind) | 227.9- 339.2<br>291.5- 477.00 | The cost varies as per specification, installation site, | [68] |

Total Cost of coal switchover with renewables = Loss of 212 GW of coal generation + Decommissioning cost of 212 GW + Cost of 424 GW renewables to replace decommissioned 212 GW of Coal generation
Total Cost of switchover (lower range) = 678.4+10.82+519.4 = 1208.62 billion USD
Total Cost of switchover (Maximum Range) =1420+165.48+816.2= 2401 billion USD
Average cost of switchover = 1804.6 billion USD

The GOI planned expenditure is 80 billion USD for 2026-27. It is a mammoth task to raise such a large amount of capital for the switch to renewables. It justifies the Indian Government's stance on the phase-down of coal-fired plants. Historical data from the Ministry of Power indicate that India added the highest renewable capacity of 20 GW/year over the last decade. Based on historical figures, it will take approximately 20 Years to replace the existing coal-fired capacity, and additional generation capacity will be required to compensate for population growth.98% /annum, urbanization growth@2%/ annum, and 6.5% economic growth/annum to meet the economic growth objective [70]. On the contrary, these assets can supply electricity for the next 40-50 years without any import burden. The CCUS retrofit on these existing plants can be the most viable solution, as indicated in Table 10

Table 10: Cost of CCUS to the existing plants (IEA)

| Capacity in GW | CCUS cost/ton of CO2 capture | CO2 emissions from Indian coal-fired plants | Assumptions |
|---|---|---|---|
| 212GW | 50-100 USD | 1527 million tonnes | Capex is 80%; all coal plants will be retrofitted |

Minimum cost for CCUS retrofit on existing plants =1527*.80*50= 61.080 billion USD
Maximum cost for CCUS retrofit on existing plants = 1527*.80*100= 122.160 billion USD
Average cost for CCUS retrofit on existing plants = (122.160+61.080)/2 =91.62 billion USD

The exhibits demonstrate, through preliminary calculations, that 212 GW of Coal power generation can be made environmentally compliant, provide energy security, and maintain the social status quo for decades at an average cost of 91.62 billion USD, compared to the renewable switchover cost of 1804.60 billion USD. The CC retrofit also yields nonmonetary benefits, including job retention in the power and mining sectors, additional jobs created by CCUS technology, additional revenue from carbon utilization, and reduced CO2 emissions, thereby slowing the rate of environmental degradation. The calculations shown are preliminary, and the project evaluation requires a detailed analysis because these costs depend on the process, location, and existing plant specifications.

Table11. CCUS and Its Non-Monetary Benefits

| Security | Social | Environment | Sustainability | Compliments SDG Goals |
|---|---|---|---|---|
| Coal Reserves utilisation and a self-sufficient energy system | Job creation and new skill sets | Reduces CO2 emissions | Uses CO2 for the generation of e-fuel, hence import reduction | SDG 13- Action to reduce GHG is achieved through CCUS |
| Reliable source of power | No redundancy in coal mines or coal-fired stations | Reducing vulnerability risk of coastal states | Creates a new commodity market from waste | SDG 7: Use of renewables and CCS |
| No disruption to the existing infrastructure | Improves health by emission control | Reduces the adverse effects of climate change | Reduces carbon footprint through recycling | SDG 8: economic growth and decent work |
| Value realization from existing assets | No interstate migration for lost jobs | Reduces environmental adaptation | Produces new products like refrigerants, firefighting equipment | |
| Flexibility to meet load demand | No loss of revenue for coal-dependent states | Reduces Environmental degradation | Preserve natural resources for future generations | |

The above synthesis identifies the core components of a viable energy pathway for India. The literature also reveals areas of debate, unresolved trade-offs, and implementation gaps. The following claims and evidence table, research gaps matrix, and open research questions—derived directly from the reviewed studies—are presented here as analytical outputs that will inform the Discussion and Recommendations sections of this paper.

3.1.3 Energy security rationale**:**

Rapid economic growth has driven up $CO_2$ emissions by over 3% annually in recent decades. [6,157]This makes decarbonization urgent but politically and economically challenging. Any realistic pathway must therefore acknowledge that coal will not be phased out abruptly; rather, the focus must shift to reducing its emissions intensity while maintaining energy security and

avoiding import dependence. The domestic availability of coal insulates India from global price volatility and geopolitical supply disruptions that affect oil and gas markets.

3.1.4Developmental constraints**:**

Coal-fired power generation remains among the most affordable sources of electricity in India, particularly for base-load supply. The levelized cost of electricity from existing (fully depreciated) coal plants is significantly lower than that of new renewable projects with storage and lower than that of imported coal or natural gas. For a country where 89% of the population falls into low- and middle-income brackets (World Inequality Report, 2022–23), affordability is a critical policy constraint. Rapid coal phase-out without adequate alternative capacity would risk electricity price increases, energy poverty, and economic disruption.

3.1.5Strategic Role of CCUS

Hard-to-abate sectors—including supercritical coal power plants, steel, cement, and chemicals—are major sources of emissions that renewable energy alone cannot quickly deliver deep cuts. [5,9,153,154,156,157,161]. CCUS functions as an enabler: integrated modelling shows that combining advanced coal technologies with CCUS can reduce emissions by up to 45% over business-as-usual by 2050, [162] . Retrofitting existing plants with CCUS or co-firing biomass is mandatory to cut emissions while preserving jobs, grid stability, and sunk capital[158] Furthermore, captured $CO_2$ can be converted into fuels (e.g., methanol), fertilizers (e.g., urea), aggregates, and building materials, thereby supporting industrial innovation and improving economic viability.[6,153].

3.1.6 Technical constraint – parasitic load:

A critical technical constraint that must be acknowledged is the parasitic load of CCUS. Post-combustion carbon capture consumes approximately 20–30% of a coal plant's electrical output to operate the capture process (solvent regeneration, compression, and pumping). For a typical 1,000-MW coal plant, this reduces the net electricity delivered to the grid by 200–300 MW. [163] Note that this penalty can be partially offset by: (a) using waste heat from the plant for solvent regeneration, (b) powering capture equipment from dedicated renewable sources (e.g., co-located solar parks), or (c) oversizing the turbine. Without mitigation, the parasitic load significantly increases the effective cost of electricity from CCUS-retrofitted plants and must be factored into any economic assessment.

3.1,7 Complementarity with Renewable Energy Expansion

Aggressive deployment of renewables—solar and wind—is essential for long-term decarbonization; scenario analyses indicate non-fossil capacity could reach up to 64% by 2030 [60,164]. The renewables alone face significant challenges: intermittency requires large-scale storage and grid upgrades, and regional disparities risk leaving coal-dependent states behind unless addressed through targeted policies.[60] Thus, CCUS and renewables are not competitors but complements: renewables provide low-cost clean electricity for new capacity. At the same time, CCUS decarbonizes the legacy coal fleet and hard-to-abate industrial processes during a multi-decade transition.

### 3.1.8 Policy and Economic Considerations

Coal-CCS is currently more expensive than unabated coal or renewables; high capital and operating costs remain a major barrier in the absence of strong carbon pricing or subsidies.[13]. Effective implementation requires a hybrid policy framework that combines compulsory standards (emission caps, performance norms) with voluntary market mechanisms such as carbon credits and trading, as well as public-private partnerships and dedicated R&D support.[5,153,165]. Equally important are just transition policies: social impacts—particularly job losses in coal-mining regions of eastern India—necessitate reskilling programs, alternative livelihood creation, and equitable distribution of new clean energy opportunities [155,156].

Table12: Key Claims and Supporting Evidence for the Viable Energy Pathway

| Claim | Reasoning | Representative Citation |
|---|---|---|
| Large-scale CCUS is essential for decarbonizing India's hard-to-abate sectors while maintaining energy security. | Multiple modeling studies show that deep emission cuts are only possible with CCUS in power and industry, alongside renewables. | [4,9,153,162] |
| Renewables alone cannot immediately replace all coal-based generation or industrial processes. | Grid stability and intermittency issues; slow pace of industrial electrification; regional disparities | [60,62,164] |
| Coal-CCS is currently less cost-effective than renewables but necessary for legacy asset decarbonization. | Levelized cost assessments show higher costs and water use vs. solar/wind; carbon pricing needed for competitiveness. | [166] |
| Retrofitting existing plants with CCUS or biomass co-firing enables gradual transition without abrupt job loss. | Scenario analysis shows retrofits reduce abatement costs and social disruption compared to immediate phase-out. | [158] |
| Social justice and just transition policies are critical to avoid regional inequities during coal transition. | The literature highlights risks to livelihoods in eastern states; the need for reskilling and support programs. | [156,167] |
| Full-scale commercial deployment of CCUS faces significant technical and economic barriers in India today. | Most projects remain at pilot stage; high capital costs and infrastructure gaps persist. | [5,165] |

The reviewed literature reveals an uneven distribution of research attention across key topics and outcomes. Emissions reduction modelling is relatively well represented across power

sector CCS (eight studies), industrial CCS (six studies), and renewables integration (twelve studies), but just transition policies have received only five studies in this category. Cost-effectiveness analysis shows a similar pattern: renewables integration leads with nine studies, followed by power sector CCS with five, industrial CCS with three, and transition policies with only two. Pilot and commercial project documentation is sparse overall, with power sector CCS (four studies) and renewables integration (eight studies) receiving more attention than industrial CCS (two studies) and just transition (one study). Most notably, social impact assessment remains severely under-researched: only two studies address power sector CCS, one addresses industrial CCS, three address renewables integration, and six address just transition policies—indicating that while just transition is discussed conceptually, empirical social impact evaluations across technology pathways are largely absent.

Three priority research questions emerge from the synthesis of the literature. First, how can policy frameworks best incentivize large-scale commercial deployment of CCUS in India's power sector? Answering this question is crucial because understanding effective incentive structures is the first step toward overcoming current cost and infrastructure barriers that keep CCUS at pilot scale. Second, what are the most effective strategies for ensuring a just transition for workers and regions dependent on coal? Addressing social impacts will directly determine the political feasibility and public acceptance of any low-carbon pathway that involves reduced coal use. Third, how can integrated planning optimize synergy between the expansion of renewables and targeted CCUS retrofitting? Coordinated system design has the potential to minimize overall costs and emissions while maximizing grid reliability and social equity during the multi-decade transition period.

## 4. Results

The literature review yielded two sets of findings corresponding to the two objectives of this paper. The analysis confirms that four major interconnected categories of barriers constrain CCUS deployment in India’s coal-fired power sector.

4.1 Objective 1: To identify barriers for slow diffusion of CCUS in India

- Financial Barriers: High capital expenditure and operational costs are the most frequently cited obstacles, with capture costs ranging from ₹340–4,500/tonne (approximately $4-54/ton) excluding additional transport and storage expenses. The absence of robust carbon pricing or sufficient government subsidies renders CCUS projects financially unattractive compared to renewables or unabated coal operations.
- Regulatory Barriers: India lacks a comprehensive regulatory framework for CCUS covering long-term storage liability, site monitoring requirements, permitting processes for $CO_2$ pipelines and storage sites, and clear rules on pore space ownership. Fragmented or ambiguous regulations increase project risk and delay implementation
- Political Barriers: Political resistance stems from the deep entrenchment of coal in regional economies—particularly eastern Indian states—and the influence of vested interests such as industry conglomerates and labor unions. Concerns about employment loss among coal workers create further opposition to rapid decarbonization or large-scale CCUS adoption without parallel just transition policies

- Social Barriers: Public acceptance is highly variable (40–60% approval rates from available surveys) but generally hampered by low awareness of CCUS technologies, skepticism about safety (e.g., leakage risks), fears of continued fossil fuel dependence ("greenwashing"), NIMBY attitudes toward local storage sites and infrastructure development, and lack of trust in government or project developers

4.2 Objective2: A Viable Energy Pathway for India

The literature supports a phased, integrated pathway that balances coal dependence, energy security, and climate commitments through four strategic pillars.

- Pillar 1 – Aggressive Renewable Energy Expansion: Non-fossil capacity is projected to reach up to 64% by 2030. Renewables provide low-cost clean electricity for new capacity and are essential for long-term decarbonization
- Pillar 2 – Strategic CCUS Retrofitting: Hard-to-abate sectors—power, steel, cement, and chemicals—account for 60–80% of India's $CO_2$ emissions. Integrated modeling shows that combining advanced coal technologies with CCUS can reduce emissions by up to 45% relative to business-as-usual by 2050, even as absolute coal use rises. Retrofitting existing plants with CCUS or co-firing biomass preserves jobs, grid stability, and sunk capital
- Pillar 3 – Robust Policy and Financial Frameworks: Effective implementation requires hybrid policy mechanisms combining compulsory standards (emission caps, performance norms) with voluntary market instruments (carbon credits, trading), along with public-private partnerships and dedicated R&D support
- Pillar 4 – Just Transition Measures: Social impacts—particularly job losses in coal-mining regions of eastern India—necessitate reskilling programs, alternative livelihood creation, and equitable distribution of new clean energy.

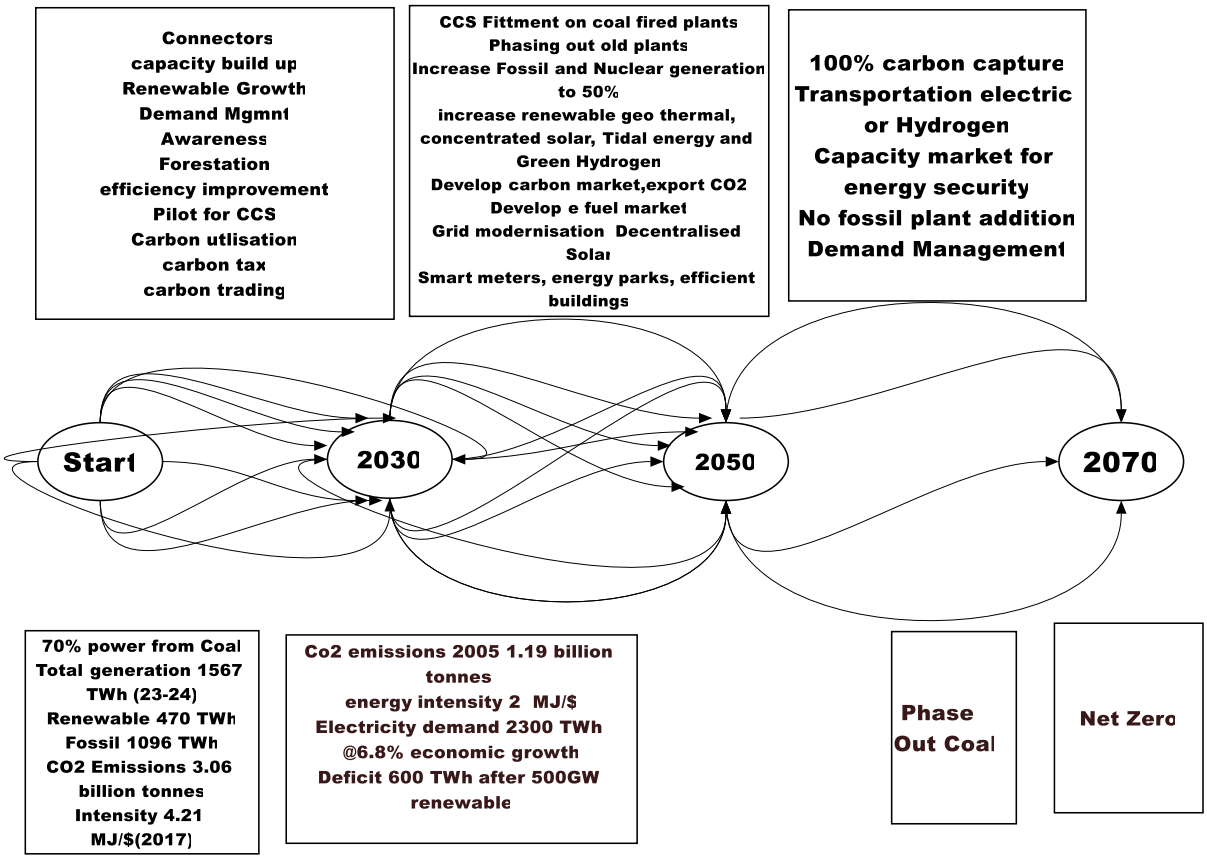


Figure4: Proposed pathway

## 5. Discussion

### 5.1 Interpretation of Findings

The results confirm that CCUS occupies a paradoxical position in India's energy transition discourse. On one hand, modeling studies consistently show that net-zero targets cannot be achieved without large-scale CCUS in hard-to-abate sectors, given coal's projected role through 2040–2050. On the other hand, the financial, regulatory, political, and social barriers are so formidable that no commercial-scale CCUS project exists in India's coal power sector today. This gap between modeled necessity and on-the-ground reality is the central tension in India's CCUS challenge.

The four barrier categories are not independent; they form a self-reinforcing cycle. Regulatory uncertainty deters investment, keeping costs high due to lack of learning-by-doing. Political resistance from coal-dependent regions weakens policy signals, undermining carbon pricing and leaving social concerns unaddressed. Low public trust further reduces political will. Breaking this cycle requires coordinated, multi-dimensional interventions rather than isolated fixes.

5.2 Comparison with International Experience

International comparisons offer valuable lessons for India. The United States and European Union have successfully scaled CCUS only after establishing three preconditions: strong policy signals (carbon taxes or trading schemes), targeted subsidies for early adopters (e.g., 45Q tax credit in the US), and robust legal frameworks for storage liability, monitoring, and safety standards. [22,93,94]India currently lacks all three. Importantly, studies show that even substantial government financing does not guarantee project success if underlying regulatory or market conditions remain unfavorable. [22].

5.2.1 Global CCUS deployment scale:

As of 2024, there are approximately 135 CCUS facilities in the power generation sector globally, with many more projects at various stages of planning and implementation,

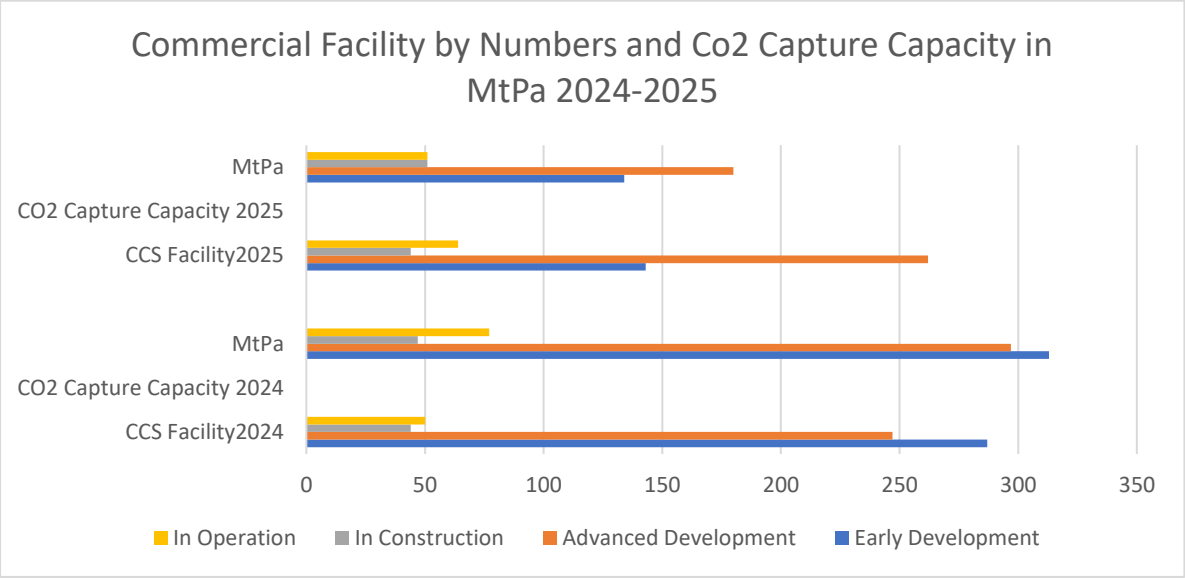


Figure5: Commercial facilities and Co2 capture capacity[168]

Global CCS Institute, 2024;[5,154]. These include commercial-scale operations, demonstration projects, and pilot facilities across North America, Europe, China, and Australia. In contrast,

Global Snapshot on deployment of CCS technology in 2025 is presented in the table:

Table 13: Global Snapshot and headlines on CCS[168]

| | |
|---|---|
| Number of facilities in operation rises 54% year on year | Total number in operation: 77 |
| Total number of facilities rises 17% year on year | Total number of facilities: 734 |

| | |
|---|---|
| Total capture capacity rises 23% year on year | Capture capacity 513 MtPa |
| Capture capacity in construction in July 2025 | 44 MtPa |

India currently has only one pilot CCUS plant in operation — located at an NTPC power station — compared to 176 operational CCUS units worldwide (including industrial applications beyond power generation). This stark disparity reflects not a lack of technical capability but the absence of enabling policy and financial frameworks. [6,93]

5.2.2 Successful Canadian example – Boundary Dam**:**

SaskPower's Boundary Dam Unit 3 in Saskatchewan, Canada, became the world's first commercial-scale coal-fired power facility to implement post-combustion carbon capture in 2014[169]. The 115 MW plant captures approximately 1 million tonnes of $CO_2$ annually, which is sold for enhanced oil recovery (EOR) at nearby oil fields (International Carbon Capture Storage Knowledge Center). This project demonstrated that coal-CCS is technically feasible at commercial scale, though it experienced higher-than-expected capital costs and operational challenges in its first years of operation.

5.2.3 Learning curve effects – Shand Power Station:

A follow-up project at SaskPower's Shand Power Station (Canada) provides evidence of learning-by-doing[170]. The feasibility report on the second-generation CCS retrofit at Shand indicated a 67% reduction in capital cost per tonne of $CO_2$ captured compared to the first-generation Boundary Dam project (International Carbon Capture Storage Knowledge Center, 2021). This cost reduction was achieved through improved solvent chemistry, optimized process design, and supply chain maturation. For India, this suggests that early investments in pilot and demonstration projects, while costly, can reduce costs for subsequent deployments — provided a pipeline of projects exists to capture learning effects.

5.2.4 CCUS adoption in other coal-dependent Asian economies:

India is not alone in facing the coal-CCS dilemma. China, the world's largest coal user, has aggressively pursued CCUS deployment, with multiple large-scale projects in operation or under construction across power generation, coal-to-chemicals, and steel sectors[5,171] Indonesia and Japan — both significantly dependent on coal-based power generation — have also added CCUS retrofitting options to their coal-fired plants and are developing regulatory frameworks to support deployment.[5,51] These countries face similar challenges to India: high costs, infrastructure gaps, and policy uncertainty, but their progress outpaces India's. Primarily due to stronger government-led coordination, clearer long-term decarbonization targets with interim milestones, and dedicated funding mechanisms for carbon capture R&D and demonstration.

Table 13. Key lessons for India from international experience: Synthesizing the international literature, five specific lessons emerge for India:

| Lessons | Source | Implications for India |
|---|---|---|
| 1. Policy signals must be long-term and consistent | [22,94] | India's current mixed signals (building new coal plants while promoting renewables) deter CCUS investment. |
| 2. Early-stage subsidies are essential to bridge the cost gap | [93]; US 45Q model | India needs production tax credits or capital expenditure subsidies modelled on 45Q |
| 3. Carbon pricing (floor price) is necessary for revenue certainty | [172] | Coal cess should be increased and linked to a carbon credit mechanism. |
| 4. $CO_2$ utilization (EOR, methanol, urea) improves project economics | [6,153] | India should prioritize CCUS clusters near fertilizer plants or oil fields. |
| 5. Storage liability frameworks must be enacted before large-scale deployment | [57,78] | No commercial CCUS project will proceed without clear rules on long-term liability. |

5.2.5 The international gap – social acceptance and just transition**:**

Notably, even successful CCUS deployments in Canada, the US, and Europe have faced public resistance. The NIMBY ("Not in My Backyard") phenomenon — opposition to local $CO_2$ pipelines and storage sites — has delayed or cancelled projects[58,63]. International experience shows that transparent community engagement, benefit-sharing mechanisms (e.g., local employment, revenue sharing), and independent safety monitoring are essential for building social license. India has yet to develop such community engagement frameworks for CCUS, representing a significant gap that this review highlights.

India can learn from both the successes and failures of international CCUS deployment. The technical feasibility is proven; the cost trajectory is downward with learning; and the policy instruments are known (carbon pricing, subsidies, liability frameworks). What India lacks is not knowledge but coordinated, sustained political will and a dedicated implementation agency. Without these, CCUS will remain at pilot scale while coal emissions continue for decades.

Table14: Global CCUS Deployment Snapshot (Selected Countries)

| Country/ Region | Operational CCUS Facilities (Power sector and Industry) | Notable Coal-CCS Projects | Key Policy Instrument |
|---|---|---|---|
| United States | ~40 | Petra Nova (Texas) — 240 MW, now offline | 45Q tax credit ($85/tonne $CO_2$ captured |
| Canada | ~15 | Boundary Dam (115 MW, 2014); Shand (second generation) | Carbon pricing + provincial subsidies |
| China | ~30+ (rapidly growing) | Multiple power and coal-to-chemicals projects | State-led R&D + demonstration mandates |
| Europe | ~20 (mostly industrial) | No commercial coal-CCS (phase-out underway) | EU ETS carbon trading |
| Australia | ~10 | Gorgon LNG (not power, but large-scale storage) | Government grants + carbon credits |
| India | 1 (pilot only) | NTPC pilot plant | None (under development) |

5.3 The Renewables vs. CCUS Debate

A key finding from the literature is that framing renewables and CCUS as competing options is misleading. Renewables are already cost-effective for new capacity and will dominate long-term electricity generation. The renewables cannot immediately replace existing coal infrastructure—which represents decades of sunk capital and employs millions—nor can they fully decarbonize industrial process heat. CCUS serves a complementary role: decarbonizing the legacy fleet during a multi-decade transition while renewables scale up. This complementarity is especially important for grid stability, as coal with CCS can provide dispatchable low-carbon power when solar and wind are unavailable.

### 5.4 Trade-offs and Unresolved Issues

Despite the promise of a balanced pathway, several trade-offs remain unresolved. First, coal-CCS has a significantly higher water footprint than renewables, which is problematic for water-stressed regions in India. Second, the cost of CCUS remains high even with optimistic learning curves; diverting subsidies from renewables to CCUS could slow overall decarbonization. Third, retrofitting decisions must be made on a plant-by-plant basis: younger, more efficient supercritical plants are better candidates than older subcritical units. Fourth, the political economy of coal regions means that even well-designed CCUS policies may face resistance if perceived as prolonging coal dependence rather than enabling a genuine transition.

### 5.5 Research Gaps Identified

The literature review also reveals significant research gaps. Social impact assessment across technology pathways is severely under-researched; only two studies address the social impacts of power-sector CCS, and only one addresses industrial CCS. Empirical studies on public perception at the community level are lacking, as are comparative assessments with other developing countries. Longitudinal studies tracking shifts in public perception as pilot projects scale up do not yet exist. These gaps constrain evidence-based policymaking.

## 6. Recommendations

Based on the results and discussion, the following recommendations are proposed for policymakers, industry stakeholders, and researchers.

### 6.1 Recommendations for Policy

- Establish a Comprehensive CCUS Regulatory Framework: The government should enact clear legislation covering long-term storage liability, site monitoring requirements, permitting processes for $CO_2$ pipelines and storage sites, and pore space ownership rules. This framework must be in place before large-scale private investment can be expected [22,57].
- Implement Robust Carbon Pricing: The existing coal cess should be increased and explicitly linked to a carbon credit mechanism or trading scheme. Revenues should be ring-fenced to fund CCUS R&D, demonstration projects, and infrastructure [5,13].
- Launch Targeted Subsidies and Incentives: Modelled on the US 45Q tax credit, India should introduce production tax credits or capital expenditure subsidies for early CCUS adopters. A reverse auction mechanism for low-carbon power from retrofitted coal plants could accelerate deployment[5,93] .
- Mandate Just Transition Plans: For every coal region affected by transition, the government should co-design with local communities a just transition plan that includes reskilling programs, alternative livelihood creation, and infrastructure investment in clean energy industries [155].

### 6.2 Recommendations for Industry

- Prioritize Retrofitting of Young, Efficient Supercritical Plants: Not all coal plants are suitable for CCUS retrofitting. Industry should conduct plant-level techno-economic

assessments, prioritizing large, relatively new supercritical units located near potential storage sites or $CO_2$ utilization hubs [158].

- Develop $CO_2$ Utilization Hubs: Captured $CO_2$ can be converted into methanol, urea, building aggregates, and synthetic fuels. Industry should explore clustering CCUS projects with fertilizer plants, chemical complexes, or enhanced oil recovery operations to create revenue streams that offset capture costs[6,153] .
- Invest in Pilot-to-Commercial Scale-Up: Industry-led consortiums should accelerate the transition from pilot to commercial demonstration. Public-private partnerships can share financial risk while building operational experience [5,58].

6.3 Recommendations for Research

- Conduct Community-Level Empirical Studies: Future research should move beyond general surveys to place-based, mixed-methods studies of public perception in potential CCUS host communities. Understanding local concerns is essential for designing acceptable projects [63,64].
- Develop Sub-national Political Economy Analyses: Research should examine how regional variations in coal dependence, governance quality, and labour union strength shape resistance or support for CCUS across Indian states. Such analysis can inform tailored policy interventions[60,61].
- Evaluate Incentive Mechanisms Under Indian Market Conditions: Cost-effectiveness analyses of different subsidy and carbon pricing designs—tailored to India's specific electricity market, interest rates, and fiscal constraints—are urgently needed to guide policy design[13,154].
- Track Longitudinal Changes in Public Perception: As pilot projects move to commercial scale, researchers should track how awareness, trust, and acceptance evolve, identifying critical junctures where communication or engagement strategies can be improved[63].
- Assess Water-Energy-$CO_2$ Nexus: Given India's water stress, integrated assessments of water use across renewable, coal-CCS, and other low-carbon pathways are needed to avoid unintended trade-offs[13] .

## 7. Summary

India's pursuit of developed-economy status by 2047, coupled with its net-zero by 2070 commitments, creates an unavoidable need to decarbonize its coal-dominated power sector. This systematic review had two objectives: first, to identify the financial, regulatory, political, and social barriers to CCUS deployment in India's coal-fired power sector; and second, to propose a viable energy pathway that balances coal dependence, energy security, and climate commitments through strategic CCUS adoption.

## 7.1 Summary of Findings for Objective 1 (Barriers)

The literature confirms that CCUS is a necessary — though not sufficient — component of any realistic pathway to net-zero for India. Four interconnected categories of barriers currently constrain the deployment.

Financial barriers are the most frequently cited obstacle, with capture costs ranging from ₹340 to ₹ 4,500/tonne, excluding additional transport and storage expenses. The absence of robust carbon pricing or sufficient government subsidies renders CCUS projects financially unattractive compared to renewables or unabated coal operations. Most Indian projects remain at pilot scale due to limited access to finance and high perceived investment risks.[5,57,58,154].

Regulatory barriers include the lack of a comprehensive framework covering long-term storage liability, site monitoring requirements, permitting processes for $CO_2$ pipelines and storage sites, and clear rules on pore space ownership. Fragmented or ambiguous regulations increase project risk and delay implementation. [22,57,59].

Political barriers stem from the deep entrenchment of coal in regional economies. Five coal-bearing states (Odisha, Jharkhand, Chhattisgarh, West Bengal, Madhya Pradesh) hold 97.4% of reserves, have below-average GDP, and depend heavily on coal revenue (Rs 53,309 crores annually). The coal sector employs approximately 1 million people (1% of the labour force) and contributes 2.5% to GDP. Indian Railways earns 47% of its freight revenue (Rs 65,856 crores) from coal transport. These dependencies create strong resistance to rapid decarbonization in the absence of just transition policies.[60–62].

Social barriers include low public awareness of CCUS (approval rates of 40–60% in available surveys), scepticism about safety and leakage risks, fears of "greenwashing," NIMBY attitudes toward local storage sites, and a lack of trust in government or project developers. [58,63,64].

Interplay of barriers: These four categories are not independent but form a self-reinforcing cycle. Regulatory uncertainty deters investment, keeping costs high due to lack of learning-by-doing. Political resistance from coal-dependent regions weakens policy signals, undermining carbon pricing and leaving social concerns unaddressed. Low public trust further reduces political will. Breaking this cycle requires coordinated, multi-dimensional interventions rather than isolated fixes.

## 7.2 Summary of Findings for Objective 2 (Viable Energy Pathway)

The literature supports a phased, integrated pathway that balances coal dependence, energy security, and climate commitments. This review synthesizes the evidence into four strategic pillars.

Pillar 1 – Aggressive renewable energy expansion: Non-fossil capacity is projected to reach up to 64% by 2030. Renewables provide low-cost clean electricity for new capacity and are essential for long-term decarbonization[60,164]. The renewables alone cannot immediately replace existing coal infrastructure due to intermittency, storage requirements, and grid stability constraints.

Pillar 2 – Strategic CCUS retrofitting: Hard-to-abate sectors—power, steel, cement, and chemicals—account for 60–80% of India's $CO_2$ emissions. Integrated modeling shows that combining advanced coal technologies with CCUS can reduce emissions by up to 45% over business-as-usual by 2050, by retrofitting existing plants with CCUS and co-firing biomass to preserve jobs, grid stability, and sunk capital.[9,153,156–158,162] . A critical technical constraint is the parasitic load of CCUS (20–30% of plant output consumed by capture), which can be partially mitigated through waste heat recovery or co-located renewable capacity.

Pillar 3 – Robust policy and financial frameworks: Effective implementation requires hybrid policy mechanisms combining compulsory standards (emission caps, performance norms) with voluntary market instruments (carbon credits, trading), along with public-private partnerships and dedicated R&D support[5,153,154,165] . International experience demonstrates three preconditions for success: strong policy signals (e.g., carbon pricing), targeted subsidies for early adopters (e.g., the US 45Q tax credit), and clear legal frameworks for storage liability and safety standards. [22,93].

Pillar 4 – Just transition measures: Social impacts—particularly job losses in coal-mining regions of eastern India—necessitate reskilling programs, alternative livelihood creation, and equitable distribution of new clean energy opportunities [155]Without such measures, political resistance will continue to block both CCUS deployment and broader energy transition.

7.4 Key Insights from International Comparison

India currently has only one pilot CCUS plant, compared to approximately 135 CCUS facilities in the power sector globally and 176 operational units across all sectors.[53] [168]. Successful deployments in Canada (Boundary Dam, 2014; Shand station with 67% capital cost reduction), China, the United States, and Indonesia offer five key lessons for India:

- Policy signals must be long-term and consistent (mixed signals deter investment)
- Early-stage subsidies are essential to bridge the cost gap
- Carbon pricing (floor price) is necessary for revenue certainty
- $CO_2$ utilization (EOR, methanol, urea) improves project economics
- Storage liability frameworks must be enacted before large-scale deployment

India lacks all five. The technical feasibility of CCUS is proven; the cost trajectory is downward with learning; the policy instruments are known. What India lacks is coordinated, sustained political will and dedicated implementation mechanisms.

7.4 Answer to the Two Research Objectives

Objective 1 (Barriers): This review has identified and categorized four interconnected barriers to CCUS deployment in India's coal-fired power sector — financial (high costs, weak carbon pricing), regulatory (no comprehensive framework), political (coal-dependent state economies, employment, railway revenue), and social (low awareness, NIMBY, distrust). These barriers form a self-reinforcing cycle that keeps CCUS at pilot scale.

Objective 2 (Viable Pathway): This review has proposed a four-pillar pathway: (1) aggressive renewable expansion, (2) strategic CCUS retrofitting of young, efficient supercritical coal

plants, (3) robust policy and financial frameworks (carbon pricing, subsidies, liability rules), and (4) just transition measures for coal-dependent regions and workers. CCUS and renewables are complements, not competitors.

### 7.5 Final Conclusion

CCUS offers a middle path for India — one that allows continued utilization of domestic coal resources for energy security and economic development while reducing $CO_2$ emissions in line with net-zero by 2070 commitments. The gap between modeled necessity and on-ground reality remains wide. Without coordinated action to address financial, regulatory, political, and social barriers — including carbon pricing, targeted subsidies, a comprehensive legal framework, and just transition policies — CCUS will remain at pilot scale, and India risks either missing its climate targets or sacrificing the developmental benefits of its coal resources.

The pathway exists. The question is whether the political will can be mobilized to walk it.

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