CCS in India

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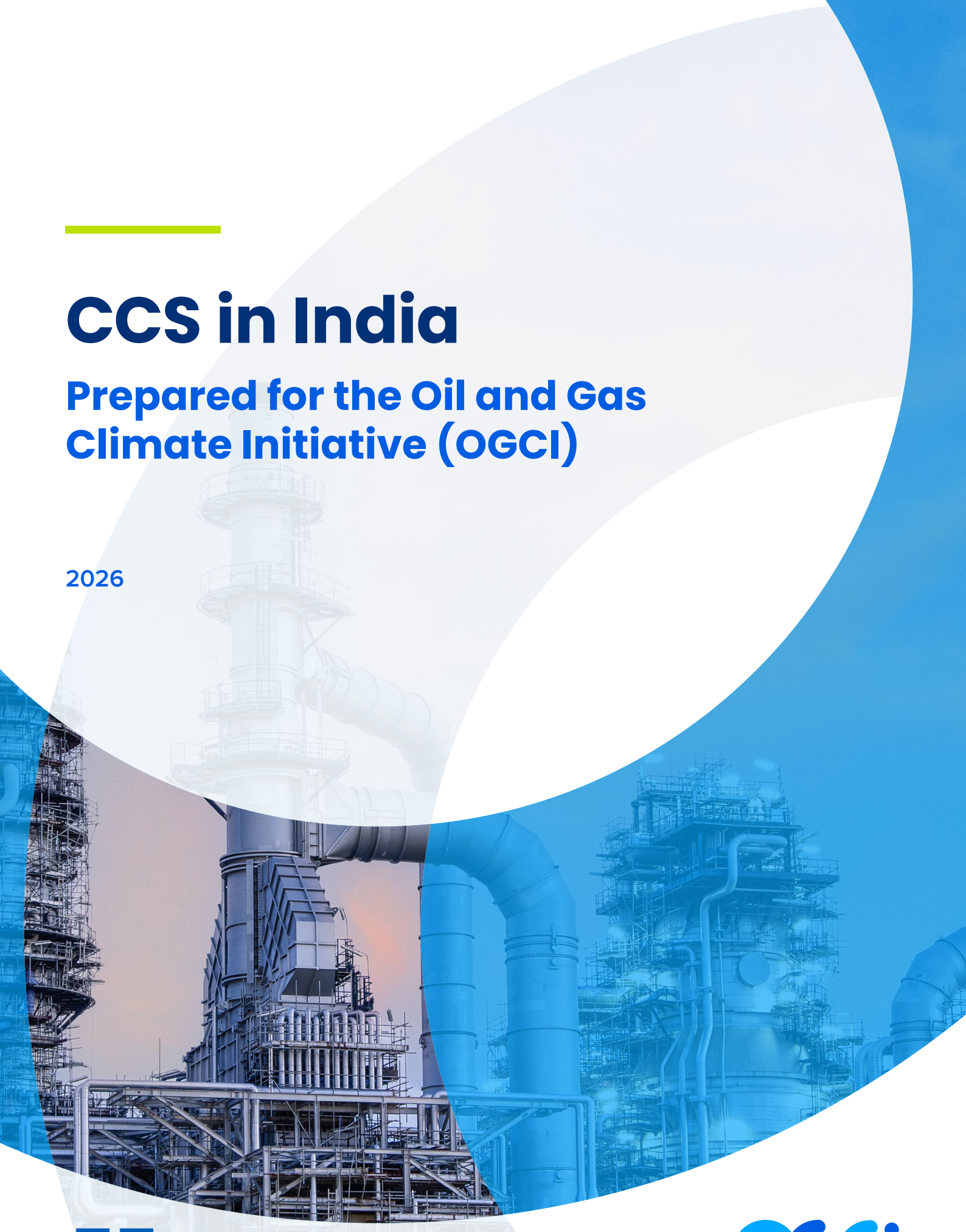

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Acronyms

ABEX	Abandonment Expenditure
ADB	Asian Development Bank
ADOE	Alberta Department of Energy
AEPA	Alberta Environment and Protected Areas
AER	Alberta Energy Regulator
ANPRM	Advance Notice of Proposed Rulemaking
BCER	BC Energy Regulator
BECCS	Bioenergy with carbon capture and storage
BEE	Bureau of Energy Efficiency
BF	Blast Furnace
BLM	Bureau of Land Management
BMRP	Baseload Market Reference Price
BNDES	Brazilian Development Bank
BOF	Basic Oxygen Furnace
BSCSP	Big Sky Carbon Sequestration Partnership
BSEE	Bureau of Safety and Environmental Enforcement
BSI	British Standards Institution
CAPEX	Capital Expenditure
CBEs	Brazilian Emission Quotas
CCC	Carbon Credit Certificate
CCS	Carbon capture and storage
CCSA	Captured Carbon Storage Act (Manitoba 2024)
CCTS	Carbon Credit Trading Scheme
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CDR	Carbon Dioxide Removal
CEEAGs	Climate, Energy and Environmental Aid Guidelines
CEPA	1999 Canadian Environmental Protection Act
CEQ	Council on Environmental Quality
CERF	Carbon Emissions Reduction Facility
CFR	Code of Federal Regulations
CIB	Canada Infrastructure Bank
CIFIA	Carbon Dioxide Transportation Infrastructure Finance and Innovation Act
CISAF	Clean Industrial State Aid Framework
CLDP	Carbon Legal Defence Project

CMAP	Carbon Management Advisory Program
CO_2	Carbon Dioxide
CO_2-EOR	Carbon Dioxide Enhanced Oil Recovery
CO_2e	Carbon Dioxide equivalent
CO_2RE	Global CCS Institute CO_2RE database
COP	Conference of the Parties
CPCB	Central Pollution Control Board
CPUC	California Public Utilities Commission
CSA	Canadian Standards Association
CSLF	Carbon Sequestration Leadership Forum
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DEQ	Department of Environmental Quality
DGH	Directorate General of Hydrocarbons
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
ECCC	Environment and Climate Change Canada
EEA	European Economic Area
EEAGs	Energy and Environmental Aid Guidelines
EIA	Environmental Impact Assessment
EIB	European Investment Bank
EJ	Exajoule
EOR	Enhanced Oil Recovery
EPA	Environment Protection Authority
ERCB	Energy Resources Conservation Board
ETS	Emissions Trading Scheme
EU	European Union
EU ETS	European Union Emissions Trading System
FECM	Office of Fossil Energy and Carbon Management
FEED	Front-End Engineering Design
FERC	Federal Energy Regulatory Commission
GCCSI	Global CCS Institute
GDP	Gross Domestic Product
GGR	Greenhouse Gas Removals
GHG	Greenhouse Gas

GIS	Geographic Information System
GSA	General Services Administration
Gt	Gigatonnes
$GtCO_2$	Gigatonnes of CO_2
$GtCO_2e$	Gigatonnes of CO_2 equivalent
HPHT	High Pressure High Temperature
ICC	Industrial Carbon Capture
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IIJA	Infrastructure Investment and Jobs Act
IMO	International Maritime Organization
IOCL	Indian Oil Corporation
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISO	International Organization for Standardization
ITMO	Internationally Transferred Mitigation Outcome
KRIBHCO	Krishak Bharati Cooperative Limited
kt	kilotonnes
LCOE	Levelised Cost of Electricity
LNG	Liquefied Natural Gas
M&V	Measurement and Verification
MFF	Multiannual Financial Framework
MMV	Measurement, Monitoring and Verification
MoEFCC	Ministry of Environment, Forest and Climate Change
MRGG	Management and Reduction of Greenhouse Gases
MRGG Act	Management and Reduction of Greenhouse Gases Act
MRV	Monitoring, Reporting and Verification
$MtCO_2$	Million tonnes of CO_2
Mtpa	Million tonnes per annum
NDC	Nationally Determined Contribution
NEPA	National Environmental Policy Act
NITI	National Institution for Transforming India
NPRM	Notice of Proposed Rulemaking
NSTA	North Sea Transition Authority
NTSB	National Transportation Safety Board
NZIA	Net Zero Industry Act
OBBBA	One Big Beautiful Bill Act

OCED	Office of Clean Energy Demonstrations
OGCI	Oil and Gas Climate Initiative
OISD	Oil Industry Safety Directorate
OPEX	Operating Expenditure
P&A	Plugging and Abandonment
P10	10th percentile estimate
P50	50th percentile (median) estimate
P90	90th percentile estimate
PHMSA	Pipeline and Hazardous Materials Safety Administration
PISC	Post-injection site care
PNGRB	Petroleum and Natural Gas Regulatory Board
R&D	Research and Development
RD&D	Research, Development and Demonstration
SDWA	Safe Drinking Water Act
SEIAA	State Environment Impact Assessment Authority
SMR	Steam Methane Reforming
SPCB	State Pollution Control Board
tCO_2	tonnes of CO_2
tCO_2-e	tonnes of CO_2 equivalent
tCO_2e	tonnes of CO_2 equivalent
TSL	Tata Steel Limited
TVD	True Vertical Depth
UIC	Underground Injection Control
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
USDW	Underground Sources of Drinking Water
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WHP	Wellhead Pressure

Executive Summary

Photo: Adobe Stock

Executive Summary

India has a significant potential to deploy CCS at scale; cutting emissions from hard-to-abate industrial sectors while supporting continued economic growth and energy security. This report has been prepared to assess potential avenues for CCS to move from concept to scalable deployment in India, with a particular focus on factors that could affect whether early projects become technically credible, investable and implementable. It brings together four complementary strands of analysis: (1) a review of India's current policy, legal, regulatory and commercial landscape, including where existing statutes may be adapted and where CCS-specific provisions are likely needed; (2) an assessment of near-term CO_2 storage and associated infrastructure options, anchored in a screening-level evaluation of the Southern Cambay Hub storage opportunity as a potential opportunity; (3) a hub analysis that maps and clusters major point sources and develops a phased capture-transport-storage concept aligned to realistic storage and infrastructure constraints; and (4) an economic and energy-system modelling perspective on CCS's role in least-cost pathways to India's net-zero ambition.

Policy, Legal, Regulatory and Commercial

India has committed to a decarbonisation pathway to reach net zero emissions by 2070. Levers the Indian Government has adopted include:

- Achieving 50% of its energy requirements from renewable and other non-fossil sources by 2030,
- Expanding non-fossil electricity capacity to 500 GW,
- Reducing projected cumulative emissions by one billion tonnes by 2030,
- Cutting emissions intensity of GDP by 45% from 2005 levels by 2030.

Within this context, CCS has been recognised as a key tool to support deep emissions reduction in hard-to-abate sectors and to underpin India's longer-term carbon management strategy. Building on the 2022 NITI Aayog report on CCUS policy frameworks and deployment mechanisms and the development of a national mission for CCUS in 2024, India is now at a stage where it could move from high-level policy intent to establishing a comprehensive legal, regulatory, commercial and financial framework for CCS deployment.

In the absence of a CCS-specific legal and regulatory framework, India's existing legal frameworks could potentially be adapted to support CCS across the full project lifecycle. Among the potentially relevant statutes and instruments are the:

- Oilfields (Regulation and Development) Act, 1948
- Mines and Minerals (Development and Regulation) Act, 1957
- Environmental legislation such as the:
  - Water Act, Forest (Conservation) Act
  - Air Act
  - Environment (Protection) Act
  - the Environment Impact Assessment (EIA) Notification
- Manufacturer, Storage and Import of Hazardous Chemicals Rules
- Energy Conservation Amendment Act, 2022
- Petroleum and Natural Gas (Amendment) Rules, 2003
- PNGRB Act, 2006

While these instruments provide important building blocks, none offer a complete CCS-specific permitting or governance regime, and significant gaps remain in areas such as project-specific approvals for CO_2 transport and storage, long-term liability, financial security, monitoring and verification, and structured stakeholder engagement.

A comparative review of mature CCS regimes in the United States, Alberta (Canada), the European Union and the United Kingdom demonstrate different but complementary approaches to regulating storage, transport, liability and environmental protection. These jurisdictions provide good examples of the use of dedicated CCS legislation, integration into existing environmental and water protection laws, and the development of detailed well and storage standards. They also illustrate how clear licensing frameworks, robust monitoring and reporting requirements, and explicit long-term liability arrangements can provide

regulatory certainty and support investor confidence.

A comprehensive CCS legal and regulatory framework for India could draw from the approaches followed in the jurisdictions evaluated and could follow either the development of a standalone CCS legal and regulatory framework or pursuing a more incremental approach that amends existing sectoral and environmental laws to incorporate CCS-specific provisions. A standalone framework could offer greater clarity and coherence for investors, project developers and regulators, but would require substantial new legislative work and institutional coordination. An adaptation pathway could leverage familiar regulatory processes and agencies, but would demand extensive, detailed amendments across multiple acts, rules and notifications to ensure comprehensive coverage of the CCS value chain. In both cases, careful attention would be needed to define roles and responsibilities across central and state institutions, align CCS regulation with India's emerging CCTS and emissions trading architecture, and ensure that environmental safeguards, public consultation and long-term stewardship arrangements are commensurate with the risks and expectations associated with permanent CO_2 storage.

To support CCS deployment, India could consider developing CCS-relevant policy mechanisms and business models, and access sources of climate finance that could help catalyse early projects in the country. As with legal and regulatory frameworks, India could draw on international experience, including Carbon Contracts for Difference and related revenue support models developed in Europe and other regions.

India already has significant policy momentum and a broad base of potentially adaptable legislation to support CCS permitting and regulation. As well as access to emerging international support mechanisms. A clearly defined CCS-specific regulatory framework could be one factor that reduces uncertainty for potential CCS projects moving from concept and demonstration toward investment decisions.

Hub Analysis

India's industrial CO_2 emissions profile is dominated by power generation and heavy industry, with national emissions of approximately 3,060 Mtpa in 2024 and major point sources concentrated in several coastal and industrial corridors.

For this analysis, current and prospective emissions were mapped across coal, gas and biomass power; natural gas processing; refining; cement and concrete; iron and steel; ammonia and fertilisers; and selected petrochemicals, with each sector assessed for CCS suitability. Coal-fired power remains central to electricity supply, providing roughly 70% of generation, while cement, iron and steel, ammonia/urea and petrochemicals contribute significant, hard-to-abate process and combustion streams. Future growth to 2030 is driven primarily by expansions in refining, petrochemicals and coal power, while cement and steel capacities remain broadly stable given current underutilisation.

Spatial clustering of all mapped point sources generated 31 clusters, which were then ranked qualitatively against criteria such as distance to storage, emissions volume and growth, source concentration, pipeline co-location, subsurface data availability, existing CCS activity and accessibility. Based on the screening criteria used in this study, the South Cambay Hub scored highly, reflecting proximity to the Gandhar-Ankleshwar storage complex, industrial emissions, a share of higher-concentration sources, existing oil and gas pipelines, subsurface data and ongoing CCS-related work.

All hub design and cost estimates remain high-level, with uncertainties in emissions data for some facilities, limited visibility on future project pipelines beyond 2030, and strong dependence on storage-side performance and regulatory evolution. Even with these uncertainties, the South Cambay Hub presents a plausible pathway to decarbonise several industrial sources at scale.

CO_2 Storage and Infrastructure

The Southern Cambay Hub is identified in this screening analysis as a potential early storage opportunity for further assessment, combining a suitable onshore storage complex with proximity to major point sources and existing petroleum

infrastructure and licence. The hub concept uses the Eocene Hazad Member as the primary reservoir, sealed by the Kanwa Shale, within a prolific and mature hydrocarbon basin consistently ranked as having very high CO_2 storage potential in national assessments.

The storage complex is a multi-layer, tide-influenced deltaic system subdivided into 12 Gandhar Sands (GS0-GS12) that exhibit strong vertical and lateral heterogeneity due to stacked distributary channels, mouth bars and flooding surfaces.

Theoretical storage resources estimated using a DOE-style volumetric method combined with Monte Carlo simulation to represent uncertainty in areal extent, thickness, porosity and in-situ CO_2 density. Under optimistic open-boundary assumptions, the cumulative P50 storage resource across GS4-GS12 is 341 $MtCO_2$, with a P10-P90 range of 180-585 $MtCO_2$. The screening results suggest individual units may be more suited to small- to medium-scale projects and could potentially be assessed in a stacked configuration, positioning the Southern Cambay Hub as a medium-capacity complex rather than a gigatonne-scale basin-wide resource.

A phased hub development could be outlined to align storage buildout with capture deployment. A potential approach could involve Phase 1 targeting 2.85 Mtpa, Phase 2 targeting 9.77 Mtpa and Phase 3 4.38 Mtpa, requiring two, seven and three injectors for high/mid injectivity, compared with 29, 98 and 44 injectors for the low-injectivity case. These are screening-level estimates only and should not be used for investment, permitting or project sanction decisions without further appraisal.

Economics

From an economic perspective, in the modelled scenarios, CCS can play a significant role in some lower-cost pathways to net zero, particularly when CCS can be combined with international access to large-scale storage. For this analysis, The GENZO model has been utilised. GENZO is a bottom-up technology-focused model based on the Open Source Energy. Modelling System (OSeMOSYS) framework. GENZO model scenarios show that CCS deployment, especially in industrial and BECCS applications, becomes increasingly attractive as emissions constraints tighten, changing the technology mix selected by the model across fossil, biomass, renewable, electrification, hydrogen and CCS options under the emissions constraints assessed. At the same time, restrictions on storage availability – either through slow domestic development or limits to international storage access – are associated in the model with higher-cost pathways in some scenarios that rely heavily on renewable to hydrogen to electricity supply chains and deep structural changes across industry, buildings and transport.

Scenario design varies both the rate at which global and Indian storage capacity can be developed and whether India is allowed to use storage outside its borders. Faster storage growth and international access enable a balanced technology mix that combines renewables, electrification, CCS and hydrogen, while domestic-only variants push the system toward early fossil fuel phase out, very large renewable buildouts and extensive hydrogen production for dispatchable power and industrial feedstocks. Across all net zero scenarios, total primary energy use falls relative to a steady state baseline due to efficiency gains, but domestic-only cases require higher total primary energy because the round-trip conversion of electricity to hydrogen and back to electricity is significantly more energy-intensive than direct fossil plus CCS pathways.

CCS deployment patterns reflect these structural choices. In scenarios with international storage access and sufficient storage growth, electricity generation with CCS ramps sharply after 2035 as storage capacity becomes abundant and the model selects CCS for dispatchable low-carbon power in scenarios with greater storage availability. Industrial CCS is dominated by BECCS across all scenarios, because industrial bioenergy with CCS provides both negative emissions and useful energy in sectors where alternative abatement options are limited.

01

Policy, Legal, Regulatory and Commercial Review

Photo: Adobe Stock

1. Policy, Legal, Regulatory and Commercial Review

1.1 Key messages

- India has yet to establish a CCS -specific legal and regulatory framework, although it has made progress in this regard through NITI Aayog's comprehensive report on CCUS policy framework and deployment mechanisms in India, released in 2022, and the development of a national mission for CCUS in 2024.
- Considering the pathways pursued by other regions, there are two primary approaches to establishing a CCS-specific legal and regulatory framework in India. One pathway is to adopt standalone CCS legislation, which provides a unified, purpose-built framework that offers greater clarity for investors, project developers, and regulators. Another approach involves amending and integrating CCS-specific provisions into India's existing body of environmental, energy, and resource management law. Analysis of existing Indian laws and regulations relevant to CCS reveals that no single current framework is comprehensive enough to support CCS on its own. While opportunities exist to adapt elements of the current legal regime, pursuing this route would require detailed, sustained legislative and regulatory rewriting across relevant statutes and subordinate instruments to address the breadth of issues in a full-chain CCS framework.
- Legal and regulatory frameworks in mature jurisdictions could provide guidance on the most appropriate approaches to the establishment of a comprehensive CCS-specific framework for India, and provisions that should be included in such frameworks. These jurisdictions include the United States (US), the European Union (EU) and the United Kingdom (UK).
- A comparison of existing legal and regulatory frameworks in the jurisdictions noted above to existing Indian frameworks indicates several gaps and issues to consider when developing CCS-specific provisions. These gaps and issues are summarised in Appendix 1 (Gap Analysis and Issues Register). Policies, laws and regulations in India relevant to CCS

1. Relevant Indian policies included in the analysis

At COP26 in 2021, India pledged to meet 50% of its energy requirements from renewable and other non-fossil sources by 2030, expand non-fossil electricity capacity to 500 GW, reduce projected cumulative carbon emissions by one billion tonnes by 2030, cut the emissions intensity of GDP by 45% from 2005 levels by 2030, and achieve net zero emissions by 2070 (Government of India, 2022).

In this context, in November 2022, the National Institution for Transforming India (NITI) Aayog, a planning organisation under the Indian government, released a comprehensive report: "Carbon Capture, Utilisation and Storage (CCUS) policy framework and deployment mechanisms in India" (NITI Aayog et al., 2022). The report highlights the potential opportunities for CCUS within the country, emphasising the importance of adopting a hub-and-cluster model to drive the economics and large-scale implementation of these technologies. It also estimates India's

theoretical CO_2 storage capacity at 400 to 600 gigatonnes. Additionally, the report addresses the financial challenges to CCUS projects, underscoring the need for government support to fund initial demonstration projects.

Building on these recommendations, the government has initiated the development of a national mission for CCUS (Carbon Herald, 2024b). Led by NITI Aayog and the Indian Ministry of Power, one of its key objectives is to develop economic incentives, such as carbon pricing and taxation mechanisms, that encourage the widespread adoption of this technology.

2. Relevant Indian laws and regulations included in the analysis

A well-defined legal and regulatory framework is essential for the successful deployment of CCS technologies. Such a framework serves several key functions, including:

- Providing regulatory certainty for investors and project developers.
- Defining operator liabilities.
- Enforcing high industry standards.
- Enhancing public confidence by ensuring a structured approach to risk management.

India has not yet enacted a CCS-specific legal and regulatory regime. However, several existing laws and regulations governing the oil, mineral, and environmental sectors may be applicable to various stages of the CCS project lifecycle. They could provide a functional basis for the development of a future CCS-specific framework. For instance, the Oilfields (Regulation and Development) Act, 1948, and the Mines and Minerals (Development and Regulation) Act, 1957, could be relevant in regulating subsurface exploration and storage activities related to CCS projects. Table 1 sets out the laws and regulations in India that were identified in this analysis as having relevance to CCS.

Table 1. Existing Indian laws and regulations with relevance to CCS projects

Law or regulation	Key features	Category	Potential relevance to CCS
Oilfields (Regulation and Development) Act, 1948	Empowers the central government to make rules for: • regulating the grant of mining leases or prohibiting the grant of such leases in respect of any mineral oil or in any area, • the conservation and development of mineral oils.	Oil legislation	Wells drilled for CO_2 storage in subsurface formations may fall under this law's jurisdiction, as it governs the "drilling, re-drilling, deepening, shutting down, plugging and abandoning of oil wells in an oilfield and for the limitation or prohibition of such operations and for the taking of remedial measures to prevent waste of or damage to oil".
Mines and Minerals (Development and Regulation) Act, 1957	Empowers the central government to make rules for: • prospecting and mining operations under licence or leases, • the termination of prospecting licences, exploration licences or mining leases.	Mineral legislation	It might be relevant in the case of interactions between CCS and other exploration and mining operations.
Water (Prevention and Control of Pollution) Act, 1974	Establishes measures for the prevention and control of water pollution and for maintaining or restoring water quality.	Environmental legislation	It CO_2 outlines water quality requirements that are relevant to CCS projects due to water and groundwater operations.
Forest (Conservation) Act, 1980	Establishes measures for the conservation of forests and the diversion of forest land for non-forestry purposes.	Environmental legislation	Any forest land used for CO_2 capture facilities, pipelines or storage sites would have to comply with the provisions of the Forest Act.
Air (Prevention and Control of Pollution) Act, 1981	Establishes measures for the prevention, control and abatement of air pollution.	Pollution control legislation	It does not explicitly list CO_2 as a pollutant.
Environment (Protection) Act, 1986	Empowers the central government to take all necessary measures to protect and improve the quality of the environment in order to prevent, control and abate environmental pollution.	Environmental legislation	It provides for inspection of facilities to ensure compliance with environmental standards. This could include CCS facilities.

Law or regulation	Key features	Category	Potential relevance to CCS
Environment Impact Assessment (EIA) Notification, 2020	Streamlines the process for obtaining prior environmental clearance for specific projects.	Environmental legislation	The process for obtaining prior environmental clearance may apply to some CO_2 capture units.
Manufacturer, Storage and Import of Hazardous Chemicals Rules, 1989	Regulates the storage and handling of hazardous chemicals, including safety standards and protocols to prevent accidents, leaks or spills.	Waste legislation	Industries storing or transporting hazardous chemicals must obtain the necessary licences from regulatory authorities and adhere to safety standards, and environmental and health regulations.
Petroleum and Natural Gas Regulatory Board Act, 2006	Empowers the Petroleum and Natural Gas Regulatory Board (PNGRB) to regulate the refining, processing, storage, transportation, distribution, marketing, and sale of petroleum, petroleum products, and natural gas.	Oil and gas legislation	The Act governs the transportation of oil and natural gas through pipelines, which could be extended to include CO_2 pipelines for CCS projects.
Energy Conservation Amendment Act, 2022	Empowers: • the central government to implement a CCTS • The BEE to administer the CCCs.	Pollution control legislation	CCS is not currently recognised under the CCTS, although there are plans to incorporate it in the offset mechanism as part of the second phase.
Petroleum and Natural Gas (Amendment) Rules, 2003	Provides detailed rules for activities related to the exploration and production of mineral oils.	Oil legislation	Several provisions could cover CCS activities, such as the Government's direction to reduce waste.

Notes:

1. Current versions of the Oil Industry Safety Directorate (OISD) standards are available for purchase online; they were unavailable when the comparative study was undertaken. The analysis includes dated versions (dates included where possible) of associated standards that were available (online) without purchase.
2. The Petroleum Act, 1934, was not analysed, as it mainly covers downstream petroleum activities and products, and would not be relevant to CCS activities.
3. A draft set of rules (Petroleum and Natural Gas Rules, 2025) has been obtained; however, these rules were not in force at the time of this report.

3. Issues register – comparative analysis

METHOD OF ASSESSMENT

The Institute's analysis is based on a select set of criteria, covering the most pertinent requirements for a legal framework to be adaptable for CCS. The criteria selected for the analysis are similar to those selected by the Institute in the development of its Legal and Regulatory Indicator in 2023, and are:

- Clarity and efficiency of the administrative process for regulatory approvals.
- Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure).
- Comprehensiveness in providing for project siting and environmental impact assessments.
- Comprehensiveness in providing for meaningful stakeholder and public consultation.
- Comprehensiveness in dealing with long-term liability and financial security.

The laws and regulations identified as relevant to CCS have each been assessed against the selected criteria, and an indicator has been assigned to each criterion, indicating the level of comprehensiveness to support the incorporation of CCS.

The analysis identified issues that would need to be addressed for each law or regulation to adequately support CCS, if policymakers chose to adapt those instruments for CCS.

To assess the comprehensiveness of a law or regulation to cover all aspects of a CCS project across the various project stages, the Institute has identified the aspects through the adoption of a consolidated regulatory model, which is set out in Appendix 2.

This model is a consolidation of assessments and guidance frameworks developed over the past decade by prominent intergovernmental, research, and academic institutions, including the International Energy Agency (IEA)[1], the Asian Development Bank (ADB)[2], the Commercial Law Development Program (CLDP)[3], and others.

The results of this detailed analysis are included in Appendix 1: Gap analysis and Issues Register.

Assessment of comprehensiveness to support CCS

A summary of the assessment results is provided in Table 2 below. India does not have a specific permitting and approvals process that covers CO_2 transport and storage. Some permitting and approvals could potentially be considered under existing regimes, notably those that cover the transport of hydrocarbons and the exploration and production of oil and gas. Upstream oil and gas operations also require injection operations of various fluids, and in the interim these regulatory regimes can be adapted or amended to cover the injection of CO_2 for geological storage. The laws discussed in Table 2 are existing laws that address regulatory and permitting issues for infrastructure development. They are listed because of their adaptability for CCS should the government decide to amend them.

1 Legal and Regulatory Frameworks for CCUS: An IEA CCUS Handbook.
2 Prospects for carbon capture and storage in Southeast Asia.
3 Carbon Capture, Utilisation, and Storage: Handbook for Policymakers.

Table 2. Assessment of existing laws and regulations against key criteria for adaptability to support CCS

- Comprehensive enough to support CCS
- Could support CCS, but needs more development
- Needs extensive development to support CCS

Law or regulation	Clarity and efficiency of the administrative process for regulatory approvals	Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)*	Comprehensiveness in providing for project siting and environmental impact assessments	Comprehensiveness in providing for meaningful stakeholder and public consultation	Comprehensiveness in dealing with long-term liability and financial security
Oilfields (Regulation and Development) Act, 1948	🔴	🟠	🔴	🔴	🔴
Mines and Minerals (Development and Regulation) Act, 1957	🔴	🟠	🔴	🔴	🔴
Water (Prevention and Control of Pollution) Act, 1974	🟠	🔴	🟠	🔴	🔴
Forest (Conservation) Act, 1980	🔴	🔴	🟠	🔴	🔴
Air (Prevention and Control of Pollution) Act, 1981	🟠	🔴	🔴	🔴	🔴
Environment (Protection) Act, 1986	🟠	🔴	🟠	🔴	🔴

Law or regulation	Clarity and efficiency of the administrative process for regulatory approvals	Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)*	Comprehensiveness in providing for project siting and environmental impact assessments	Comprehensiveness in providing for meaningful stakeholder and public consultation	Comprehensiveness in dealing with long-term liability and financial security
Environment Assessment Notification, 2006	●	●	●	●	●
Manufacturer, Storage and Import of Hazardous Chemicals Rules, 1989	●	●	●	●	●
Energy Conservation Amendment Act, 2022	●	●	●	●	●
Petroleum and Natural Gas (Amendment) Rules, 2003	●	●	●	●	●
Petroleum and Natural Gas Regulatory Board Act, 2006	●	●	●	●	●

* A detailed assessment of each aspect of the CCS project lifecycle is included in a later section.

Identification of issues

This section identifies issues in the laws and regulations analysed that could prevent their adaptability to include provisions related specifically to CCS project approvals, permitting and regulation.

Oilfields (Regulation and Development) Act, 1948

The Oilfields Act regulated oilfields for the development of mineral oil resources. While concise, it applies to all storage areas of India – onshore and offshore. The law has several articles and notably covers the following topics:

- The validity of mining leases.
- The power to make rules for mining leases, and for mineral development being vested in India's central government.
- Mineral oil royalties
- The power of the central government to modify existing leases.
- Penalties
- Inspection

The law is not granular and does not delve into the regulatory details necessary for oilfield development, and thus there is no reference for which sections could be amended to include CCS. While certain sections of this law (leases, penalties, and inspection) provide the potential for amendment to include CCS, the law would still not be comprehensive enough for CCS project development. Table 3 provides an analysis of this Act against key criteria that are relevant for adaptation of the Act to support CCS project development.

Table 3. Oilfields (Regulation and Development) Act, 1948 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🔴	The Act was set up for the development of mineral oil resources. The law applies to all areas of India – onshore and offshore However, currently, the act does not have CCS-related provisions.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🟠	The Act is very broad and high-level. While adaptable for several types of infrastructure development project, the act does not present a comprehensive framework for the CCS project lifecycle.
Comprehensiveness in providing for project siting and environmental impact assessments	🔴	The Act does not provide any definition for project siting and EIAs. It is structured in a way that describes the power of the Government, mainly its power to make and modify rules for mining leases and mineral development.
Comprehensiveness in providing for meaningful stakeholder and public consultation	🔴	This Act, enacted early after India's independence, does not define or adequately discuss stakeholder and public consultation.
Comprehensiveness in dealing with long-term liability and financial security	🔴	There are some articles discussing penalties. While these can be adapted for long-term liability and financial security, it is not currently properly defined.

Mines and Minerals (Development and Regulation) Act, 1957

The Mines and Minerals Act was developed to regulate mines and minerals, like the Oilfields Act of 1948, this legislation applies to all areas to both onshore and offshore regions of India. This Act provides significantly more details, with articles organised into the following chapters, with a short discussion on relevant articles:

- General restrictions on undertaking prospecting and mining operations.
    - This chapter cover the types of operations can be conducted under the licence, lease, or concession area, with the conditions, restrictions, and the associated time periods and areas.
- Procedure for obtaining a mineral concession in respect of land in which the minerals vest in the government.
    - This chapter covers the application process for leases, licences, concessions, and the rights of their respective holders. Furthermore, it discusses the power of the central government to make rules and amendments.
- Rules for regulating the grant of mineral concessions.
    - This chapter cover the broad power of the central government to make rules, to grant licences and leases, and to make modifications. This section also makes specific mention of India's territorial waters and continental shelf.
- Special powers of the central government to undertake prospecting or mining operations in certain cases.
    - This chapter coverS the broad power of the central government to delineate certain areas and determine where activities can and cannot be conducted. An article also mentions reserving certain areas for conservation.
- Development of minerals.
    - This chapter covers some details around mineral development. For example, the opening of mines, maintenance, waste disposal, submission of records, and fines are among the topics discussed.
- Miscellaneous.
    - This chapter covers a wide range of different subjects – like inspection, penalties, offences by companies, delegation of power, and the power of state governments, to name a few.

While this Act is more granular than the Oilfields Act of 1948, it still does not provide the level of regulatory specificity required for CCS project development. It does not set out detailed provisions that could readily be adapted to incorporate CCS-related activities. Although certain sections may offer scope for amendment, the Act in its current form does not constitute a comprehensive framework capable of addressing the technical, operation and long-term regulatory requirements of CCS. Table 4 assess the Act against the key criteria relevant to its potential adaptation for CCS.

Table 4. Mines and Minerals (Development and Regulation) Act, 1957 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🔴	The Act was set up to develop and regulate mines and minerals. The law, like the Oilfields Act of 1948 also applies to all areas of India – onshore and offshore. However, currently, the act does not have CCS-related provisions.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🟠	The Act is very broad and high-level. While adaptable for several types of infrastructure development project, the act does not present a comprehensive framework for the CCS project lifecycle.
Comprehensiveness in providing for project siting and environmental impact assessments	🔴	The Act does not provide any definition for project siting and EIAs. It is structured in a way that describes the authority of the Government.
Comprehensiveness in providing for meaningful stakeholder and public consultation	🔴	Stakeholder and public consultation are not defined or adequately discussed in this law.
Comprehensiveness in dealing with long-term liability and financial security	🔴	There are some articles discussing penalties and offences by companies. While these can be adapted for long-term liability and financial security, it is not properly defined.

Water (Prevention and Control of Pollution) Act, 1974

Background

Enacted by the Indian central government, the Water (Prevention and Control of Pollution) Act, 1974, served as the foundation of India's regulatory framework for environmental preservation. The Act aims to:

- Prevent, control and abate water pollution.
- Maintain and restore water quality for drinking, irrigation and industrial purposes.
- Assess pollution levels and punish polluters.

Additionally, it has established two agencies responsible for enforcing the provisions of this law:

- The Central Pollution Control Board (CPCB) at the national level.
- The State Pollution Control Boards (SPCBs) at the state level.

Since its enactment in 1974, the Act has undergone several amendments, respectively in 1988, 2003 and 2024, to address evolving environmental challenges.

Main regulatory provisions

Section 25 of the Water Act, 1974 establishes a consent system requiring prior approval from the respective State Pollution Control Board before setting up any industry, operational process, or treatment and disposal system that may discharge sewage or trade effluents into a stream, well or sewer, or on land. The CPCB and the SPCBs are empowered with regulatory enforcement, which includes the authority to conduct inspections and the monitoring of industrial facilities. They are also authorised to sample and analyse effluents to ensure compliance with pollution control standards. Non-compliance with the Act's provisions results in severe penalties, including fines, imprisonment for major offences, and, in extreme cases, the closure of industries or plants found to be in violation.

Relevance for CCS

Given the potential for CCS operations to impact water and groundwater resources, such as through the discharge of effluents or the injection of CO_2 into subsurface formations, CCS projects might require prior consent from the respective SPCBs before commencing operations that could affect water bodies or groundwater. Table 5 provides an analysis of this Act against key criteria that are relevant for adaptation of the Act to support CCS project development.

Table 5. Water (Prevention and Control of Pollution) Act, 1974 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🟠	The Act provides a structured regulatory process for industries discharging effluents into water bodies, requiring them to obtain prior consent from the respective SPCBs. However, it does not explicitly address CCS-related approvals, leading to potential ambiguity if applied to CCS projects.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🔴	The Act primarily regulates water pollution and does not cover aspects of CCS project lifecycles, such as pre-injection, operation, closure, and post-closure, including into subsurface water formations.
Comprehensiveness in providing for project siting and environmental impact assessments	🟠	The Act provides regulatory authorities with some responsibilities for monitoring and regulating activities that impact water bodies: • Powers of entry and inspection to assess facilities and manufacturing processes. • Powers to take samples of sewage or effluents and reporting of analysis. • Powers to take legal action in case of water pollution in wells. However, there are no specific EIA requirements for CCS under this Act.
Comprehensiveness in providing for meaningful stakeholder and public consultation	🔴	The Act does not mandate stakeholder engagement and public participation in decision-making processes related to CCS.
Comprehensiveness in dealing with long-term liability and financial security	🔴	There are no provisions for long-term liability management, financial assurance, or closure requirements in the Act.

Forest (Conservation) Act, 1980

The Forest Conservation (FC) Act of 1980 was created to restrict the use (diversion) of forested land for purposes other than forest growth and maintenance, requiring prior approval from the central government (Ministry of Environment and Forests, 1980). The Act applies to all of India except the state of Jammu and Kashmir and supersedes local laws in the applicable states. Multiple additional rules and guidelines were released between 1981 and 2014 addressing the following topics that are potentially relevant to CCS:

- Creation of a GIS decision-support database
- FC Act approvals required before lease under the Mines and Minerals Development and Regulations Act of 1957
- Pre-approval site inspection
- Operational monitoring and verification of approved sites
- Conditional approval revocation

The Act specifies the entities responsible for reviewing forest diversion proposals and for monitoring during project construction and operation, including the use of remote sensing data. It requires that proposal information aligns with the GIS database, ensuring consistency in forest designations, plot locations and boundaries, protected status under the Wildlife Protection Act of 1972, migratory corridors, and relevant past activities in the area. While the Act provides a regulatory framework for activities in or near forested areas, it lacks the following metrics and requirements necessary for CCS operations; hence, no further explanation is provided in table format:

- Baseline environmental data
- Impact assessment
- Stakeholder engagement
- Risk mitigation measures
- Criteria for operational monitoring
- Penalties for non-compliance
- Emergency management planning
- Financial risk management
- Long-term liability

Air (Prevention and Control of Pollution) Act, 1981

The Air (Prevention and Control of Pollution) Act, enacted in 1981 and amended in 1987, establishes the regulatory framework for controlling air pollution in India. It empowers the CPCB and the SPCB to set emission standards, grant consents, monitor compliance and enforce penalties

While the Act provides a regulatory framework for regulating conventional sources of air pollution, it is not designed to address the complexities of CCS projects, In particular:

- It does not address the full lifecycle of CCS projects.
- It lacks specific provisions for EIAs related to CCS projects. However, it gives power of entry and inspection to persons empowered by a state board.
- It does not establish frameworks for stakeholder engagement and public consultation.
- It does not address long-term liability issues related to CO_2 storage.

Background

The Air (Prevention and Control of Pollution) Act, 1981, was India's first dedicated legislation to combat air pollution. It was enacted following India's participation in the 1972 Stockholm Conference, aimed at controlling emissions from industrial and vehicular sources to protect environmental and public health.

The 1987 Amendment significantly strengthened the Act by:

- Integrating it with the Water Act, 1974 governance structures (via unified national and state Pollution Control Boards).
- Expanding enforcement powers and penalties.
- Adding noise as an air pollutant.
- Enabling courts and pollution control boards to take proactive action against polluters.
- Removing industry-specific limitations by omitting the Schedule.

Main Regulatory Provisions

Institutional Structure

- The CPCB/SPCBs handle both water and air pollution (Sections 3 & 4 amended).

- Boards are empowered to issue consents, monitor emissions, and enforce compliance.

Expanded Powers & Tools (Post-1987)

- Consent Mechanism Strengthened: Boards can grant, cancel, or conditionally approve consents (Section 21)

- Proactive Legal Authority:
  - Section 22A: Boards may approach courts to restrain polluters.
  - Section 31A: Boards can direct closures, regulate utilities, or impose conditions.

- Public Involvement:
  - Section 43: Citizens may file complaints after giving 60 days' notice.

- Broader Scope:
  - Addition of noise as a pollutant.
  - Removal of industry-specific Schedule allows regulation of emerging technologies like CCS.

- Financial Provisions:
  - Boards may borrow funds (Section 33A) to support regulatory functions.

Enforcement & Penalties

- Stronger Penalties:
  - Minimum imprisonment of 1.5 years for key violations (Section 37).
  - Enhanced fines for general contraventions (Section 39).

- Court Jurisdiction Defined:
  - Only Metropolitan or First-Class Judicial Magistrates can try cases under this Act.

Relevance for CCS

While the Act is not designed with CCS in mind, it has limited indirect relevance in the following ways:

- Emission Controls at Source: CO_2 emissions from capture facilities would fall under the Act's authority.
- Board Powers: CPCB/SPCBs have wide-ranging powers to monitor, direct, and enforce emission limits.
- Legal Flexibility: Removal of the Schedule means CCS-related emissions can be regulated without needing amendments.

Table 6 provides an analysis of this Act against key criteria that are relevant for adaptation of the Act to support CCS project development.

Table 6. Air (Prevention and Control of Pollution) Act, 1981 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🟠	The Act provides a clear and structured process for obtaining consent to establish or operate industrial plants in designated air pollution control areas. There are specified timelines (four months) for consent decisions, appeal mechanisms (Section 31), and conditions for control equipment.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🔴	The Act is designed to control air pollution at the point of emission, not to manage sub-surface or geological storage of CO_2. There are no provisions for long-term site monitoring, post-closure stewardship, or site integrity after CO_2 injection – critical elements of CCS.
Comprehensiveness in providing for project siting and environmental impact assessments	🔴	While the State Boards can advise on the suitability of industrial sites (Section 17(h)), the Act does not mandate or describe any EIA process.
Comprehensiveness in providing for meaningful stakeholder and public consultation	🔴	The Act includes a mechanism for citizens to file complaints (Section 43), but it does not require public consultation or participation during the permitting or licensing process.
Comprehensiveness in dealing with long-term liability and financial security	🔴	There are no provisions for long-term liability management, financial assurance, or closure requirements in the Act.

Environment (Protection) Act, 1986

Background

The Environment (Protection) Act (EPA), 1986, derives its authority from the Constitution (Forty-second Amendment) Act, 1976, which mandates the State to protect and improve the environment, as well as to safeguard the forests and wildlife of the country. As a result, the EPA serves as umbrella legislation under which it has facilitated several key regulations, including:

- The Environmental Impact Assessment (EIA) Notification, 2006, and amended version.
- The Hazardous Waste Management Rules, 1989.
- The Manufacture, Storage, and Import of Hazardous Chemicals Rules, 1989.

Main regulatory provisions

The EPA specifically empowers the central government to take measures to protect and improve the environment, including:

- Coordinating actions by the state governments, officers and other authorities.
- Planning and executing nationwide programmes for the prevention, control and abatement of environmental pollution.
- Laying down standards for the quality of environment, emission or discharge of environmental pollutants from various sources.
- Restricting areas in which any industries, operations or processes shall not be carried out or shall be carried out subject to certain safeguards.
- Laying down procedures and safeguards for the prevention of accidents which may cause environmental pollution and remedial measures for such accidents.
- Laying down procedures and safeguards for the handling of hazardous substances.
- Examining manufacturing processes, materials and substances that are likely to cause environmental pollution.
- Carrying out and sponsoring investigations and research relating to problems of environmental pollution.
- Inspecting any premises, plant, equipment, machinery, manufacturing or other processes, materials or substances.
- Establishing environmental laboratories and institutes to carry out the functions entrusted to such environmental laboratories and institutes under this Act.
- Collecting and disseminating information in respect of matters relating to environmental pollution.
- Preparing manuals, codes or guides relating to the prevention, control and abatement of environmental pollution.

Relevance for CCS

Section 2 of the Act defines "*environmental pollutant*" broadly as "*any solid, liquid or gaseous substance present in such concentration as may be, or tend to be, injurious to environment*". This definition is sufficiently wide to potentially encompass CO_2. As such, the EPA could apply to certain aspects of CCS activities. Specifically, it could permit inspections at CCS facilities to ensure compliance with environmental standards, as well as the adoption of corrective measures to mitigate any potential environmental harm resulting from CCS operations.

Table 7 provides an analysis of this Act against key criteria that are relevant for adaptation of the Act to support CCS project development.

Table 7. Environment (Protection) Act, 1986 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🟠	The Act provides a structured regulatory process for environmental governance.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🔴	The Act focuses on general environmental protection and does not cover aspects of CCS project lifecycles, such as pre-injection, operation, closure, and post-closure.
Comprehensiveness in providing for project siting and environmental impact assessments	🟠	The Act could enable inspections at CCS projects to ensure compliance with environmental standards, although CCS projects are not explicitly mentioned. Furthermore, the EPA indirectly supports environmental impact assessment through the EIA Notification, 2006, which is derived from the EPA (see following sub-section).
Comprehensiveness in providing for meaningful stakeholder and public consultation	🔴	The Act does not directly mandate meaningful stakeholder engagement and public participation in decision-making processes related to CCS.
Comprehensiveness in dealing with long-term liability and financial security	🔴	There are no provisions for long-term liability management, financial assurance, or closure requirements in the Act.

Environment Impact Assessment Notification, 2006

Background

The Environment Impact Assessment (EIA) Notification, 2006, issued under the Environmental (Protection) Act, 1986, establishes the procedure for obtaining environmental clearance for a variety of projects that could potentially affect the environment.

A draft EIA Notification (2020) was proposed but has not been notified. Accordingly, the 2006 Notification remains in force.

Main regulatory provisions

The EIA Notification, 2006 mandates prior environmental clearance from either a national or state regulatory authority, depending on the project category:

- Category A requires clearance from the Ministry of Environment, Forest and Climate Change.
- Category B requires clearance from the State Environment Impact Assessment Authority (SEIAA).

The EIA process in India typically involves the following stages:

- Screening: to determine whether a project requires an EIA based on predefined criteria.
- Scoping: to identify key environmental issues and set the terms of reference for the EIA report to be prepared by the project proponent.
- Public consultation: consisting of public hearings at or near the project site, as well as written responses from other concerned stakeholders.
- Appraisal, at the state or national level, making recommendations to grant or reject clearance.

Although the draft EIA Notification, 2020, proposed reducing the notice period for public hearings from 30 days to 20 days, this change was never implemented due to the non-finalisation of the draft.

Relevance for CCS

The EIA Notification, 2006, does not explicitly mention CO_2 capture, CO_2 transport or CO_2 storage as standalone projects requiring prior environmental clearance at the national or state levels. However, some aspects of the CCS value chain may fall under existing EIA requirements for mining or infrastructure projects. Further clarification from regulatory authorities may be needed to determine the exact applicability of EIA provisions to CCS projects.

Table 8 provides an analysis of this Notification against key criteria that are relevant for adaptation of the Notification to support CCS project development.

Table 8. Environment Impact Assessment Notification, 2006 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🟠	The Act provides a structured regulatory process for obtaining environmental clearance for a variety of projects. However, it does not explicitly address CCS-related approvals, leading to potential ambiguity if applied to CCS projects.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🔴	The Act focuses on environmental clearance for a variety of projects but does not cover aspects of the CCS project lifecycle, such as pre-injection, operation, closure, and post-closure.
Comprehensiveness in providing for project siting and environmental impact assessments	🟠	An EIA is mandatory for Category A projects in India. However, further clarification from regulatory authorities may be needed to determine the applicability of EIA provisions to the different parts of the CCS value chain.
Comprehensiveness in providing for meaningful stakeholder and public consultation	🟠	Public consultation is one of the mandatory steps of the environmental clearance process in India. However, further clarification from regulatory authorities may be needed to determine the applicability of EIA provisions to the different parts of the CCS value chain.
Comprehensiveness in dealing with long-term liability and financial security	🔴	There are no provisions for long-term liability management, financial assurance, or closure requirements in the Act.

Manufacturer, Storage and Import of Hazardous Chemicals Rules, 1989

The Manufacturer, Storage and Import of Hazardous Chemicals and Import Rules were established in 1989 under the Environmental (Protection) Act of 1986 and are overseen by the CPCB within the Indian central government's Ministry of Environment and Forests and Climate Change (MoEF) (Ministry of Environment and Forests, 2022). The rules were revised in 2008 as the Hazardous Waste Management, Handling, and Transboundary Rules and amended again in 2016 to include transport guidelines, monitoring and reporting, emergency planning, site closure and post-closure procedures, and penalties for non-compliance.

The portions of the rules relevant to the CCS value chain are those addressing hazardous waste generation, collection, handling, processing, transport, conversion, storage, and disposal. The rules assign duties of authorities, including the MoEF, CPCB, and subnational governments, for regulatory approval processing and oversight, as well as the responsibilities and requirements of operators concerning designated hazardous chemicals. While the designated chemicals do not include CO_2, the rules outline the following elements that may be relevant and adaptable to CO_2 transport and storage:

- Regulatory approval process
- Identifying potential accident hazards
- Risk mitigation
- Worker safety training
- Compliance with transboundary chemical transport guidelines
- On- and off-site emergency planning
- Monitoring and reporting
- Compliance and safety reporting
- Site closure and post-closure procedures

The rules provide a foundational framework that can be expanded to apply to CO_2 transport and storage for CCS operations by including:

- Classification of CO_2 as an approved substance for transport and storage
- Exploration authorisation for potential CO_2 storage sites
- Storage site assessment
- Impact assessment
- Stakeholder engagement
- Financial security and insurance requirements
- Long-term monitoring
- Post-closure liability transfer

Energy Conservation Amendment Act, 2022

Background

The *Energy Conservation (Amendment) Act, 2022* amends the Energy Conservation Act, 2001 and introduces a CCTS, expanding India's framework for emissions management and non-fossil energy deployment.. These changes align with India's net zero goals and international climate commitments.

Main Regulatory Provisions

Definition Inclusions:

- New definitions introduced, including "carbon credit certificate" and "carbon credit trading scheme" (Section 2).
- "Energy" now explicitly includes fossil, non-fossil, and renewable sources.

Carbon Credit Trading Scheme (Section 14, clause w; Section 14AA):

- Central government empowered to create a carbon credit trading mechanism.
- Registered entities that reduce emissions can earn and trade carbon credits.
- Certificates can be issued by the Government or authorised agencies.

Minimum Non-Fossil Source Usage (Section 14, clause x):

- Central government may mandate minimum use of non-fossil energy sources by designated consumers.

Role of BEE (Section 13):

- BEE can recommend carbon trading rules, empanel experts, and work with international agencies.
- BEE may authorise testing bodies and promote energy-efficient and emission-reducing technologies.

Penalties and Enforcement (Section 26):

- Non-compliance with norms or trading schemes can attract financial penalties.
- Specific fines outlined for industries and vehicles not meeting standards.

Relevance for CCS

The Act does not explicitly mention CCS, but it creates a supportive legal environment for CCS deployment through the following mechanisms:

- Carbon Credits for Emission Reductions: CCS can be recognised under the carbon credit scheme for reducing point-source CO_2 emissions, enabling financial returns through credit trading.
- Designation of Entities: Industrial units using CCS may qualify as registered entities eligible to earn CCC.
- Compliance Tool: CCS can help industrial units meet mandatory non-fossil fuel usage targets or emission standards, reducing their penalty exposure.

Table 9 provides an analysis of this Act against key criteria that are relevant for adaptation of the Act to support CCS project development.

Table 9. Energy Conservation Amendment Act, 2022

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🟠	The Act empowers the central government and the BEE to regulate and authorise entities under the CCTS. However, no specific processes are outlined for approval of CCS projects or related technologies.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🔴	The Act does not explicitly refer to CCS or provide regulatory guidance tailored to its unique lifecycle stages. There are no provisions for monitoring, reporting, verification (MRV), site closure procedures, or long-term site stewardship.
Comprehensiveness in providing for project siting and environmental impact assessments	🔴	The Act does not contain provisions for project siting, land use planning, or EIAs. While the involvement of the Ministry of Environment, Forest and Climate Change is included, its role in project-level decision-making (like CCS siting or permitting) is not defined.
Comprehensiveness in providing for meaningful stakeholder and public consultation	🔴	The Act does not require stakeholder or public consultation in any part of its implementation, including the formulation of schemes like the carbon trading program.
Comprehensiveness in dealing with long-term liability and financial security	🔴	There are no provisions related to long-term liability, post-closure responsibilities, or financial assurance for infrastructure like CCS.

Petroleum and Natural Gas (Amendment) Rules, 2003

The Petroleum and Natural Gas (Amendment) Rules, 2003 (hereby referred to as 'Rules') are a set of rules and regulations maintained by the Directorate General of Hydrocarbons (DGH), an agency under the jurisdiction of the Indian central government's Ministry of Petroleum and Natural Gas. These Rules were developed per the requirements of Sections 5 and 6 of the Oilfields (Regulation and Development) Act of 1948, with the first available iteration originating in 1959, and are "amended from time to time" as per the DGH's parlance. The 2003 Amendment is the most recent one maintained on the DGH's website[4].

These rules provide significantly more detail on activities related to exploration and production and provide a useful framework that can be used to develop CCS-related rules and regulations. The Rules use offshore terminology and are thus assumed to apply to both onshore and offshore areas. The Rules begin by listing a detailed set of definitions (both technical and project-related), many of which are familiar terms that are also applicable for CCS-related development.

The Rules cover the following topics:

- Article 4 requires that there can be no prospecting or mining except under a licence or a lease. This is not unlike the requirements in both the Oilfields Act of 1948 and the Mines and Minerals Act of 1957.
- Articles 5-14 lay out the following:
  - Definitions, terms, and conditions under which the central or state governments grant licences and leases.
  - The associated fees and security deposits.
  - The rights of the licensee/lessee.
  - Area and term length of licences and leases.
  - Petroleum-related royalties.
- Article 15 briefly covers surveying and the related fees.
- Article 16 covers the identification of the leased areas.
- Article 17 covers the responsibilities of the licensee/lessee regarding transfer or assignment of the licence/lease.
- Article 18 covers the right of pre-emption vested in India's central government.
- Article 19 covers general provisions, and an overall code of conduct expected of the licensee/lessee when conducting activities in the licence/lease.
- Article 19A covers the recovery of helium from natural gas. While this is a production-related activity, it does cover separation or extraction of gases, which could be adaptable to the capture part of the CCS value chain.
- Articles 20-23 cover the suspension and cancellation of licences and leases and the associated fees.
- Article 24 specifically covers the handling of cores and samples and the associated analysis.
- Article 25 is a direction from the central government to reduce waste.
- Article 26 provides general guidance on the spacing of wells.
- Article 27 covers the right of the central government to restrict production if deemed necessary.
- Article 28 covers the licence or lease specific regulation of operations that can be set up by the central government.

4 A draft set of rules (Petroleum and Natural Gas Rules, 2025) has been obtained however, these rules were not in force at the time of this report.

- Article 29 covers the responsibility of the central government to provide notices to licensees/ lessees to ensure the prevention of the escape of petroleum or the access of water (assumed to be underground sources of drinking water). This article can be applicable to CCS and can be adapted to develop CCS-related rules and regulations.

- Articles 30 and 31 cover the suspension of operations and shutting down of wells, along with the responsibilities of the licensee/lessee to not suspend drilling, abandon or recondition wells, resume drilling or production after abandonment, etc., without notification from the central government. These articles can be applicable to CCS and can be adapted to develop CCS-related rules and regulations.

- Article 32 covers the rights of the central government to assign an appropriate agency to supervise the provisions in the Rules. This article can also be adapted to develop CCS-related rules and regulations.

- Articles 32A and 33-35 cover penalties, dispute resolution, the saving of licences and leases related to a rule that was passed in 1949, and the power of the central government to provide exemption from certain rules.

Table 10 provides an analysis of these Rules against key criteria that are relevant for adaptation of the Rules to support CCS project development.

Table 10. Petroleum and Natural Gas (Amendment) Rules, 2003 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals		These Rules, which were developed under the authority of the Oilfields (Regulation and Development) Act of 1948, provide significantly more detail for activities related to exploration and production and provide a useful framework that can be used to develop CCS-related rules and regulations. The Rules use offshore terminology and are thus assumed to apply to both onshore and offshore areas. However, currently, the act does not have CCS-related provisions.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)		While there are several articles and sections of the Rules that can be adapted for CCS, a comprehensive framework for the CCS project lifecycle is not present. The portions of the Rules that can be modified are discussed above.
Comprehensiveness in providing for project siting and environmental impact assessments		Definitions for project siting and EIAs are not present.
Comprehensiveness in providing for meaningful stakeholder and public consultation		There are articles that address dispute resolution. While they can be adapted for stakeholder and public consultation, there is no definition for the same at this time.
Comprehensiveness in dealing with long-term liability and financial security		There are articles that address penalties. While these can be adapted for long-term liability and financial security, it is not properly defined.

Petroleum and Natural Gas Regulatory Board Act, 2006

Background

Enacted in 2006, the Petroleum and Natural Gas Regulatory Board (PNGRB) Act established the Petroleum and Natural Gas Regulatory Board. This Board is responsible for regulating the midstream and downstream segments of the oil and gas sector in order to ensure adequate supply, promote competitive markets and protect consumers' rights.

Main regulatory provisions

The PNGRB is empowered to register market entities and infrastructure, regulate access to pipelines and associated tariffs, monitor prices, and take corrective action to prevent restrictive trade practices. It also sets technical and safety standards, among other responsibilities within its mandate. In addition, the Board is required to maintain a data bank and information system relevant to its regulatory activities. It has the authority to verify data submitted by regulated entities and conduct inspections of facilities and documentary records.

Relevance for CCS

The Act governs the transportation of oil and natural gas through pipelines, and its scope could potentially be extended to include the regulation of CO_2 pipelines for CCS projects:A more detailed analysis based on the select set of criteria is provided below:

The PNGRB has jurisdiction to regulate certain activities related to petroleum, petroleum products, and natural gas. These include the following:

- Refining
- Processing
- Storage
- Transportation
- Distribution
- Marketing
- Sale

It is notable that all these activities are downstream of the production of crude oil and natural gas, which the act specifically excludes in articles 1 and 2. The Act covers all of India, both onshore and offshore.

The Act covers the following topics that may be of significance to CCS, should amendments be made to include it:

- Chapter I, articles 1-2: the title of the act and definition of terms.
- Chapter II, articles 3-10: the establishment of the board, qualifications of the Chairperson and other members, board meetings, and other particulars relating to the board's functioning.
- Chapter III, articles 11-13: the actual functions and powers of the board. The board is authorised to "declare pipelines as common or contract carrier". These articles can be applied to CCS and can be adapted to develop CCS-related rules and regulations.
- Chapter IV, articles 14-23: discusses the registration and authorisation of entities that will be regulated by the act. This section also covers common/contract carrier entities and specifically mentions pipelines falling under these categories. These articles can be applied to CCS and can be adapted to develop CCS-related rules and regulations, specifically for CO_2 pipelines. Articles 20, 21, 22 (and others) also discuss natural gas distribution networks and their associated infrastructure; these can also be adapted to CCS since distribution networks are essential to the proper functioning of CCS hubs.
- Chapter V, articles 24-29: covers dispute settlement, complaints, investigations and penalties.
- Chapter VI, articles 30-37: covers appeals to the appellate tribunal, which also relates to dispute settlement.
- Chapter VII, articles 38-41: covers the payments to the board members. It also covers the setting up of a fund called the Petroleum and Natural Gas Regulatory Board Fund, which is authorised to disburse fees, penalties, charges, salaries, and allowances.

- Chapter VIII, articles 42-43: covers the powers of the central government and its power to act in the best interests of the country, including in foreign relations and acting in the public interest to maintain or increase the supply of petroleum or natural gas. This chapter is unique and can be adapted for CCS by integrating with India's commitments towards carbon management mentioned in other polices and laws.

- Chapter IX, articles 44-50: covers offences and punishment. This is different from dispute settlement in that it covers willful disobedience of the directions of the board and/or orders from the appellate tribunal.

- Chapter X, articles 51-63: covers miscellaneous items like maintaining information, the obligations of entities, the power of the central government to make rules, power of the board to make regulations, and for them to be laid before parliament. This chapter can be adapted for CCS, especially the articles on rules and regulations.

Table 11 provides an analysis of this Act against key criteria that are relevant for adaptation of the Act to support CCS project development.

Table 11. Petroleum and Natural Gas Regulatory Board Act, 2006 assessment

Criteria	Assessment based on the selected criteria	Justification
Clarity and efficiency of the administrative process for regulatory approvals	🟠	The Act governs the transportation of oil and natural gas through pipelines, and its scope could potentially be extended to include the regulation of CO_2 pipelines for CCS projects. However, currently, the act does not have CCS-related provisions.
Comprehensiveness to cover all aspects of a CCS project lifecycle (pre-injection, operation, closure, post-closure)	🟠	While there are several articles and sections of the Act that can be adapted for CCS, the Act does not present a comprehensive framework for the CCS project lifecycle. The portions of the Act that can be modified are discussed above.
Comprehensiveness in providing for project siting and environmental impact assessments	🔴	The Act does not provide any definition for project siting and EIAs.
Comprehensiveness in providing for meaningful stakeholder and public consultation	🔴	Several articles address dispute settlement, complaints, investigations and penalties. While these can be adapted for stakeholder and public consultation, there is no definition for the same at this time.
Comprehensiveness in dealing with long-term liability and financial security	🔴	Several articles address offences, willful disobedience, and punishment. While these can be adapted for long-term liability and financial security, it is not properly defined.

4. Review of CCS regimes in other jurisdictions

The selection of jurisdictions for review was based on the maturity of CCS legal and regulatory frameworks, and the experience of these jurisdictions in supporting and permitting CCS projects. The jurisdictions included in this report are:

- The United States
- Alberta, Canada
- The European Union
- The United Kingdom

The review aims to provide lessons learnt from experience in these jurisdictions that could be applicable to the formulation of a CCS legal and regulatory framework in India.

THE UNITED STATES

CCS-related policy landscape

In the US, the policy landscape is nuanced with support from the federal and state governments. The federal government has provided accelerated policy support for CCS in recent years through direct financial support to expand the nation's CCS infrastructure and improved fiscal incentives in the form of expanded tax credits.

The federal government has been reviewing and finalising the regulatory regime for offshore storage, while updates to CO_2 pipeline transportation and safety have been provided. In addition, specific guidance and initiatives, such as the release of the joint policy statement and principles for responsible participation in voluntary carbon markets (White House, 2024) and the Voluntary CDR Challenge, demonstrate continued federal engagement in carbon management and CDR-related policy development (DOE, 2024c). As with all jurisdictions globally, the durability and clarity of long-term policy support remain important considerations for project developers.

In 2024, CCS legislation gained significant interest at the US state level. With the growth in supportive federal policies, an increasing number of states took the initiative to pass state-level laws. These laws support the buildout of the governance framework for CCS to support deployment of the technology in various industries. This includes legislation governing transport, storage, pore space, liability and other aspects of the CCS value chain, as well as granting primary enforcement responsibility or primacy to various states.

Legal and regulatory assessment

In the US, legislation has had a profound impact on CCS project development and provides much of the regulatory framework to support projects. They are elaborated on in the sections below.

Safe Drinking Water Act of 1974

Passed by the US Congress in 1974, the Safe Drinking Water Act (SDWA) is designed to regulate the supply of drinking water with the intention of protecting the health of the public (EPA, 2004). The law was updated and modified in 1986 and 1996 and covers the sources of drinking water like groundwater wells, reservoirs, springs, lakes, and rivers. The US EPA is a federal agency with the authority to enforce the SDWA. Subsequently, the EPA sets standards to protect the drinking water supply through standard- setting and the monitoring of contaminants.

The UIC program, managed by the EPA, is designed to protect Underground Sources of Drinking Water (USDWs). Of the six classes of wells under the UIC program, Class VI wells are used exclusively for the geologic sequestration of CO_2 (EPA, 2022). The purpose of the Class VI program is to address the impact of the long-term storage of CO_2 on USDWs (EPA, 2024b, 2024a). The Class VI regulations do not make a distinction between a pilot versus a commercial project. Class VI rules apply for any project where CO_2 is sequestered in subsurface formations, both onshore and offshore within state territorial waters.

Although the promulgation of requirements for Class VI wells in 2010 was based on the existing UIC Program's requirements for all other well types, new requirements were introduced to address the unique aspects of operations conducting geologic sequestration of CO_2. The EPA's preamble to the Class VI rule states that "tailored requirements on the existing UIC regulatory framework are necessary to manage the unique nature of CO_2 injection for geologic sequestration" (EPA, 2010a). Since the UIC Program's objective is to protect underground sources of drinking water, the EPA highlighted a range of unique risk factors associated with CO_2 injection. This led to the establishment of comprehensive and more specific requirements designed to address the unique properties of CO_2, distinct from the requirements for other well classes (EPA, 2010b).

Other unique requirements include obligations of the owner or operator to monitor, model and report the movement of the CO_2 plume after injection, stringent monitoring and reporting requirements and post-injection site care and monitoring requirements. The latter, for example, requires monitoring for a default period of 50 years following the cessation of injection. A summary of the permanence requirements for Class VI wells can be found in Appendix 1 to this report.

Through the introduction of these further requirements, the EPA has attempted to address the unique risks and nature of CO_2 storage activities, extending beyond the sole objective of protecting underground sources of drinking water, which is the primary focus of other well classes. However, the choice to regulate CO_2 injection under its safe drinking water protection regime is demonstrative of a specific policy choice by the US government.

The safeguards in the US regime that address the unique risks of CO_2 injection, while different from objectives in jurisdictions that regulate CCS under environmental protection regimes or under dedicated standalone legislation, have clear objectives to protect the wider environment.

Bipartisan Infrastructure Law of 2021

The passing of the bipartisan Infrastructure, Investment, and Jobs Act (a US Federal legislation) in 2021 provided the US Department of Energy (DOE) with over US$62 billion in funding for investments in new technologies, energy efficiency, power, and manufacturing (DOE, 2021). The bill authorises US$21.5 billion of this funding to be used for research hubs and clean energy demonstrations. Almost half of this amount, more than US$10 billion, is earmarked for industrial emissions reduction, carbon capture and DAC (DOE, 2021). The DOE refers to this area of infrastructure development as carbon management, renaming the Office of Fossil Energy as the Office of Fossil Energy and Carbon Management, or FECM (FECM, 2021).

Inflation Reduction Act of 2022

The Inflation Reduction Act (IRA) boosted the 45Q tax credit for the capture, geological storage and utilisation of CO_2. A short summary of the increases in US$/tonne of CO_2 is presented below. Additional details on the 45Q tax credit can be found in Section 45Q Tax Credit below.

- Geological storage of CO_2:
  - From power generation and industrial facilities: US$85 (was US$50).
  - From direct air capture (DAC) facilities: US$180 (was US$50).

- Utilisation of CO_2:
  - From power generation and industrial facilities: US$60 (was US$35)
  - From DAC facilities: US$130 (was US$35).

This law broadened the ability to transfer the 45Q tax credit. During the 12-year period mentioned above, the entity that originally received the 45Q tax credit could transfer the entire amount or any portion of it to another tax-paying entity in exchange for a cash payment. Furthermore, this cash payment would not be taxed.

Executive Order – Unleashing American Energy

On 20 January 2025, President Trump signed an Executive Order (EO) titled "Unleashing American Energy". While Section 7 of this EO requires all US Federal agencies to stop the disbursement of funds appropriated through both the IIJA of 2021 and the IRA of 2022 that are related to electric vehicles and charging stations, funds related to CCS projects are not directly mentioned. In May 2025, DOE Secretary Chris Wright announced that 24 awards from the Office of Clean Energy Demonstrations (OCED) would be terminated (Department of Energy, 2025). The Secretary mentioned that this would result in "$3.6 billion in savings". The announcement specifically mentioned that the funding was terminated for CCS projects.

One Big Beautiful Bill Act of 2025

In 2025, the US Congress passed the One Big Beautiful Bill Act (OBBBA), which preserved the 45Q tax credit (Global CCS Institute, 2025; OBBBA, 2025).

Features that remain the same include:

- For geological storage:
  - Point-source capture tax credit remains the same at US$85/tonne.
  - DAC tax credit remains the same at US$180/tonne.
- The inflation adjustment year remains the same; 2027 indexed to 2025.

New features included in the OBBBA are:

- CO_2 utilisation now has a parity with CO_2 storage in 45Q. CO_2 used or converted into a product or CO_2 that is injected (and thus stored geologically) through enhanced oil recovery or natural gas recovery (qualified projects) qualify for the same tax credit (in US$) as CO_2 that is sequestered through geological storage.
- The tax credit for utilisation or geological storage with enhanced recovery, captured through DAC, increased from US$130/tonne to US$180/tonne.
- Restrictions for Foreign Entities of Concern (FOECs).

United States pipeline legislation

In the US, several federal statutes govern the regulation of pipelines, especially pipeline safety. Historically, the regulation of pipelines began with the Natural Gas Pipeline Safety Act of 1968, whose jurisdiction applied to natural gas (Natural Gas Pipeline Safety Act, 1968). Regulation of hazardous liquids began with the Hazardous Liquids Pipeline Safety Act of 1979, which defined a hazardous liquid as a "petroleum or a petroleum product" (Hazardous Liquids Pipeline Safety Act, 1979).

The federal government possesses statutory jurisdiction for siting CO_2 pipelines when they cross federal lands (DOE, National Energy Technology Laboratory and Great Plains Institute, 2017). If a pipeline (any pipeline) needs to traverse federal lands, federal statutes apply, and the BLM– an agency within the US Department of the Interior – grants a right-of-way under the MLA of 1920 or the Federal Land Policy and Management Act of 1976 (DOE, National Energy Technology Laboratory and Great Plains Institute, 2017). These pipelines also carry a common carrier transportation status (not private or proprietary). Common carrier status is afforded to those pipelines that offer services to third parties, subject to contractual agreements. Montana and North Dakota provide useful definitions (Montana Code Annotated, 2021; North Dakota Century Code, 2023).

The federal government does have jurisdiction to regulate the safety of CO_2 pipelines. The six statutes that form the legal basis for PHMSA – an agency within the US Department of Transportation – to regulate pipeline safety (Department of Transportation 2022) are:

1. Natural Gas Pipeline Safety Act of 1968 (US Congress, 1968).

2. Hazardous Liquid Pipeline Safety Act of 1979 (US Congress, 1979).

3. Pipeline Inspection, Protection, Enforcement and Safety Act of 2006 (Act, 2006).

4. Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011 (Act 2011, 2012).

5. Protecting our Infrastructure of Pipelines Enhancing Safety (PIPES) Act of 2016 (Act, 2016).

6. Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2020, Public Law No. 116-260, Division R, 27 December 2020, (Act, 2020).

Regulations that govern the safety of pipelines, like other Federal regulations, are listed and elaborated in the relevant and applicable CFR. For CO_2 pipelines, 49 CFR Part 195 applies. The scope of this CFR *"...prescribes safety standards and reporting requirements for pipeline facilities used in the transportation of hazardous liquids or carbon dioxide."* While this CFR in its original form did not include the transportation of CO_2 by pipeline, the API in 1989 recommended that the Office of Pipeline Safety (OPS), an office within the Pipeline and Hazardous Materials Safety Administration (PHMSA), amend this regulation to include CO_2, which ultimately resulted in the Research and Special Programs Administration (RSPA, PHMSA's predecessor) amending the CFR (Federal Register, 1991; IEAGHG, 2013).

The regulation is broad in scope, covering compliance, general inspection, repair, material inspection, pipe transportation, welding, pipeline location, installation, valving, associated equipment (pumping), protection, and record keeping.

In May 2022, PHMSA announced new safety measures to protect the public from CO_2 pipeline failures after the 2020 leak in Satartia, MS (PHMSA, 2022). The pipeline safety measures include:

- Conducting solicitations to research and strengthen CO_2 pipeline safety.
- Conducting a failure investigation and completing a 2020 CO_2 pipeline failure report.
- Issued notices of violations and penalties for the probable violations of federal pipeline safety regulations.
- Updating CO_2 pipeline standards to include emergency preparedness and response requirements through initiating new rulemaking, issued an advisory bulletin to all pipeline operators nationwide that stressed the need to plan for and mitigate the risks of geohazards and land movements that could pose risks to the integrity of pipelines.

On 10 January 2025, PHMSA published a proposed rule on CO_2 pipeline safety requirements. The notice of proposed rulemaking (NPRM) references the 2020 Satartia accident and subsequent response. Several amendments were also proposed (Columbia Climate School, 2025; PHMSA, 2025a).

ALBERTA, CANADA

CCS-related policy landscape

The Canadian constitution assigns responsibility to the provinces to regulate CCS activities that take place onshore and within their provincial boundaries. Accordingly, the provinces of Alberta, British Columbia, Saskatchewan, Nova Scotia, Quebec and Manitoba have all sought to address CCS to some extent in their policy, legal, and regulatory frameworks.

Despite onshore CCS activities being regulated primarily at the provincial level, the Canadian federal government's jurisdiction over federal lands, lands crossing provincial or international boundaries and offshore areas means that projects situated in these areas will be required to obtain federal regulatory approvals and comply with relevant federal regulatory frameworks (Craik et al., 2022).

Further, regulatory competence for CCS projects is divided or shared between the provincial and federal governments, depending on the subject matter involved. In Canada, the provinces have been assigned constitutional jurisdiction over natural resources, while the federal government retains jurisdiction over matters involving trade and commerce, international and intra-provincial matters, taxation and criminal law. The provinces and the federal government also share jurisdiction over environmental protection, including climate change mitigation. Thus, Canada's domestic legal and regulatory framework that governs and incentivises CCS is a combination of provincial and federal efforts.

Legal and regulatory assessment

Background to the CO_2 storage regulatory regime

In 2010, Alberta became the first jurisdiction in Canada to promulgate comprehensive CCS legislation with the enactment of the CCS Statutes Amendment Act, which made significant amendments to several existing acts, including:

- The Mines and Minerals Act
- The Oil and Gas Conservation Act
- The Energy Resources Conservation Act
- The Public Lands Act
- The Surface Rights Act

Shortly after the legislative framework for CCS was established, the Government of Alberta issued the Carbon Sequestration Tenure Regulation in 2011, introducing procedures for CCS operators seeking tenure rights for deep carbon storage sites (Massicotte et al., 2011a).

The development of CCS-specific legislation was driven primarily by Alberta's recognition of CCS as the primary mechanism to reduce GHG emissions in its 2008 Climate Change Strategy, and a series of federal and provincial policy initiatives for CCS projects between 2007 and 2010.

Prior to the CCS Statutes Amendment Act, CCS projects were regulated under several laws and directives of the Energy Resources Conservation Board (ERCB) governing analogous projects, including acid gas disposal, natural gas storage and enhanced oil recovery. The ERCB had approximately 25 years of experience with acid gas reinjection and small-scale CO_2 transportation. Hence, a usable regulatory framework existed that covered elements relevant to CCS, including public safety, environmental protection and resource conservation. However, long-term monitoring protocols were absent, and due to the size and unique nature of CCS projects, the ERCB regulations could not be used in their current form to regulate CCS projects.

The CCS Statutes Amendment Act was intended to fill the gap, by having as its main aims the clarification of pore space ownership, the transfer of long-term liability for injected CO_2 to the province post closure, and the creation of a stewardship fund for remedial and ongoing monitoring costs. The ERCB was given the regulatory authority to issue approvals and licences for CCS projects, while the ERCB and Alberta Department of Energy (ADOE) had joint jurisdiction over CCS projects (Massicotte et al., 2011b).

Alberta's legal and regulatory authority

In June 2013, Alberta proclaimed the Responsible Energy Development Act (REDA). The Act established the AER and transferred all regulatory functions of the ERCB, as well as those held by Alberta Environment and Sustainable Resource Development related to public lands, water and the environment, to the AER (Government of Alberta, 2023). The AER became the sole regulator for energy-related developments under the following acts (Alberta Energy Regulator, 2022):

- Oil and Gas Conservation Act
- Oil Sands Conservation Act
- Coal Conservation Act
- Geothermal Resource Development Act
- Pipeline Act

The AER also has shared regulatory responsibilities, together with two government departments, under the following Acts:

- Environmental Protection and Enhancement Act
- Water Act
- Public Lands Act
- Mines and Minerals Act

Alberta, therefore, has three different regulatory authorities overseeing carbon capture, transport and storage activities – the AER and two provincial government departments: the Department of Energy and Minerals, and the Department of Environment and Protected Areas. See Figure 1 for how these duties are distributed (Alberta Energy Regulator, 2023a).

Alberta

Alberta Energy Regulator

Alberta Energy and Minerals	Alberta Environment and Protected Area	Alberta Energy Regulator
• ensures the development of policy and regulatory frameworks to enable the advancement of CCUS in the province, • issues tenure rights for evaluation and sequestration of carbon dioxide, and • manages the Post-Closure Stewardship Fund that carbon sequestration operators pay into to offset costs associated with the long-term monitoring and maintenance of sequestration site assessments for monitoring and closure plans.	• regulates carbon dioxide capture facilities not connected to, or associated with, energy resource activity (e.g., chemical manufacturing plant), • leads implementation of the Emissions Reduction and Energy Development Plan, and • manages the Technology Innovation and Emissions Reduction (TIER) regulatory system that promotes CCUS by allowing companies to generate credits.	• regulates energy-related facilities that capture carbon dioxide; • regulates pipelines that transport carbon dioxide; • regulates subsurface injection activities; • oversees measurement, monitoring, and verification (MMV) plans and closure plans, and • issues closure certificates.

Figure 1. The responsibilities of regulatory authorities in Alberta

THE EUROPEAN UNION

CCS-related policy landscape

To drive the development of CCS across Europe, the EU has implemented a diverse array of policy, legal and regulatory mechanisms that can be categorised into three main areas (Global CCS Institute, 2024b):

- **Direct policy requirements and financial incentives**, i.e. instruments that directly encourage investors to invest in CCS technologies.
- **Supportive policies and programmes**, which encompass formal expressions of ambition or strategic statements, direct funding or grants, and other initiatives that provide indirect support to CCS projects.
- **Legal and regulatory governance structures**, which involve regulatory frameworks for CO_2 transport, permitting processes, etc.

The CCS-related policy landscape in the EU differs from other regions, such as North America, where significant tax credits for CO_2 storage play a major role in CCS development.

Direct policy requirements and financial incentives

EU CCS Directive

Adopted in 2009, the EU CCS Directive establishes a comprehensive regulatory framework for the environmentally safe storage of CO_2. It applies to commercial-scale facilities with a total storage volume above 100 kilotonnes (kt) of CO_2 in onshore and offshore geological formations. The directive sets out strict protocols for pre-injection, operation, closure and post-closure activities, along with permitting procedures for exploration and CO_2 storage.

When adopting the EU CCS Directive, the EU amended several pre-existing pieces of EU environmental legislation to address provisions related to the capture and transport of CO_2, as well as requirements for environmental approvals. These amendments included:

- Council Directive 85/337/EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment.
- Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.
- Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants.
- Directive 2004/35/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage.
- Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste (Text with EEA relevance).
- Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste.
- Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 concerning integrated pollution prevention and control (Text with EEA relevance).

Net Zero Industry Act (NZIA)

Adopted in June 2024 in response to the US Inflation Reduction Act, the NZIA aims to stimulate investment in net zero technologies while enhancing the competitiveness of EU industry and supporting the energy transition. The act sets two key targets for 2030:

- **An overall net zero technology target**: The EU's manufacturing capacity for net zero technologies should meet at least 40% of annual deployment needs.

- **A CCS-specific target**: An EU-wide target of 50 Mtpa of CO_2 injection capacity by 2030, with the possibility to introduce an additional target for 2040 by December 2028.

To meet the CO_2 injection target, the NZIA required oil and gas producers to contribute proportionally based on their share of crude oil and natural gas production in the EU between 1 January 2020 and 31 December 2023. However, the NZIA also included two exemptions from this target:

- **Small-scale production**: Entities with oil and gas productions below a certain threshold (to be defined in a future Delegated Regulation) are exempt.
- **Decision by EU Member States**: EU Member States may exempt domestic oil and gas producers if their national CO_2 injection capacity already exceeded the quota allocated to producers.

Additionally, the NZIA introduced an 18-month maximum deadline for granting all necessary permits for CO_2 storage site operations.

EU Emission Trading Scheme (EU ETS)

The EU ETS is a market-based mechanism aimed at capping greenhouse gas (GHG) emissions. It applies to installations in the energy sector, manufacturing industries, as well as aircraft operators flying with the EU and departing to Switzerland or the UK. Since January 2024, the EU ETS has been progressively covering maritime emissions. By 2023, the EU ETS had successfully reduced emissions from European power and industry plants by approximately 47% compared to 2005 levels (European Commission, 2023).

Under the EU ETS, each participant must surrender an allowance for every tonne of CO_2 equivalent emitted. However, it can avoid this obligation if it successfully captures, transports, and stores CO_2 at a site authorised under the EU CCS Directive, thus providing an economic incentive for CCS deployment. The most recent revision of the EU ETS Directive, published in May 2023, expanded its scope to encompass all CO_2 transport methods, no longer limiting the scheme to CO_2 pipelines.

Furthermore, it should be noted that all the elements of the CCS value chain – CO_2 capture, transport and storage – are covered by the scope of the EU ETS. Consequently, operators engaged in these activities must report their operational and fugitive emissions annually as per the EU ETS compliance cycle. The EU Monitoring and Reporting Implementation Regulation details the methodology for calculating and reporting these emissions (see the section on the EU MRR for further details).

Supportive policies and programmes

EU 2040 climate target and Industrial Carbon Management Strategy

In February 2024, the European Commission presented its proposed 2040 climate plan, complementing the existing binding commitments to reduce GHG emissions by 55% by 2030 (compared to 1990 levels) and achieve climate neutrality by mid-century in the European Climate Law (European Commission, 2024a). A key element of this non-binding communication is the recommendation to enshrine a net 90% reduction in GHG emissions by 2040 into the European Climate Law.

The European Commission emphasised the key role of CCS and CDR in achieving this target, as demonstrated by the simultaneous release of the EU Industrial Carbon Management Strategy (European Commission, 2024b). The latter estimates that around 280 Mtpa of fossil, biogenic and atmospheric CO_2 should be captured by 2040, increasing to 450 Mtpa by 2050.

To support these objectives, a coordinated EU-wide approach is essential, ensuring clear guidance for Member States. The Commission has outlined several key measures to facilitate implementation, including:

- Developing a regulatory framework for CO_2 transport.
- Mapping and promoting investment in potential storage sites.
- Advancing CDR initiatives through policy and financial incentives.
- Establishing a knowledge-sharing platform to accelerate CCUS deployment.

Clean Industrial Deal

The Clean Industrial Deal, released in February 2025, outlines the European Commission's strategy to foster a business environment that drives both decarbonisation and industrial competitiveness (European Commission, 2025). It includes a series of initiatives and recommendations, some of which may support the deployment of CCS across the EU:

- Reviewing the EU ETS Directive in 2026, with the potential inclusion of CDR.
- Clarifying GHG emissions accounting rules for low-carbon fuels through the adoption of the dedicated delegated act.
- Establishing an Industrial Decarbonisation Bank to facilitate investment in carbon reduction projects.
- Creating a new state aid framework to facilitate investments in CO_2 capture.

EU funding programmes

The EU has launched several funding programmes to support the research, demonstration and commercial deployment of CCS. Table 12 provides a summary of the most relevant funding initiatives.

Most funding programmes, except for the Innovation Fund and the Recovery and Resilience Facility, are financed through the Multiannual Financial Framework (MFF). The current MFF (2021-2027) allocates €1.211 trillion to the following political priorities: cohesion (35%), agriculture (33%), internal market (12%), external policy (9%), administration (7%), migration (2%) and defence (1%). The European Commission, the European Parliament and the Council were due to start negotiations on the next MFF (2028-2034) in summer 2025. These negotiations will shape the future financial landscape for CCS funding and other strategic EU priorities.

In contrast, the EU Innovation Fund, funded by revenues from the EU ETS, focuses on the deployment of innovative clean technologies, including CCS and CDR solutions, underscoring the carbon market's pivotal role in advancing the EU's green transition. Depending on the carbon price, the Innovation Fund is expected to provide up to €40 billion[5] for the period 2020-2030. On 3 December 2024, the European Commission launched eight new calls for proposals, some of which could support CCS and CDR projects (European Commission, 2024c).

Finally, the Recovery and Resilience Facility, part of the NextGeneration EU recovery instrument, was established in February 2021 to address the economic and social impacts of the Covid-19 crisis. With a budget of €723 billion over 2021-2026, it offered grants and loans to EU Member States, which had to submit a comprehensive national recovery and resilience plan detailing the reforms and public investments they planned to implement by 31 December 2026. Several national recovery and resilience plans included CCS funding, such as the Belgian plan that allocated €95 million investment in a CO_2 and hydrogen backbone and is expected to be completed by August 2026.

Table 12. EU funding programmes relevant to CCS (Global CCS Institute and PNO, 2024)

EU fund	Eligible countries	Types of CCS projects eligible	Maximum co-funding rates	Operating period
Horizon Europe	EU Member States and associated countries	CCS research Projects (TRL 3-7)	Between 60% and 100% of eligible costs	2021-2027
Innovation Fund	EU Member States, Norway, Iceland and Liechtenstein	EII with CCS, BECCS, CO_2 transport and storage (TRL7-9)	60% of relevant costs	2020-2030

5 Based on a carbon price of €75/tonne. On 10 February 2025, the EU ETS allowance was traded at €82.94 (Trading Economics, 2025).

Connecting Europe Facility – Energy	EU Member States, Ukraine and Moldova	CO_2 infrastructure (from the fence of emitters to the well head of the storage site)	Between 50% and 75% of eligible costs	2021-2027
Recovery and Resilience Facility	EU Member States	Depends on the scope of national recovery and resilience plans	Depends on national calls for funding	2021-2026
Just Transition Fund	EU Member States but restricted to projects located in their Territorial Just Transition Plans	CCS projects applied to EU ETS installations upon strict conditions	Between 50% and 85% of relevant costs, depending on the region where the project is located	2021-2027
InvestEU	EU Member States, EFTA, candidate countries, etc.	Various components of the CCS value chain		2021-2027
LIFE	EU Member States, Iceland, Moldova, North Macedonia, and Ukraine	CCS, excluding construction of carbon capture and storage infrastructure	60% of eligible costs for standard action projects	2021-2027

EU state aid frameworks

Under Article 107 of the Treaty on the Functioning of the European Union, state aid is generally prohibited unless it can be justified on grounds of general economic development. Any aid measures proposed by the national authorities of any EU Member States must be notified to the European Commission, which examines on a case-by-case basis whether the aid mechanism is compatible with the internal market and can therefore be authorised. The three members of the European Economic Area (EEA) – Iceland, Liechstenstein and Norway – must request the exemption from the EFTA Surveillance Authority.

Two Commission Communications are of particular importance for CCS projects: the Climate, Energy and Environmental State Aid (CEEAGs), and the Clean Industrial Deal State Aid Framework (CISAF).

Climate, Energy and Environmental State Aid (CEEAG)

In February 2022, the European Commission adopted the CEEAGs to enable Member States to support Green Deal objectives while limiting distortions of competition. The guidelines define categories of permissible aid, each subject to specific assessment criteria. For CCS projects, two categories of aid are particularly relevant:

- Aid to energy infrastructure, which may include projects such as CO_2 pipelines, CO_2 export terminals or storage facilities.
- Aid to decarbonisation, which covers technologies that reduce GHG emissions, including CO_2 capture. In this context, Member States may finance up to 100% of eligible costs, provided the aid induces a change in behaviour among beneficiaries that leads to accelerated decarbonisation beyond what the market would have achieved on its own, and that no overcompensation occurs. Aid must be limited to the minimum necessary to carry out the supported activity.

In addition to these two categories, CO_2 infrastructure projects operated under a legal or natural monopoly may be considered free of state aid and thus exempt from state aid control, meaning they are automatically approved. These guidelines also introduce the possibility of using carbon contracts for difference (CCfDs) as a funding mechanism for industrial decarbonisation initiatives.

Table 13 provides an overview of state aid schemes adopted by EU Member States to support CCS, approved under the CEEAGs.

Table 13. Examples of existing state aid schemes adopted by EU Member States supporting CCS

EU Member State	Legal framework	Type of projects	Aid instrument	Amount	Scheme duration	Commission decision
The Netherlands	Energy and Environmental Aid Guidelines (EEAGs)[6]	Renewable electricity, gas and heat, use of industrial waste heat and heat pumps, electrification, waste incineration, CCS, and hydrogen	Direct grant	€30 billion	Until 31 December 2025	December 2020
Denmark	CEEAGs	CCS	Direct grant	€1.1 billion	January–April 2023	January 2023
Denmark	CEEAGs	Bioenergy with CCS (BECCS)	Direct grant	€350 million	Until 31 December 2024	December 2023
Sweden	CEEAGs	BECCS	Direct grant	€3 billion	July 2024–December 2028	July 2024
Greece	CEEAGs	Onshore and offshore infrastructure part of Prinos project	Direct grant	€150 million	From October 2024	October 2024
France	CEEAGs	Electrification, CCS, CCU and energy efficiency	CCfD	€3 billion	15-year contract (Auction phase closes May 2025)	December 2024
Germany	CEEAGs	Electrification, CCS, CCU, energy efficiency and hydrogen	Other, direct grant	€5 billion	Until 31 December 2026	March 2025

6 The EEAGs, in force from 2014 to 2021, were the predecessors to the CEEAGs.

Clean Industrial State Aid Framework (CISAF)

In June 2025, the European Commission adopted CISAF to simplify state aid rules in order to accelerate the roll-out of renewable energy, deploy industrial decarbonisation and ensure sufficient capacity of clean technology manufacturing in Europe.

Under CISAF, EU Member States may establish state aid schemes for various projects, including CO_2 capture, subject to strict conditions outlined below:

- Projects must begin operations within 60 months after the date of state aid approval.
- Projects must be connected to a net zero strategic CO_2 storage initiative as defined by the NZIA, or to another CCUS value chain.

Legal and regulatory governance structures

EU CCS Directive Guidance Documents

In 2011, the European Commission developed four guidance documents to help EU Member States implement the CCS Directive. To ensure their continued relevance and address ambiguities identified in the first CCS projects, the Commission announced the need for updates in 2023.

Following extensive consultations, the European Commission published the four revised guidance documents in July 2024 (European Commission, 2024d, 2024e, 2024f, 2024g). These updates focus on advanced CO_2 storage technologies in mafic/basalt rocks and depleted hydrocarbon reservoirs, as well as issues related to corrosion and safety, and the regulatory transition from hydrocarbon production to CO_2 storage. Additionally, they provide enhanced criteria for identifying suitable geological areas suitable for CO_2 storage and exploration.

Although non-binding, these documents offer clarity to Member States for the transposition of the EU CCS Directive into national regulations.

EU Monitoring and Reporting Regulation

In September 2024, the European Commission adopted a revision of the EU Monitoring and Reporting Implementing Regulation (MRR). A key CCS-related change is the expanded definition of CO_2 transport and CO_2 transport infrastructure, which now includes CO_2 transport methods beyond CO_2 pipelines. Additionally, the revision allows CO_2 transport operators to exclude CO_2 still in transit on 31 December from their emissions report, provided it is transferred to a storage site or another EU ETS installation by 31 January of the following year. These updated rules took effect on 1 January 2025, with CO_2 transport operators now responsible for both operational and fugitive emissions.

Legal and regulatory assessment

Table 14 provides a structured assessment of how effectively the current EU policy, legal and regulatory framework summarised in Section CCS-related policy landscape supports the deployment of CCS. This overview is structured around the four main phases of a CO_2 storage project – pre-injection, operation, closure, and post-closure. For each regulatory consideration, the table indicates the level of suitability of the existing framework, using the following key:

- Comprehensive enough to support CCS
- Could support CCS, but needs more development
- Needs extensive development to support CCS

The assessment is grounded in reference to the relevant EU directives or national legislation.

Table 14. Assessment of the key regulatory considerations for each stage of a CCS project in the EU

- Comprehensive enough to support CCS
- Could support CCS, but needs more development
- Needs extensive development to support CCS

Regulatory consideration	Assessment	Reference
Pre-injection		
Classification and purity of CO_2 streams		EU CCS Directive
Ownership of the pore space		National legislation
Competition with other users and preferential rights		EU CCS Directive
Ownership of title of CO_2		Revised EU ETS Directive
Authorisation to conduct assessment		EU CCS Directive
Environmental Impact Assessment		EU CCS Directive and EIA Directive
Engaging the public in decision-making		EU EIA Directive
Site characterisation requirements		EU CCS Directive
Construction and development requirements		National legislation
Operation		
CO_2 capture		EU CCS Directive
CO_2 transport		EU CCS Directive
Authorisation of storage activities		EU CCS Directive
Development of plans		EU CCS Directive
MMV		EU CCS Directive
Corrective measures and remediation		EU CCS Directive
Liability during the project period		EU CCS Directive and revised EU ETS Directive
Third-party access to CO_2 infrastructure		EU CCS Directive
Closure		
Authorisation for site closure		EU CCS Directive
Well plugging and decommissioning		EU CCS Directive
Post-closure		
Post-closure site care and monitoring		EU CCS Directive
Transfer of liability and stewardship		EU CCS Directive
Financial security		EU CCS Directive

THE UNITED KINGDOM

As one of the CCS frontrunners in Europe, the UK has also implemented a mix of policy, legal and regulatory mechanisms to support its development.

CCS-related policy landscape

Direct policy requirements and financial incentives

Energy Act 2008

The UK introduced the Energy Act 2008, which established a licensing regime for offshore CO_2 storage, ahead of the EU CCS Directive. To comply with the EU CCS Directive's national transposition requirements, the UK enacted several additional regulations in the following years:

- Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
- Storage of Carbon Dioxide (Termination of Licences) Regulations 2011
- Storage of Carbon Dioxide (Amendment of the Energy Act 2008 etc.) Regulations 2011

Similar to the EU, the UK's transposition of the EU CCS Directive also required significant amendments to existing legislation, including the Offshore Petroleum and Pipelines (Assessment of Environment Effects) Regulations 1999 and the Offshore Combustion Installations (Prevention and Control of Pollution) Regulations 2001.

UK Emissions Trading Scheme

The UK government launched the UK ETS in January 2021, following the UK's exit of the EU ETS. Due to their common origins, the UK ETS and the EU ETS share many design features.

The UK ETS covers energy-intensive industries, power and heat generation, and aviation. In recent years, the UK ETS Authority has conducted several public consultations to include additional sectors in the scheme, such as greenhouse gas removals (GGRs) from maritime emissions (UK Government et al., 2024).

Similar to the EU ETS, under the UK ETS, each participant must surrender one allowance for every tonne of CO_2 equivalent emitted. However, it can avoid this obligation if it successfully captures, transports, and stores CO_2 at a site authorised under the Energy Act 2008, thus providing an economic incentive for CCS deployment. Additionally, participants in the UK ETS, including operators of CCS facilities, must hold a GHG emissions permit or emissions monitoring plan before commencing operations.

As part of the EU-UK Trade and Cooperation Agreement, both the UK and the EU have pledged to give serious consideration to linking their carbon pricing schemes. A linked market would enhance cost efficiency, price stability and liquidity. However, as of August 2025, the UK ETS remains independent, with no formal linkage to the EU ETS.

Supportive policies and programmes

UK vision for a competitive CCUS market

In December 2023, the UK government outlined a strategic vision for developing a competitive CCUS market by 2035 (UK Department for Energy Security & Net Zero, 2023). This vision aligns with the UK's broader objective to become net zero by 2050, with CCUS playing a crucial role in decarbonising the economy and enabling negative emissions.

The UK's CCUS approach is structured around three different stages:

- Market creation, thus deploying CCUS infrastructure to capture 20-30 Mtpa of CO_2 by 2030.
- Market transition, i.e. establishing a competitive CCUS market.
- A self-sustaining CCUS market and reaching net zero by 2050.

Legal and regulatory governance structures

The Energy Act 2023 introduces a licensing framework for CO_2 transport infrastructure, including pipelines and associated systems. Under this regime, licensed operators are permitted to charge third parties for access. Licences will be granted through a competitive process managed by Ofgem, ensuring transparency, fairness, and efficiency. The Act also places a duty on CO_2 transport service providers to keep Ofgem regularly informed, strengthening regulatory oversight.

The UK's approach to long-term CO_2 storage liability is governed by a comprehensive legal and regulatory framework established under the Energy Act 2008 and supporting instruments, such as the Storage of Carbon Dioxide (Licensing etc.) Regulations 2010. This framework closely aligns with the EU CCS Directive, but is tailored to the UK through detailed guidance issued by the North Sea Transition Authority (NSTA).

As the UK's offshore CO_2 storage regulator, the NSTA has published several key guidance documents to support permit and licence applicants:

- Guidance on the Application for a Carbon Dioxide Appraisal and Storage Licence (April 2022): Offers exploration operators clear instructions on application requirements and the NSTA's evaluation criteria.
- Guidance on Applications for a Carbon Storage Permit (November 2023): Provides comprehensive support for companies applying for a storage permit under an existing Appraisal and Storage Licence. It details eligibility criteria, the application process, and regulatory expectations.
- Guidance on the Content of an Offshore Carbon Storage Permit Application (March 2024): Specifies the documentation, technical assessments, and standards required for a complete and compliant permit application.

In the UK, all subsurface ownership rights are expressly vested in the Crown. Operators must therefore obtain a lease from the Crown Estate (or the Crown Estate Scotland for Scottish waters), which grants rights to use the pore space in addition to applying for a storage licence from the NSTA.

Legal and regulatory assessment

Table 15 provides a structured assessment of how effectively the current EU policy, legal and regulatory framework summarised in Section CCS-related policy landscape supports the deployment of CCS. This overview is structured around the four main phases of a CO_2 storage project – pre-injection, operation, closure, and post-closure. For each regulatory consideration, the table indicates the level of suitability of the existing framework, using the following key:

- Comprehensive enough to support CCS
- Could support CCS, but needs more development
- Needs extensive development to support CCS

Table 15. Assessment of the key regulatory considerations for each stage of a CCS project in the UK

- Comprehensive enough to support CCS
- Could support CCS, but needs more development
- Needs extensive development to support CCS

Regulatory consideration	Assessment	Reference
Pre-injection		
Classification and purity of CO_2 streams	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Ownership of the pore space	●	Crown Estate
Competition with other users and preferential rights users	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Ownership of title of CO_2	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Authorisation to conduct assessment	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Environmental Impact Assessment	●	Infrastructure Planning (Environmental Impact Assessment) Regulations 2017
Engaging the public in decision-making	●	Infrastructure Planning (Environmental Impact Assessment) Regulations 2017
Site characterisation requirements	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Construction and development requirements	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Operation		
CO_2 capture	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
CO_2 transport	●	The Energy Act 2023
Authorisation of storage activities	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Development of plans	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
MMV	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010

Regulatory consideration	Assessment	Reference
Corrective measures and remediation	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Liability during the project period	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Third-party access to CO_2 infrastructure	●	The Energy Act 2023
Closure		
Authorisation for site closure	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Well plugging and decommissioning	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Post-closure		
Post-closure site care and monitoring	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Transfer of liability and stewardship	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010
Financial security	●	Storage of Carbon Dioxide (Licensing etc.) Regulations 2010

1.2 Opportunities for development of a CCS legal and regulatory regime for India

India currently lacks a dedicated legal and regulatory regime governing CCS. To establish such a framework, the Indian government could consider two main approaches based on approaches from other jurisdictions:

1. Developing a new standalone CCS legal and regulatory framework.
2. Adapting existing legislation and regulatory frameworks.

Each approach presents distinct merits and challenges, which are analysed in Sections 5 and 6. The chosen framework should best align with India's broader policy, legal and regulatory landscape.

5. Standalone CCS legal and regulatory framework

Dedicated CCS legislation offers the advantage of providing a unified regulatory framework, enhancing clarity for investors, project developers, and regulators. It would consolidate all relevant aspects of CO_2 storage – such as site selection, storage liability, monitoring, reporting and verification requirements, environmental standards, etc. – into a single legal structure, thus streamlining regulatory compliance.

However, developing new legislation can be time-consuming and resource-intensive compared to amending existing laws. The process of developing new laws often entails extensive stakeholder consultation, legal drafting, and the establishment of new regulatory bodies or mechanisms.

6. Adaptation of existing legislation and regulatory frameworks

A potentially pragmatic approach to facilitating the adoption of CCS in India could involve adapting existing legal and regulatory frameworks to accommodate CCS-related activities. Given the operational parallels between CCS, particularly CO_2 transport and storage, and oil and natural gas operations, integrating CCS into current legal structures may provide a practical regulatory avenue. However, CCS projects might also be associated with industrial facilities or large-scale infrastructure projects that may be more challenging to accommodate in an adaptation of existing Oilfields or Petroleum legislation. A less complicated and fragmented approach would be to develop a stand-alone CCS legal and regulatory framework for all CCS projects. Another consideration in selecting the most suitable approach to establishing CCS legislative provisions is the effectiveness of the legislative approvals process in India, i.e., this process will determine if the development of a new legal framework will be more or less time-consuming than adopting amendments to existing legislation.

Norway's experience, summarised in Table 16, provides a valuable real-life example of the adaptation of existing legislation to accommodate CCS provisions.

Table 16. Norway's experience with regulatory adjustments

Norway's evolving regulatory framework for CCS

Norway provides a compelling case study in how CCS can be successfully integrated into existing legal frameworks. The Sleipner project, located in the North Sea, became the world's first commercial CCS facility when it began operations in 1996. Operated by Equinor (former Statoil), it currently stores approximately 1 Mtpa in a deep saline formation.

At the time of launch, Norway had no dedicated legal framework for CCS. Instead, the regulatory approvals for the CO_2 storage part of the Sleipner project were obtained using existing laws – primarily the Petroleum Act, which enabled CO_2 injection as part of a broader petroleum operation. This was supported by a lifecycle-based regulatory approach and bolstered by the Norwegian CO_2 tax on offshore oil and gas operations, which created strong financial incentives for storage over emission.

It was not until 2012 that Norway adopted CCS-specific legislation, following the incorporation of the EU CCS Directive into the EEA agreement. This led to the formal granting of a CO_2 storage permit, based on the requirements of the EU CCS Directive, for Sleipner in 2016, two decades after the project commenced.

7. Legislation suitable for adaptation

CCS could interact with various legal and regulatory frameworks, including:

- Oil and natural gas legislation governing the exploration, production, and transportation of oil and gas resources, which may be particularly relevant to CCS projects involving CO_2 storage in depleted oil and gas fields or enhanced oil and gas recovery.
- Mineral legislation that covers the exploration, production and export of mineral resources, with subsurface activities that might interfere with CCS operations.
- Environmental legislation that governs the protection of the environment, including waste management, pollution prevention, environmental impact assessments, and groundwater protection.
- Land laws that regulate land use and property rights, including provisions related to the ownership of the fixed facilities, surface infrastructure, and sub-surface pore space.
- Health and safety legislation that establishes requirements for ensuring worker safety and risk mitigation measures associated with potential hazards in industrial facilities.
- Pipeline legislation that covers pipeline authorisation and construction processes, third-party access, or the transboundary movement of CO_2.

8. Regulatory pathways in India that may be successfully adapted to regulate CCS

The CCS value chain comprises three distinct sub-sectors – capture on surface, transportation, and storage subsurface. The technological expertise needed to facilitate the development of each sub-sectoral component of a CCS solution is unique and is typically held by different private and public sector entities.

However, developing an overall CCS project requires that the individual development in each sub-sector is harmonised with the whole. Thus, a suite of supporting policies is required. The following summarises and provides an overview of key regulatory elements would need to address to ensure that a functioning transport and storage network is built to support CO_2 capture. These policies should ideally be part of an overarching policy framework that also integrates monetary incentives and the development of hubs and clusters.

To establish rules to regulate safety in the offshore oil and gas industry, India's Ministry of Petroleum and Natural Gas set up the Oil Industry Safety Directorate (OISD) in 1986 (OISD et al., 2025a). It is a technical directorate that has the authority to self-regulate the Ministry. Activities under its jurisdiction include Exploration and Production (E&P), Process and Engineering, Pipelines, and Marketing. At least two of these broad areas of activity have overlaps with CCS – E&P and Pipelines.

OISD is designated as a competent authority to develop standards for the offshore oil and gas industry. It has been granted the authority to set them by India's central government so that the Ministry may exercise its duties conferred in Section 8 of the Oilfields (Regulation and Development) Act of 1948 (Ministry of Petroleum and Natural Gas Notification, 2008). In many regions of the world, this segment of the oil and gas industry is the most technically challenging due to the water depth, higher subsurface temperatures and pressures and the associated logistical, operational, and safety-related challenges of operating in an offshore environment. OISD develops and revises the standards.

Several OISD standards are referenced here due to their compatibility with CCS-related operations. These standards can be adapted to formally include CCS where possible, i.e., the capture, transport, and storage of CO_2. However, current versions of these standards require purchase from the OISD; they were unavailable when the comparative study was undertaken. The analysis hereunder includes dated versions (dates included where possible) of associated standards that were available (online) without purchase. A full listing of all current OISD standards is on the OISD website (OISD et al., 2025b).

Drawing on international practise, a CCS regulatory pathway in India could consider the following elements:

Governance

An overall CCS project/site management governance framework could be established to oversee the entire process. This framework would help ensure compliance with regulatory authorities and would help address issues as they emerge. Regulatory authorities would be responsible for overseeing and enforcing these policies.

Environmental Impact

Rules and regulations would need to be developed to address the potential environmental impact of CO_2 capture, transport, and storage. The impacts of CO_2 leaks on air, water, land, and the overall ecosystem would need to integrate local considerations into the project's overall impact. Project-specific mitigation measures and monitoring requirements would need to be developed.

- Adopt provisions in the Environment (Protection) Act of 1986 to include CCS-related activities as part of the Environmental Impact Assessment (Gazette of India & Ministry of Environment, 2020).

Public consultation

Specific regulations need to be developed if jurisdictions require public consultation, disclosure of information, or the input of the public related to CO_2

capture, transport, and storage projects. These would need to be tailored to address community issues while providing transparency.

- Adopt provisions in the Environment (Protection) Act of 1986 to include CCS-related activities to obtain Environmental Clearance (Gazette of India & Ministry of Environment, 2020). Public consultation is one of the stages included in the process.

Permitting

There is usually a permitting process that entities must follow to establish a CO_2 storage facility. This process may involve environmental impact assessments, risk assessments, and public consultations. Authorities may set criteria for selecting suitable storage sites, considering geological, hydrological, and environmental factors. Entities involved in the transportation of CO_2 would typically need permits or licences from relevant regulatory authorities. The permitting process may involve demonstrating adherence to safety standards, emergency response plans, and environmental considerations.

- OISD-STD-105 (Work Permit System) is adaptable and can be used for CCS-related activities. Formally including CCS would help to expand the scope of the standard. The 2004 version was reviewed.

Subsurface access

Policies and regulations need to be developed to address the conditions under which different private (and/or public) sector entities can access CO_2 storage facilities. This could involve access for industrial emitters seeking to store their captured CO_2.

- Adapt OISD-STD-181 (Geophysical Operations) to formally include surveying and seismic recording for horizons that would serve as storage reservoirs for CO_2. Chapters 5 and 9 concern surveying and seismic operations, respectively. The 2010 version was reviewed.

Operations

Regulations would need to be developed to define the operational requirements for CO_2 storage facilities. This would include injection and monitoring protocols to ensure the safe and secure containment of CO_2. Compliance with technical standards and best practices for storage site operation is often mandated.

- Adapt OISD-STD-174 (Well Control) to formally include injection operations for CO_2, especially chapters 4.0 and 4.1, which deal with well control and well planning. Chapters 7.1, 7.2, 7.3, 7.4, and 7.5, which deal with identifying influxes or identifying scenarios where the wellbore is pressure-underbalanced (due to exceeding the fracture gradient because of injection operations), are also relevant. The 2023 draft version was reviewed.

- Adapt OISD-STD-175 (Cementing Operations) to formally include cementing wells where the cement and casing will be exposed to injected CO_2, especially chapters 5 (primary cementing) and 6 (well abandonment). The 1999 version was reviewed.

- Adapt OISD-RP-238 (Well Integrity) to formally include CO_2 injection operations and well barrier management for CO_2 injection and possible CO_2 migration, especially chapters 5 through 9. The April 2016 version was reviewed.

- Adapt OISD-RP-242 (Drilling and Testing of HPHT Wells) for CO_2 injection wells. This recommended practice (RP) deals with drilling operations for high-pressure high-temperature (HPHT) wells. The recommended practice is descriptive and provides templates for developing drilling operational procedures, especially those that concern maintaining constant bottomhole pressure (important to avoid influxes and pressure underbalanced scenarios). This RP can be adapted to formally include operations where CO_2 is injected. The version reviewed did not include a date and was also incomplete, since only pages 26 through 30 were available.

- Adapt OISD-STD-141 (Cross-country liquid hydrocarbon pipeline) to include transportation of CO_2 by pipeline. The standard is comprehensive and covers all the topical areas that would be important to the design, running, and maintenance

of CO_2 pipelines – construction, safety, testing, commissioning, operation, and maintenance, to name a few. The 2003 version was reviewed.

Monitoring and reporting

Regular monitoring of storage sites is typically required to track the migration of the injected CO_2 plume in subsurface formations. The subsurface behaviour of injected CO_2 can help with detecting potential issues such as loss of subsurface and/or wellbore containment. Monitoring requirements may include periodic reporting to regulatory authorities to demonstrate compliance with safety and environmental standards.

Regular monitoring of CO_2 transport systems (typically pipelines) is often mandated to ensure the integrity of the infrastructure. Participating entities may be required to report any incidents, leaks, or safety breaches to regulatory authorities.

- Adapt OISD-GDN-239 (Guidelines on Annular Casing Pressure Management for Onshore Wells) to formally include wells where CO_2 was injected for subsurface storage. The standard is detailed, and chapters 6 through 15 are especially relevant for testing, monitoring, verification, record keeping, and reporting. The March 2016 version was reviewed.

- Adapt OISD-STD-188 (Corrosion Monitoring and Control of Offshore and Onshore Pipelines) to include CO_2. This is a comprehensive standard and covers all topical areas of relevance to corrosion monitoring. The 2000 version was reviewed.

- Adapt OISD-GDN-233 (Guidelines on inspection of non-piggable pipelines). This standard was unavailable, however a similarly numbered and titled OISD-STD-233 (Non-Piggable Onshore Hydrocarbon Pipeline) was reviewed. It is a comprehensive standard that can be adapted to include CO_2 as transported fluid. The draft 2025 version was reviewed.

Emergency response planning

Emergency response is an essential component of project management. Regulations that identify specific emergency response plans need to be developed for all sub-sectors of the CCS value chain. These response plans should address potential leaks, spills, or other incidents during CO_2 capture, transport, and storage.

- Adapt OISD-GDN-227 (Emergency Response Preparedness in the E&P Industry) to include CO_2 capture, transportation, and storage. The 2007 version was reviewed.

Closure

Rules and regulations that would help with the development of procedures for the closure of CO_2 storage sites need to be developed. This includes requirements for site abandonment, monitoring the site post-closure, and assessing potential liabilities. Financial assurance mechanisms may be required, or may need to be in place before the site is closed to cover the costs of site closure and potential post-closure monitoring.

- Adapt OISD-STD-175 (Cementing Operations) to formally include cementing wells where the cement and casing will be exposed to injected CO_2. Chapter 6 on well abandonment is especially relevant and can be expanded to include site closure requirements for CO_2 storage wells. The 1999 version was reviewed.

Liability and Insurance

Regulatory policies that clearly define liability and insurance requirements for damages associated with the CO_2 storage activities will help with project risk identification and risk management.

- While not perfectly aligned, several articles in the Petroleum and Natural Gas (Amendment) Rules, 2003, and Petroleum and Natural Gas Regulatory Board Act, 2006, can be amended or adapted to include liability-related issues that pertain to CCS. For additional details, refer to sub-sections Petroleum and Natural Gas (Amendment) Rules, 2003 and Petroleum and Natural Gas Regulatory Board Act, 2006.

1.3 Geological storage policy and regulation – focus on pore space development

9. Role of policy in exploration and development of CCS storage space

Policy plays a pivotal role in enabling the deployment of CO_2 storage by shaping the overall market conditions, de-risking early investments, and ensuring that development is carried out in a technically robust manner. Beyond direct financial support, policy can accelerate progress through multiple levers: incentivising early movers, promoting data sharing, mapping and assessing storage resources, providing clear regulatory frameworks, building institutional capacity, and managing long-term liability and stewardship. Together, these policy interventions help create the conditions for a viable and investable CO_2 storage sector.

One important area of policy support is providing capital investment for early-mover deployment. Because CCS storage development involves high upfront costs and uncertain returns, potential developers often adopt a "wait and see" approach – delaying investment in anticipation of learning from others' successes or failures. This dynamic can stall progress across the sector. Targeted public investment, guarantees or other financial mechanisms can help overcome this inertia by de-risking early projects and catalysing initial development.

In parallel, policy must also focus on incentivising the sharing of data and knowledge generated by these early projects. Without a clear framework for transparency, developers may be reluctant to share information that could benefit competitors, limiting the learning that others can draw from these first deployments. Policy can address this by requiring or encouraging the publication of key non-commercial data, such as geological surveys, reservoir characterisation, monitoring data, and performance results. For example, the EU's Net Zero Industry Act mandates public disclosure of CO_2 storage site data, helping to ensure that early investment leads to broad-based sectoral learning. Facilitating open access to this information accelerates the learning curve, avoids duplication, and lowers costs for subsequent projects (European Union, 2024).

Governments can also play a key role in mapping and characterising national CO_2 storage potential. Publicly supported geological assessments and the development of a national CO_2 storage atlas can help identify and prioritise promising storage basins. Making this information publicly accessible reduces early-stage exploration risk, supports coordinated infrastructure development, and enables better emitter-storage matching across regions.

Clear regulatory guidance is another essential component in supporting the safe and effective development of CO_2 storage. Developers require certainty across the entire project lifecycle, from permitting and site selection to well construction, monitoring, closure, and long-term stewardship. A robust regulatory framework, tailored to the local context, ensures that only geologically suitable sites are developed, while also streamlining approval processes and supporting investor confidence. Crucially, this framework should also address post-injection monitoring, liability transfer, and site closure. Uncertainty over long-term responsibility for a storage site can be a major barrier to private investment. Establishing clear rules – and potentially a publicly managed assurance fund – can help manage long-term risks, protect the public interest, and provide confidence that CO_2 will remain safely stored.

Capacity-building efforts are also essential to support the complex and technically demanding process of CO_2 storage deployment. Developing storage sites requires significant research, site-specific assessment, and long-term planning – including geological characterisation, modelling of subsurface behaviour, permitting, and risk management. This demands technical expertise, as well as strong regulatory and institutional capacity. Policy initiatives that can support this process – such as the creation of dedicated centres of excellence, targeted training and certification programs, and funding for applied research – can help accelerate the development of domestic expertise. Strengthening institutional capabilities at both national and subnational levels ensures effective oversight, fosters technical consistency, and builds long-term resilience within the storage sector.

To further mitigate the "chicken-and-egg" dynamic in the CCS value chain – which can discourage private sector investment in storage – policy can support the creation of vertically integrated business models. State-owned enterprises, particularly those with experience in subsurface operations and infrastructure, can act as anchor developers for early-stage projects. These entities can help de-risk investments, support infrastructure development, and facilitate knowledge transfer to the wider market.

10. Development of storage capacity in other jurisdictions

UNITED STATES

Policy

45Q Tax Credit

The 45Q tax credit is a provision under the US Internal Revenue Code that offers a federal tax incentive for the capture and either storage or utilisation of CO_2. Eligible activities include geological sequestration, enhanced oil recovery, and the permanent incorporation of CO_2 into commercial products. This tax credit is a key policy tool for supporting CCUS technologies in the US.

Significant enhancements to the 45Q tax credit were introduced through the Inflation Reduction Act (IRA), enacted in August 2022. These changes substantially increased the value of the credit and expanded eligibility for a wider range of projects and entities. See Section Legal and regulatory assessment for further details.

The IRA also introduced greater flexibility through credit transferability, allowing entities that receive the 45Q credit to transfer all or part of it to another tax-paying entity in exchange for a tax-free cash payment. Additionally, eligible entities can now opt to receive the credit as a direct payment from the government. For-profit entities can receive direct payments for a period of five years after the project begins operation, while tax-exempt entities, such as non-profits or cooperatives, can receive payments for up to 12 years (Congressional Research Service, 2023).

On 1 July 2025, the US Senate passed its version of the One Big Beautiful Bill Act (OBBBA), which includes key changes to the federal Section 45Q tax credit for carbon capture. The bill maintains the credit and introduces several provisions aimed at improving its effectiveness. These include restoring transferability for the life of the credit, aligning credit levels between carbon utilisation and geologic storage projects, and avoiding proposed delays in adjusting the credit for inflation (Carbon Capture Coalition, 2025b). Also see Section Legal and regulatory assessment for additional information on the OBBBA.

Infrastructure Investment and Jobs Act

Under the Infrastructure Investment and Jobs Act (IIJA), the US Department of Energy (DOE) announced a series of major funding initiatives aimed at building national carbon storage capacity and advancing the CCS value chain.

One of the key initiatives is the allocation of up

to US$1.8 billion to support the development of commercial-scale DAC facilities across the country. This funding will contribute to the creation of four Regional DAC Hubs, supporting both mid- and large-scale projects. These hubs are intended to become central elements of the broader CCUS infrastructure, enhancing opportunities for integrating DAC with storage and transportation systems (Carbon Herald, 2024a).

To empower local and regional governments in overseeing carbon storage activities, Section 40305 of the IIJA establishes a dedicated funding mechanism for state and tribal regulation of geologic carbon sequestration. This provision provides targeted grants to help states and tribes develop or expand their Class VI underground injection well permitting programs. These programs are essential for regulating CO_2 injection and storage projects. Beyond permitting, Section 40305 also funds long-term monitoring, compliance, and enforcement efforts. In October 2024, the DOE announced more than US$517 million to support 23 projects across 19 states, focused on developing and validating commercial-scale carbon storage infrastructure (DOE, 2024a).

The IIJA also created and funded two major programs to advance CO_2 transport and storage infrastructure. The CIFIA program, backed by US$2.1 billion, will primarily offer loans and loan guarantees to support the construction of CO_2 pipelines, which are critical for connecting capture sites to storage locations.

Additionally, the DOE has been allocated US$2.5 billion (for fiscal years 2022-2026) to develop large-scale commercial carbon sequestration projects and the necessary supporting transport infrastructure. These projects will prioritise the development of storage sites capable of receiving CO_2 from multiple capture facilities, ensuring long-term, reliable storage capacity. The initiative is a cornerstone of the DOE's strategy to support both CO_2 mitigation and CDR, reinforcing the importance of commercial CO_2 storage in meeting national climate goals (DOE, 2021).

In May 2025, the Trump Administration proposed cutting billions of dollars in federal funding for carbon capture initiatives included in the bipartisan infrastructure law. The exact scale of the proposed cuts remains unclear, as does their impact on the previously outlined funding allocations (Reuters, 2025).

Office of Clean Energy Demonstrations

The US DOE's US$1.3 billion in funding for CCUS is structured around three core areas, each targeting a different stage of project development and deployment.

The first area, Carbon Capture Demonstration Projects, allocates up to US$750 million for commercial-scale projects. This funding will support carbon capture systems integrated with CO_2 transportation and storage infrastructure at one coal-fired power plant and up to two industrial facilities. These projects aim to advance technical maturity, reduce uncertainty in both cost and performance, and demonstrate replicable solutions that can be deployed at additional sites.

The second area, Large-Scale Pilot Projects, provides up to US$450 million for pilot-scale demonstrations of transformative carbon capture technologies. These projects are intended to test next-generation capture innovations that offer significantly higher efficiency, lower costs, and better environmental performance. The focus is on proving out technologies that are not yet commercially mature but have strong potential to reshape the CCUS landscape.

The third area, Infrastructure Planning and Design, sets aside up to US$100 million to support the early-stage planning and design of shared CO_2 transport and storage networks. This funding is designed to facilitate collaboration between multiple capture projects located in close proximity, helping to lower infrastructure costs and make CCUS more accessible to a broader range of emitters. This effort is being conducted in collaboration with the Office of Fossil Energy and Carbon Management, ensuring a coordinated approach to developing the necessary infrastructure for widespread carbon capture deployment (DOE, 2024b).

In May 2025, it was announced that 24 CCS project awards, totalling £3.7 billion in DOE funding, would

be cancelled. However, as 70% of these awards were only signed in January 2025, and the December 2024 funding round was still at the application stage, it is unlikely that the cancelled projects relate to that round, though this has not been definitively confirmed (Power, 2025).

Carbon Storage Assurance Facility Enterprise (CarbonSAFE)

The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) is a flagship initiative of the DOE's Office of Fossil Energy and Carbon Management (FECM), administered by the National Energy Technology Laboratory (NETL). This program plays a pivotal role in advancing the development of large-scale, commercial CO_2 storage facilities across the US.

The primary aim of CarbonSAFE is to ensure that safe, secure, and permanent storage sites are available for CO_2 captured from industrial sources and power plants. To achieve its objectives, the CarbonSAFE program is structured into a series of distinct phases, each designed to advance a storage site from early-stage analysis to full-scale operation:

- **Phase I: Integrated Pre-Feasibility** focuses on identifying potential CO_2 storage sites and evaluating their initial technical and economic feasibility.
- **Phase II: Storage Complex Feasibility** involves more in-depth geological assessments, risk analysis, and engagement with local stakeholders to determine whether the site is suitable for long-term storage.
- **Phase III: Site Characterisation and Permitting** covers the completion of regulatory and permitting requirements, final design of CO_2 injection wells, and preparation for infrastructure development.
- **Phase IV: Construction and Operations** marks the final stage, where infrastructure is built and CO_2 injection and monitoring activities commence (DOE, 2020).

Regional Carbon Sequestration Partnerships

The Regional Carbon Sequestration Partnerships (RCSPs) are initiatives managed by the NETL. These partnerships operate under the DOE's Carbon Storage Program, which falls within the FECM.

Initially, there were seven RCSPs established across various regions in the US and Canada, each focusing on the development and demonstration of carbon storage technologies. These included:

- Midwest Regional Carbon Sequestration Partnership (MRCSP)
- Midwest Geological Sequestration Consortium (MGSC)
- Plains CO_2 Reduction Partnership (PCOR)
- Southeast Regional Carbon Sequestration Partnership (SECARB)
- Southwest Regional Partnership on Carbon Sequestration (SWP)
- West Coast Regional Carbon Sequestration Partnership (WESTCARB)
- Big Sky Carbon Sequestration Partnership (BSCSP)

With the successful completion of their objectives, the RCSPs laid the foundation for the DOE's current CarbonSAFE program. Additionally, the DOE builds on the experience and networks developed through the RCSPs via four ongoing Regional Initiatives (National Energy Technology Laboratory, 2024).

Regulatory mechanism

Underground Injection Control Program

In the US, underground sources of drinking water (USDWs) are required to be protected from underground injection. Known as Underground Injection Control (UIC), these activities are regulated by the US Environmental Protection Agency (EPA) (EPA, 2022a). Underground injection ranging from industrial and municipal waste, oil and gas-related injection,

solution mining, shallow hazardous and radioactive waste, non-hazardous fluids, and CO_2 is done through wells of different class permits.

CO_2 is injected in Class VI wells. The EPA defines CO_2 injection as long-term underground storage or geological sequestration. The regulations are extensive and cover site selection, well construction, operations, pre-injection testing, ongoing monitoring, and site closure. Specific requirements include detailed site characterisation to assess geologic suitability, strict well construction standards using multiple casing and cement layers to protect USDWs, and mechanical integrity testing before and during injection. Operators must also submit emergency and remedial response plans, conduct continuous monitoring of injection pressure and plume movement, and monitor groundwater quality throughout the process. After injection ends, a post-injection site care (PISC) period – typically at least 50 years – is required to ensure long-term containment of CO_2 (EPA, 2025).

Additionally, the regulatory process includes a public engagement component: permit applications are subject to public comment and, if warranted, public hearings to ensure transparency and community involvement. The EPA can grant primary enforcement authority, also known as primacy, to states that apply and meet the EPA's Class VI requirements. To date, four states have Class VI primacy: North Dakota, Wyoming, Louisiana and West Virginia. Arizona and Texas are in the process of applying (Carbon Capture Coalition, 2025a). Class II wells are specifically designated for the injection of fluids associated with oil and gas production, including EOR. The regulations still protect USDW, but the monitoring, site characterisation, and post-injection care are less onerous than Class VI wells.

As of 1 August 2025, 63 projects with 232 Class VI applications were under review, reflecting increased national interest in CCS as a climate mitigation strategy. Federal initiatives such as the IIJA have also encouraged this growth, prompting efforts to streamline the permitting process while maintaining rigorous environmental safeguards (EPA, 2025).

In the US, property rights are traditionally divided into two distinct estates: the surface estate and the mineral estate. The mineral estate grants ownership of underground minerals, but does not include ownership of the surrounding geological formations. As a result, the owner of the surface estate retains ownership of the geological formations and pore space beneath the land's surface.

Licensing model

In the US, the licensing model for CO_2 storage under the UIC Program – specifically for Class VI wells – follows a centralised yet flexible regulatory framework led by the EPA. The licensing process is permit-based and involves multiple stages, each designed to ensure environmental protection, public transparency, and long-term liability management.

The key components of the licensing model are:

- **Permit Application and Review:** Operators must submit a detailed permit application for each Class VI well. This includes comprehensive geologic and hydrologic data, site characterisation reports, proposed well design, and risk assessments. The EPA (or the state agency with primacy) evaluates the application based on criteria such as geologic suitability, potential for CO_2 migration, and proximity to USDWs.

- **Phased Authorisation:** Permits can be phased. For instance, operators may first be authorised to drill and test a well (construction phase) before receiving full approval to inject CO_2, depending on compliance with initial permit conditions and demonstration of mechanical integrity.

- **Public Involvement:** The permitting process requires public notification, comment periods, and sometimes hearings. This ensures community concerns are addressed early in the project development.

- **Long-Term Liability and Post-Closure Monitoring:** One of the unique features of the US licensing model is the requirement for post-injection site care (PISC) and site closure plans, typically lasting

at least 50 years after injection ends. Operators remain responsible for monitoring and corrective actions during this period, unless responsibility is transferred to a government entity, which is rare and currently lacks a uniform federal framework.

- **Financial Responsibility:** Operators must demonstrate financial resources to cover all stages of the project, including corrective action, emergency response, post-injection monitoring, and site closure. This is a critical component to ensure long-term environmental protection and reduce public financial risk (EPA, 2025).

Applicability to India

India's current progress on CCS remains limited, with most efforts concentrated on small-scale demonstration projects supported by the Department of Science and Technology. These projects have focused on developing elements of the CCUS value chain. Broader deployment at scale will require significantly more robust and coordinated investment, particularly in large-scale demonstration and commercial deployment projects.

One of the key takeaways from the US experience is the importance of comprehensive financial and policy support mechanisms – most notably the 45Q tax credit and large-scale public funding through the Inflation Reduction Act and Infrastructure Investment and Jobs Act. India could consider a similar approach by introducing targeted fiscal incentives or subsidies for CCS deployment, including direct funding support and production-linked incentives, to derisk private investment in the sector.

Mapping emitter sources to potential storage sites is another area where India can benefit from strategic planning. India should prioritise developing a national CO_2 storage atlas, similar to efforts in the US, to identify and characterise viable storage basins. This would support the clustering of emitters and facilitate the development of CCS hubs – particularly in regions with significant industrial CO_2 emissions and existing oil and gas infrastructure. According to the Global CCS Institute, India has at least five oil fields and 12 gas fields with over 20 million tonnes of CO_2 storage potential. However, more geological assessments and transparent sharing of subsurface data are essential to inform reliable site selection and encourage investor confidence (Global CCS Institute, 2024d).

India's established hydrocarbon sector provides a strong foundation for early CCS deployment, particularly through EOR opportunities. Leveraging existing infrastructure and institutional expertise can help reduce early development costs. At the same time, it is important to ensure a parallel buildout of supporting infrastructure, particularly CO_2 transport networks. The US has taken major steps in this area through initiatives like CIFIA, and similar large-scale transport infrastructure planning is crucial for India to unlock economies of scale and regional CCS markets.

On the regulatory front, India could look to the US Class VI well model as a reference for developing tailored CO_2 storage regulations. Adapting the Water (Prevention and Control of Pollution) Act or developing a dedicated CCS regulatory framework under the Central Pollution Control Board (CPCB), with State Pollution Control Boards (SPCBs) granted delegated authority, could offer a decentralised but coordinated permitting pathway. This would help balance regulatory oversight with implementation flexibility.

In addition, clear guidelines for post-injection monitoring, liability, and long-term site stewardship will be essential to assure public and private stakeholders of the safety and permanence of CO_2 storage. India may also consider the creation of a public trust or fund to manage long-term monitoring and liability as part of a robust enabling framework.

Finally, building domestic technical and institutional capacity is crucial. The US model benefits from decades of federal research investment through programs like CarbonSAFE and the Regional Carbon Sequestration Partnerships. India could establish similar regional research and demonstration networks, backed by government and industry collaboration, to accelerate the learning curve and create local expertise in site characterisation, permitting, monitoring, and risk management.

AUSTRALIA

Policy

The federal government has designated offshore zones for the storage of GHGs. Companies can seek permits to conduct assessments in areas of interest. Before commencing any exploration activities in Australian Commonwealth waters, these companies must meet a set of regulatory requirements.

The most recent acreage release, which took place in 2023, includes 10 areas located across seven sedimentary basins in Commonwealth waters – the Bonaparte, Browse, Northern Carnarvon, Perth, Otway, Bass, and Gippsland basins (Geoscience Australia, 2023).

In July 2024, offshore acreage for CCS exploration was awarded to Esso and Beach Energy in the Otway and Sorrel basins. The following month, in August 2024, an exploration permit for release area AC/P71 was awarded to INPEX. Additional exploration permits have also been granted to Chevron and Woodside Energy (S&P Global, 2024).

Within the Future Made in Australia framework, the Government committed A$556.1 million over 10 years for its Resourcing Australia's Prosperity program. This program, to be run by Geoscience Australia, will map Australia's resources and geological storage potential, which will be important for future investment. In its 2024/25 budget, the government also committed A$32.6 million over four years for regional cooperation on carbon sequestration to support the establishment of regulatory frameworks and bilateral agreements (Global CCS Institute, 2024a).

Regulatory mechanism

Jurisdiction for regulating CCS in Australia is shared between the two levels of government, based on whether activities will take place in Commonwealth or state territories. To regulate CCS activities in Commonwealth offshore territorial waters, Australia has established the Commonwealth Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPGGSA). The OPGGSA is an example of detailed and comprehensive CCS-specific provisions incorporated into existing petroleum legislation, and one of the world's first models for regulating the technology. For CCS activities taking place offshore beyond three nautical miles of the coast, regulatory competence lies with the Commonwealth, while the states and territories are responsible for activities onshore and within three nautical miles of the coast. The states of Victoria, South Australia, Queensland and Western Australia have also established legislation to govern CCS activities taking place within their jurisdictional territories.

Although regulatory competence is shared, the OPGGSA provides the central pillar of Australia's legal framework for regulating CCS. Where states and territories have established CCS-specific legislation, each of these frameworks largely mirrors the framework set up by the Commonwealth regime. The OPGGSA and the relevant state legal frameworks include a licensing system for conducting CCS activities across the project lifecycle, alongside various CCS-specific regulatory compliance and oversight obligations, allocation of appropriate regulatory authorities, and satisfaction of applicable environmental, safety and health standards for CCS projects.

The Australian government also passed the Environment Protection (Sea Dumping) Amendment (Using New Technologies to Fight Climate Change) Bill 2023, which implements Australia's obligations under the 2009 and 2013 amendments to the London Protocol. As the 2009 amendment to the London Protocol is yet to enter into force internationally, in late October 2024, the Australian government ratified the 2009 amendment and announced that it would provisionally apply the 2009 amendment from 7 November 2024 (Federal Register of Legislation Australia, 2024; IMO, 2024). Consequently, Australia would be able to implement the 2009 amendment to the Protocol domestically and enter into bilateral agreements or arrangements to conduct cross-border CO_2 transport and storage activities as per the Protocol's provisions.

In 2024, Australia also began implementing the offshore CCS Sea Dumping permit, in accordance with the permit established under the Environment Protection (Sea Dumping) Act. The Sea Dumping permit is an additional permit to be obtained from the government when conducting offshore CO_2 injection operations, alongside the relevant permits for injection activities under the Offshore Petroleum and Greenhouse Gas Storage Act (DCCEEW, 2024).

Licensing model

The Department of Climate Change, Energy, the Environment and Water (DCCEEW) is responsible for regulating offshore CCS activities. However, the process of granting statutory titles is administered by the National Offshore Petroleum Titles Administrator (NOPTA), while environmental and safety assessments fall under the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA).

The licensing model is structured around a phased project lifecycle, each with its own statutory titles and regulatory requirements.

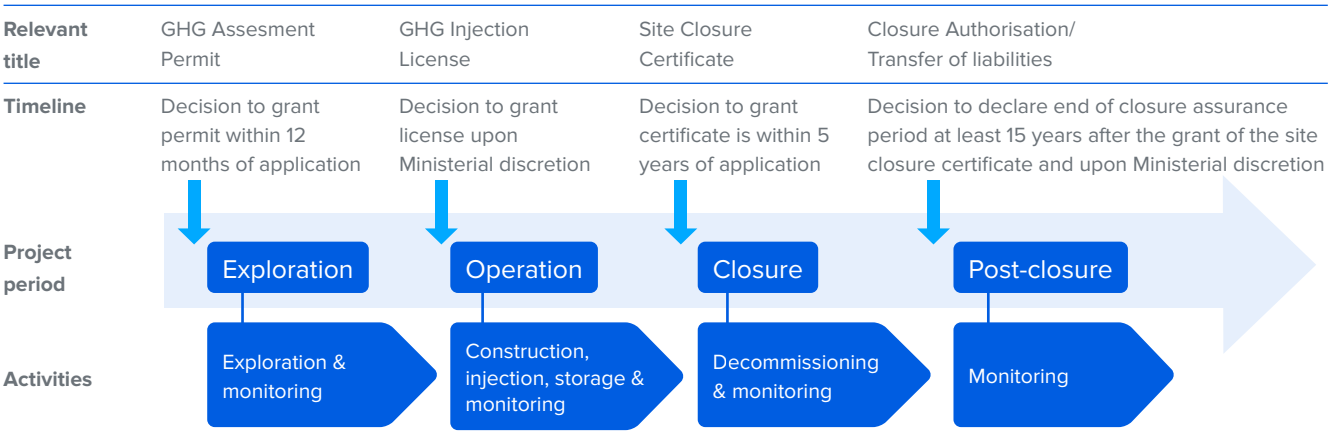


Figure 2. Licensing model for CO_2 storage projects in Australia

The first phase, exploration, begins with the release of potential storage acreage by the Commonwealth. Interested parties may nominate areas, after which geological data is prepared by Geoscience Australia. Operators must then apply for a GHG Assessment Permit, which allows for geological exploration, testing potential storage formations, and conducting appraisal injections. These permits are granted for an initial period of six years, with a possible three-year extension. Any exploration without a permit constitutes an offence under the Act.

Once a suitable geological formation is identified, the permit holder may apply to the Minister for a declaration of an identified GHG storage formation. This declaration confirms that the formation is suitable for permanent CO_2 storage and is a prerequisite for obtaining an injection licence or a holding lease. The declaration is based on criteria such as the storage capacity (minimum of 100,000 tonnes of CO_2), injection methods, sealing mechanisms, and long-term plume migration modelling.

For operators not yet ready to commence injection, a GHG Holding Lease may be granted. This lease preserves the right to develop the site in the future (within 15 years), while allowing continued appraisal activities. It remains valid for five years and can be renewed if the operator demonstrates a credible path toward future injection.

The operational stage of the project requires a GHG Injection Licence, which permits the injection and permanent storage of CO_2 within a declared storage formation. The application must include a detailed site plan, environmental plan (approved by NOPSEMA), and a provisional decommissioning plan. These plans ensure that operators assess injection behaviour, risk,

and long-term site management. An injection licence is granted indefinitely but can be cancelled if no injection activity occurs for five consecutive years.

Following the cessation of injection, the operator must apply for a Site Closure Certificate, which marks the transition to the post-closure phase. This application must include modelling and assessment of CO_2 migration and site behaviour, along with post-closure monitoring recommendations. If the Minister is satisfied, a pre-certificate notice is issued, followed by a final closure certificate once required securities are paid and decommissioning is complete.

The post-closure period is governed by a minimum 15-year closure assurance period, during which the operator remains liable for the site. After this period, the operator may request a declaration of the end of the closure assurance period. If approved, most statutory and common law liabilities for the site transfer to the Commonwealth. However, the Commonwealth's indemnification is limited to specific conditions, and operators may still retain liability in cases outside these provisions.

Throughout the licensing process, the OPGGSA includes mechanisms to manage potential conflicts with petroleum operations. A key tool is the Significant Risk of a Significant Adverse Impact test, which the Minister must apply when considering overlaps with existing or proposed petroleum titles. For pre-2008 petroleum titles, GHG titles may be refused if they pose a significant adverse impact. For newer titles, the Minister balances public interest factors to determine which activity should proceed.

Applicability to India

One of the most notable aspects of the Australian model is the structured licensing framework under the OPGGSA, which clearly delineates project phases – exploration, holding, injection, and closure – each supported by corresponding statutory titles and compliance requirements. India could consider developing a similar multi-tiered licensing model to provide legal clarity and investor confidence throughout the CCS project lifecycle. Importantly, India's framework could start with demonstration projects onshore, but eventually extend to offshore storage, especially given India's extensive Exclusive Economic Zone and deep sedimentary basins with potential for long-term CO_2 storage.

The dual governance model in Australia – where Commonwealth and state governments share regulatory responsibilities based on location – is another relevant reference. India, with its federal structure, could benefit from defining a clear division of regulatory responsibility between the central government (e.g., for offshore or inter-state transport) and state pollution control boards (for site-level permitting and enforcement). This approach would also facilitate streamlined permitting and reduce jurisdictional ambiguity.

Australia's recent ratification of the London Protocol amendments and the development of a Sea Dumping Permit system to regulate offshore CO_2 injection provide a roadmap for enabling cross-border CO_2 transport and storage. While India is still early in its CCS journey, establishing legal readiness for international collaboration could future proof its system, particularly in the context of cross border CO_2 transport.

Another key area of relevance is Australia's emphasis on geological mapping and storage resource assessment, funded through its Resourcing Australia's Prosperity Program. India would benefit from a similar national-scale initiative, potentially led by the Geological Survey of India or the Directorate General of Hydrocarbons, to publicly catalogue potential CO_2 storage basins. This would enhance private sector confidence and reduce early-stage project risk.

Finally, Australia's integration of environmental approvals by an independent approvals body (NOPSEMA) within the CCS licensing process demonstrates the importance of environmental risk assessment at each project phase. India can adopt a similar model by enhancing the role of environmental impact assessments (EIAs) specific to CO_2 storage and integrating them into the approvals process governed by the Ministry of Environment, Forest and Climate Change.

1.4 Business models to accelerate demand and adoption of CCS

Creating demand and accelerating the adoption of CCS requires innovative models that address technical, regulatory and financial challenges. Since CCS largely does not involve a commercial revenue stream, business models need to focus on balancing revenue and risk to create a viable project. Business models that have been implemented in other jurisdictions could serve as a guide to Indian policymakers. Some of these models implemented in Europe are discussed below.

11. Carbon Contracts for Difference

Carbon Contracts for Difference (CCfDs) allow industrial decarbonisation projects to compete for funding by offering a price and quantity of CO_2 reductions they can achieve relative to the business-as-usual (BAU) scenario. Projects awarded a contract are guaranteed payments to bridge the gap between their offered strike price (cost of CO_2 reduction per tonne) and a reference carbon price, typically tied to the domestic carbon market price. These agreements are designed to mitigate the regulatory risks associated with climate policy that often arise due to fluctuations in carbon market prices.

CCfDs have been implemented in several countries. In Europe, France, Germany, the UK, the Netherlands, Denmark, Spain, Sweden, and Hungary have expressed public interest or have actively developed national CCfD approaches. Meanwhile, discussions continue on the potential implementation of an EU-wide scheme through mechanisms such as the EU Innovation Fund. The recently announced Clean Industrial Deal introduces the concept of an industrial decarbonisation bank, which aims to finance industrial decarbonisation efforts using revenues from the Innovation Fund. Notably, CCfDs have been identified as the primary financial instrument for this initiative. As a result, the rollout of an EU-wide CCfD scheme is likely in the coming years.

The Netherlands and Denmark can be considered frontrunners in some respects, as projects funded through their schemes, such as Ørsted's two carbon capture facilities and the Porthos project, are already under construction. The UK government has also developed one of the most detailed and structured approaches to supporting CCS through its CCfD schemes. Given that these initiatives are still evolving, more time is needed to assess their long-term success.

The Contracts for Difference (CfD) model has been widely used to support renewable energy projects. While traditional CfDs provide revenue certainty by stabilising electricity or fuel prices, CCfDs focus on bridging the gap between the cost of implementing low-carbon technologies and fluctuating carbon market prices. The strike price of a CCfD reflects the total costs of implementing the clean technology and typically remains fixed over the lifetime of the contract, while the reference price represents the BAU scenario. Typically, using an ETS price as the reference price example, if the strike price exceeds the ETS price, the state provides top-up payments to cover the additional costs of implementing the cleaner technology. Conversely, if the strike price falls below the reference price, project proponents are sometimes required to pay back the difference. This two-way mechanism ensures that the state only supports the additional costs of clean technology while realising savings when projects become more cost-effective than the reference price. As ETS prices rise, the subsidies required are expected to decrease.

Benefits of CCfDs include:

- **Enhancing government commitment**: CCfDs incentivise high reference prices by increasing

government payout obligations when prices are low, deterring policymakers from diluting ETS policies.

- **Supporting competitive bidding:** CCfDs help establish the true cost of decarbonisation technologies through competition rather than top-down government decisions. However, the extent of this benefit depends on the bidding design and the priority given to cost in the selection process. For CCS deployment, simple competitive bidding alone is unlikely to minimise costs effectively. A more strategic approach, for example, aligning project selection with regional infrastructure development, can enable economies of scale. This coordination ensures that each awarded project influences the required strike price for future projects, driving overall cost reductions.

- **De-risking investment**: By ensuring long-term revenue certainty, CCfDs encourage innovation and the adoption of emerging technologies, eliminating the first-mover disadvantage and unlocking finance. However, the scheme could also include protective measures to mitigate cross-chain risk, such as those included in the schemes of the UK, Denmark and Germany.

12. Low-carbon business models

In 2022, the UK government set a target to deploy CCUS across four industrial clusters, aiming to capture and store 20-30 Mtpa of CO_2 by 2030 (Government of the UK, 2023e). To facilitate this, the government introduced business models for industrial carbon capture to attract private investment and scale deployment. These business models are largely based on the same principle of Contracts for Difference described above, but tailored for specific applications, and include:

- Industrial Carbon Capture (ICC) (Government of the UK, 2024) and Waste ICC Business Models (Government of the UK, 2023a)

- Hydrogen Production Business Model (Government of the UK, 2022b)

- Power BECCS Model, and the Greenhouse Gas Removals Business Model (Government of the UK, 2023d)

- Dispatchable Power Agreement (Government of the UK, 2022a)

- Transport and Storage Regulatory Investment Model (TRI model) (Government of the UK, 2023b)

- Greenhouse Gas Removals (GGR) Business Model (Government of the UK, 2023c)

In October 2024, the government announced funding of £21.7 billion over the next 25 years (Stonell, 2024). These funds have been specifically allocated to projects in Teesside and Merseyside, with the aim of capturing over 8.5 Mtpa of CO_2. While final confirmations around funding distribution are still pending, it is likely that:

- The BP/Equinor Net Zero Teesside gas power station will receive funding through the Dispatchable Power Agreement.

- The Protos Energy-from-Waste plant with CCS will be supported via the Industrial Carbon Capture (ICC) contract.

- HyNet's EET Hydrogen Production Plant 1 will be financed through the Hydrogen Production Business Model.

Industrial Carbon Capture (ICC) and Waste ICC Business Models

The ICC business models for the industrial sector and the waste sector, respectively, are similar and incorporate and aim to fill any financing gaps from projects, reduce overall subsidy to industry and improve affordability and Value for Money:

- An agreement of up to 15 years that provides the emitter with revenue support through a payment per tonne of captured CO_2, which is intended to cover operational expenses, Transport and Storage (T&S) charges and repayment of, plus a rate of return on, capital investment in carbon capture equipment; and
- Co-funding for a portion of the capital cost of capture projects through a grant, which will be available for initial projects only.

The ICC business model was adapted for the waste sector to:

- Make the ICC model more suitable for the commercial position of residual waste management facilities.
- Reflect sector-specific risks.
- Prevent the creation of perverse incentives that could undermine the waste hierarchy (which ranks waste management options according to what is best for the environment).

Hydrogen Production Business Model

This model is similar to the ICC business model but is designed to ensure hydrogen producers are subsidised when revenues are not sufficient to cover costs. Payments from the government include:

- **Variable premium**: An amount to produce and sell low-carbon or carbon-abated hydrogen.
- **Price discovery incentive**: An amount that encourages the sale of hydrogen above the price of natural gas.
- **Sale of hydrogen payment**: An additional amount to compensate hydrogen producers when demand falls below a predefined/agreed-upon level.

The Low Carbon Hydrogen Agreement is closely aligned with the latest CfD standard terms and conditions, which have been used to incentivise renewable power generation in the UK over the last decade. The LCHA will be a private law contract between a hydrogen producer and a counterparty, designated as the Low Carbon Contracts Company, which is also a counterparty to the renewables CfD (Department for Energy Security and Net Zero, 2022a) .

Power Bioenergy with Carbon Capture Business Model (Power BECCS model)

The Power BECCS model is a CfD scheme to incentivise the deployment of biomass power with CCS, thereby incentivising negative emissions and producing electricity to contribute to security of supply. Whilst the design of the approach remains to be finalised, the government has identified a preferred financing option. This preference involves offering a dual CfD under a single contract framework, i.e., one for electricity generation (£/MWh) and another for carbon capture (£/t CO_2). This approach aims to provide revenue certainty in both the carbon and electricity markets, thereby ensuring a predictable return on investment.

The government is leaning towards a payment model for the electricity Contract for Difference (CfDe) in the power BECCS projects that will use aBMRP) as the reference price. This season-ahead reference price represents the weighted average of forward electricity sales from the previous season. The BMRP was chosen for several reasons:

- **Baseload Generation for Negative Emissions**: Continuous, baseload power generation is crucial for maximising negative emissions, which are essential for meeting net zero goals.
- **Long-Term Hedging and Stability**: The BMRP aligns with current baseload CfDs, enabling generators to lock in season-ahead sales for longer-term financial stability.

- **Technical Suitability**: Biomass-based BECCS projects lack the start-up flexibility needed for dispatchable (on-demand) profiles, making a baseload model more suitable.

- **Investability and value for money**: The BMRP model is considered the most attractive for investment, the easiest to manage for projects, and the best option for value, benefiting both electricity consumers and society at large.

A key concern with the CfDe, outlined in the March 2023 government consultation (Department for Energy Security & Net Zero, 2023) is the uncertainty surrounding future biomass costs, which could result in challenges in setting a fixed strike price. To address this issue, one potential solution is to include future indexation to account for fuel price risk. On the other hand, the strike price for the carbon capture Contract for Difference (CfDc) would cover the additional costs involved in integrating and operating CCS technology at the plant. This would include CAPEX, OPEX, and any extra fuel costs associated with generation using CCS.

Another option previously considered was a fixed payment for negative emissions, but this approach could restrict opportunities to generate revenue from a future removals market. The preferred option is more flexible, enabling the integration of negative emissions into upcoming carbon markets. This flexibility aligns with the "polluter pays" principle, where those responsible for emissions bear the cost of removals. As a result, the need for government support under this contract may be reduced (Department for Energy Security and Net Zero, 2022b).

The UK government's proposed approach is unique internationally, as there is currently no existing scheme that offers a dual payment system for BECCS. Most CfDs today that involve biomass focus solely on compensation for CO_2 reduction rather than on electricity generation. For example, Denmark has introduced a negative emissions CCS fund (NECCS) that provides a subsidy based on the amount of biogenic or atmospheric CO_2 that has been stored, with a total annual subsidy cap of DKK 319.9 million (Danish Energy Agency, 2023). There is future scope for adjusting and reducing support if project operators can monetise negative emissions through credits or certificates. Currently, under this scheme, any additional revenue from negative emissions credits that is not included in the operator's submitted costs and earnings can be reduced by 90% (Clean Air Task Force, 2024a). Similarly, the recent biogenic CCfD in Sweden specifies that aid will be adjusted based on other potential revenue streams, including voluntary carbon removal certificates (Biomass Magazine, 2024). This aligns with the UK government's current stance on future revenue streams for removals.

In many instances, the use of biomass is not permitted in current CCfDs. For example, in the German/French CCfD schemes, support for biomass is only available if the applicant can demonstrate that direct electrification is technically impractical and that using hydrogen for energy is neither technically nor economically feasible. To ensure sustainability, biomass must adhere to criteria that address GHG emissions, land use, biodiversity, and social impacts. In Europe, biomass used under CfDs must meet the sustainability requirements specified in Article 29 of Directive (EU) 2018/2001 (RED II) (European Commission, 2022). The UK's Biomass Strategy aligns closely with these EU criteria, reflecting a similar commitment to sustainability standards (Department for Energy Security and Net Zero, 2023a).

Dispatchable Power Agreement (DPA)

This model is also similar to the ICC and waste models, but is designed to enable power-generating entities with CCS to be competitive with those without CCS. There is also another difference in that government payments have two components:

- **Availability**: This payment is made regardless, to enable the power-generating entity to have power generation capacity available.
- **Variable**: Government payments for the electricity produced with CCS equipment functioning. This electricity is dispatched to the grid ahead of other unabated power plants (Department for Energy Security and Net Zero, 2022c).

Currently, there are no other examples of agreements that match the unique nature of the DPA. In the European Union, power plants that generate 300 MW or more are required to implement CCS technologies as part of their operations (European Parliament and European Council, 2009). However, these plants receive no additional financial incentives to offset the significant costs associated with CCS, placing them at an unfair disadvantage to unabated generators that are not subject to the same stringent requirements.

Transport and Storage Regulatory Investment (TRI) model

The TRI model has been specifically designed for two transport and storage companies (T&SCos), selected through a competitive process, that will construct and operate T&S networks for the first two clusters established in the UK. The TRI model consists of a licence to T&SCos administered by the relevant economic regulator Ofgem, which grants them the right to impose an ullage charge, up to an allowed revenue on capture projects in exchange for delivering and operating the T&S network. This revenue is calculated under a Regulated Asset Base (RAB) model, allowing T&SCos to recover their initial construction and operating costs, and to receive a return on capital investment. The scheme consists of support mechanisms including:

- Revenue support to T&SCos if there is a shortfall in revenue collection compared with the allowed revenue due to demand side risks.
- A government support package that includes several key components to mitigate risks and provide financial security for T&SCos:
  - CO_2 leakage is expected to be managed initially through commercial insurance, but the Supplementary Compensation Agreement (SCA) is a government contract that provides payments to T&SCos if commercial insurance is unavailable or exhausted, in the event that a relevant liability arises.
  - The Discontinuation Agreement allows the Secretary of State to end the government support package. It entitles T&SCos to compensation for equity and debt investments if the T&S network becomes a stranded asset or if calls (or forecast calls) under the SCA reach a specified threshold and the government deems ongoing support unsustainable.

The UK model provides comprehensive support and is an internationally unique approach to financing CCS transport and storage infrastructure. Unlike many other international approaches, it mitigates the risk of shortfalls in demand and other events that could financially expose the T&SCos. Whilst there are other international examples of governments offering financial support for CCS transport and storage infrastructure, these are typically focused on direct grant funding, rather than measures that address risks.

Greenhouse Gas Removals (GGR) Business Model

The GGR model aims to support negative emissions by providing revenue through a CfD framework. This framework bridges the gap between a "strike price" that covers the cost of producing negative emissions, and a "reference price" that reflects the market value of the associated negative-emission certificates. The strike price is designed to cover both CAPEX and OPEX of the facility, including an allowed return on investment. Importantly, costs associated with transport and storage will be calculated and paid separately, outside of the strike price. For initial projects, the reference price will be determined by the actual price the developer achieves for selling negative emissions credits in approved markets, such as voluntary carbon markets or potentially in the UK ETS, if removals are integrated in the future.

In the absence of a mature open market and to encourage developers to secure the highest possible contractual sales price, a price-discovery incentive will be included, similar to the mechanism in the Hydrogen Production Model. This approach aims to reduce the risk of low sales prices and minimise dependence on different payments to meet the strike price. Additionally, there are considerations for including a reference price floor, which could help mitigate the government's risk of large payouts. The revenue support will be provided over a 15-year contract term.

The model also contemplates providing volume support if there is low demand for carbon credits in the market. While it is not currently intended to reimburse developers the full strike price if credits go unsold, there are discussions about a government offtake backstop, where the government could act as a buyer of last resort, or a sliding-scale approach, offering higher pricing support for initial volumes of emission credits sold. This would help developers recover costs even at lower sales volumes (Department for Energy Security and Net Zero, 2023b).

A crucial element in establishing the negative emission credits is the development of GHG removal methodologies, which will define the requirements and procedures for quantifying these removals. The government is working on options for these methodologies, in parallel with the EU's voluntary certification framework. In September 2024, the UK Government commissioned the to develop an engineered Greenhouse Gas Removal (GGR) Standard, focused on DACCS and BECCS initially. Under the first phases of the contract, BSI will define and publish methodological Minimum Quality Thresholds for early GGR projects seeking support from the Government's Business Model. These will specify what projects must cover as part of their removal quantification, monitoring and reporting, and reference best practice and existing government standards. The Minimum Quality Thresholds are expected to be published in 2025. BSI will use feedback from the Minimum Quality Thresholds to support the development of subsequent detailed methodologies for DACCS and BECCS, in the form of a series of Publicly Available Specifications (PASs). Each PAS will cover a subset of the GGR value chain, such as biomass supply, or carbon capture, transport and storage.

Internationally, the UK's approach is unique in how it offers financing to support carbon removals. A possibly comparable example is the Danish NECCS fund, which provides subsidies based on the amount of CO_2 stored rather than the market value of negative-emission credits. Under this scheme, operators retain ownership of the emission credits generated from carbon removal activities. These credits can be sold both domestically and internationally, as long as they still contribute to Denmark's climate targets. The subsidy, however, may be reduced if the storage of CO_2 generates additional income (The Danish Energy Agency, 2023).

13. Applicability of CCfD and other CfD models to CCS development in India

CCfDs and the low-carbon CfD models discussed in sections 11 and 12 could have a significant role to play in the acceleration of CCS deployment in India. The benefits of these models in the Indian context include:

- Policy clarity: Support from the government during the operational phase of a CCS project will provide confidence to developers and financiers, and may lead to favourable financing terms for early-stage commercial development.
- Support the business case for CCS: Revenue support over a 10 to 15-year period could significantly enhance the business case for CCS. In a cluster setting, when combined with direct government funding for hubs/cluster development, could achieve significant economies of scale.
- Project risk reduction: If a floor on the strike price is guaranteed, investment risk is reduced, and projects may be able to secure favourable insurance packages/premiums and favourable finance terms for commercial-scale development.

There are, however, several considerations for India before CCfDs could be used to support CCS deployment:

- Tenor and performance metrics: CCfDs should have a sufficiently long tenor to provide revenue certainty that will support the commercial feasibility of a project. Performance metrics and penalties for non-delivery should be unambiguous.
- Strike price and reference price setting: India's CCTS may be a potential basis for a reference price to underpin CCfD agreements – this is consistent with practices elsewhere, such as in the UK and the EU. The strike price could be set via bilateral negotiation or auctions. The methodology and indexation should be carefully considered, cognisant of any additional risks, such as foreign exchange risk.
- Appropriate counterparty: To reduce counterparty risk and give lenders confidence, the Indian government should establish or select a credible counterparty to enter into and manage the CCfDs with CCS project operators. The UK, for example, established the Low Carbon Contract Company (LCCC) to fulfil this role (LCCC, n.d.).

14. Demand creation for low-carbon and near-zero material

Demand for low-carbon and near-zero products and materials is a driver of decarbonisation of supply sectors through their adoption of technologies, including CCUS technologies. Demand may be from the public and/or private sector and can stimulate a competitive market and result in a "green premium" for lower carbon products. Procurement frameworks can be designed to be at the product level and/or project level.

Public procurement: With 20% of India's GDP allocated to public procurement, the government holds significant direct influence over the demand for low-emission cement.

Private Procurement: Governments also have a role in demand creation for low-carbon and near-zero products through policies that influence or directly dictate private procurement.

1.5 International Aid for deployment of CCS in India

15. The Green Climate Fund

The Green Climate Fund (GCF) is a key financial mechanism under the United Nations Framework Convention on Climate Change (UNFCCC), dedicated to supporting climate action in developing countries. With the capacity to fund large-scale infrastructure projects, including CCS, the GCF offers a variety of financial instruments such as grants, concessional loans, loan guarantees, and equity investments (Green Climate Fund, 2024).

In mid-2024, the GCF made its first investment in CCUS in Trinidad and Tobago. This initiative supports the development of a national CCUS strategy, including an assessment of storage potential in deep saline formations and the creation of a national carbon storage atlas (IEAGHG, 2024).

In India, the GCF is actively supporting climate-related efforts through both project financing and capacity-building activities:

- Number of GCF-approved and funded projects: 13
- Total GCF financing: US$803.9 million (Government of India, 2025)
- Number of readiness activities approved: 5
- Total readiness support provided: US$5.6 million (Green Climate Fund, 2025)

In 2025 India announced the establishment of a "country platform", supported by GCF's Readiness Programme, to better coordinate climate finance and build a pipeline of investable climate-resilience and mitigation projects (Mishra, 2025).

16. The Global Environment Facility

The Global Environment Facility (GEF) operates on six-year funding cycles, during which donor countries pledge financial resources. These funds are then allocated to recipient countries based on their specific needs. To access GEF funding, countries must submit project proposals that align with their NDCs. Funding is provided in the form of grants, which must be matched through co-financing from public and private sources, including international investors. The required co-financing ratio depends on the country's level of development.

Projects seeking GEF support are developed, submitted, and managed by third-party organisations known as GEF agencies. These agencies include multilateral development banks, international NGOs, and UN-affiliated organisations. Project sizes vary, with full-sized projects – the largest category – ranging from US$1 million to US$15 million.

GEF funding is primarily directed toward activities that enhance a country's ability to adopt new technologies. This includes the development of policies, technical assessments, and small-scale pilot projects. However, given the high costs associated with commercial-scale CCS projects, GEF support is generally more applicable to building foundational capacity – such as establishing legal, regulatory, and policy frameworks – rather than funding full deployments.

As of now, the GEF has not approved any CCS projects. One proposal, submitted by Brazil in 2009, did not secure the necessary funding (Global CCS Institute, 2021)

17. Article 6.4 Carbon Credit Mechanism

At the 2024 United Nations Climate Change Conference in Baku, Azerbaijan, negotiators reached a pivotal agreement on the operational framework for the Article 6.4 credit trading mechanism under the Paris Agreement. This mechanism establishes a centralised global carbon market that enables countries and private entities to generate and trade carbon credits derived from verified emission reduction or removal projects.

It is important to highlight that the final agreement reached at COP29 did not include the adoption of specific methodology standards or frameworks to ensure the quality of credits traded under the Paris Agreement Crediting Mechanism (PACM). The establishment of standardised methodologies is essential to guarantee the transparency and integrity of the carbon market, which is critical for building trust and stimulating demand.

Recognising the importance of this issue, the President of the Article 6.4 Supervisory Body emphasised the need for robust quality standards. In the final proposal released following COP29, a dedicated section called on the Supervisory Body to accelerate the development of “standards, tools, and guidelines” covering key areas such as baselines, downward adjustments, standardised baselines, suppressed demand, additionality, and leakage. It also addressed concerns related to non-permanence and reversals, including post-crediting period monitoring, reversal risk assessments, and appropriate remediation measures. This proposal was unanimously approved by negotiators on November 23, 2024, marking a critical step forward in strengthening the PACM’s operational framework (Carbon Direct, 2024).

The establishment of this mechanism is anticipated to unlock significant climate finance, particularly benefiting developing nations by channelling funds into effective emission reduction initiatives, including those relating to CCS.

18. World Bank Funding

Clean Technology Fund

This fund provides new, large-scale financial resources to invest in clean technology projects in developing countries, which contribute to the demonstration, deployment and transfer of low-carbon technologies with a significant potential for long-term GHG emissions savings. Currently, project investment in India centres around renewable energy generation, with finance to support the development of three gigawatts of new installed solar power capacity. However, in the future, CCS may receive funding (The World Bank, 2024).

International Finance Corporation

The International Finance Corporation (IFC) plays a key role in enhancing socioeconomic conditions in developing countries by investing in the growth of the private sector. Its central mission is to create opportunities that help individuals escape poverty and achieve better living standards. This is achieved by mobilising capital for private enterprises, promoting open and competitive markets, supporting businesses, and generating employment opportunities (International Finance Corporation, n.d.).

In addition, the IFC is actively working to develop markets for CCUS in the regions where it operates. It is building capacity among its clients to enable the implementation of CCUS projects. Currently, the IFC is engaged in advisory initiatives in both Nigeria and Timor-Leste.

In Nigeria, the initiative focuses on identifying key emission sources and mapping potential geological storage sites, with the aim of establishing hubs for CCUS deployment. The project places particular emphasis on industrial applications and includes an evaluation of the legal and regulatory frameworks needed to support the sector's growth. In Timor-Leste, the IFC is assisting the government in designing a legal and regulatory structure to support the development of a geological storage site located in the Timor Sea (IFC Climate and Sustainability, 2023).

19. Carbon Management Challenge

The Carbon Management Challenge (CMC) is a global initiative and collective call to action that brings together countries to accelerate the development and deployment of CCUS technologies. Launched at the Major Economies Forum in April 2023, the CMC currently includes 22 participating countries along with the European Commission.

The CMC aims to raise global ambition by driving forward carbon management projects at gigatonne scale by 2030. One of its key focus areas, Workstream 1, is centred on strengthening and developing financial policies to support carbon management efforts in developing countries. This workstream is co-led by Kenya, Indonesia, and the US, and aims to enhance existing financial mechanisms as well as explore new funding opportunities. These efforts could potentially benefit CCS projects in countries like India (CMC, 2024).

02 Hub Analysis

Photo: Adobe Stock

2. Hub Analysis

2.1 Key findings

- India's 2024 CO_2 emissions were reported to be approximately 3,060 Mtpa, with power and heavy industry dominating, and major point sources concentrated in a number of industrial corridors.
- South Cambay (Cluster 4 and Cluster 10) scored highly as a potential CCS hub area under the screening criteria used in this study, combining proximity to the Gandhar-Ankleshwar storage complex with large, diverse and growing emissions, high CO_2 concentration in many streams, existing pipelines, relatively good subsurface data and emerging CCS activity.
- The combined cluster contains 125 facilities with an estimated 119.3 Mtpa of CO_2 emissions today and 132.0 Mtpa in 2030, dominated by power (~40 Mtpa), petrochemicals (~22 Mtpa), iron and steel (~25 Mtpa), cement (~16 Mtpa), refining (~16 Mtpa).
- Storage capacity of the Ankleshwar Formation storage complex in the Cambay basin has been estimated at approximately 341 $MtCO_2$ (P50), ranging from 180-585 $MtCO_2$ across stacked sand reservoirs. This relatively limited capacity suggests that any future hub assessment may need to consider how capture sources could be sequenced or selected.
- Eleven principal sources were selected to deliver 17 Mtpa of CO_2 capture aligned with studied storage resource availability.
- The illustrative hub concept is presented in three phases: 2.85 Mtpa in Phase 1 (Vadodara focus), 12.6 Mtpa in Phase 2 (Dahej, Hazira and expanded refinery capture), and 17 Mtpa in Phase 3 (addition of selected cement and power), with pipelines progressively extended and duplicated where necessary.
- The dense phase CO_2 pipeline network largely follows existing pipeline corridors and includes a subsea crossing of the Gulf of Khambhat.
- Compression and transport to the storage site have an estimated full hub scale cost between of ~US$19.7 and US$29.5/tCO_2 at full hub capacity, with roughly two-thirds of the cost attributable to source compression requirements.
- Combined capture plus transport costs for most selected sources fall in the range of roughly US$39-111/$tCO_2$, with only smaller or lower concentration streams at the upper end (~US$124-186/$tCO_2$).
- The South Cambay Hub concept provides a potential pathway to the decarbonisation of several key industrial sites in the Gulf of Khambat area, but development depends on storage performance, enhanced emissions and project data, and coordinated progress on regulation, permitting and commercial arrangements.

2.2 Industrial CO_2 Emissions Sources

This section discusses the efforts and methodology used to identify and estimate significant industrial emitters, including their potential future emissions profile.

20. Existing Emissions Sources

India has a range of existing emissions sources across the nation, in both the energy use and industrial sectors. These sectors have experienced significant growth and development following the liberalisation of India's economy in the early 1990s, with the economy achieving average annual growth rates above 6% between 1995 and 2024 (World Bank Group, 2025).

It is estimated that India's annual CO_2 emissions in 2024 were approximately 3,060 Mtpa (Global Carbon Budget & Our World in Data, 2024), with the electricity and heat production sector as the most significant contributor to this total (IEA, 2022c; MoEFCC, 2024). The "Fourth Biennial Update Report to the UNFCCC" by the Government of India's Ministry of Environment, Forest, and Climate Change (MoEFCC) further details the specific sectors for emissions as a part of their "National Greenhouse Gas Inventory", with the top 15 key emission categories for 2020 presented in Figure 3.

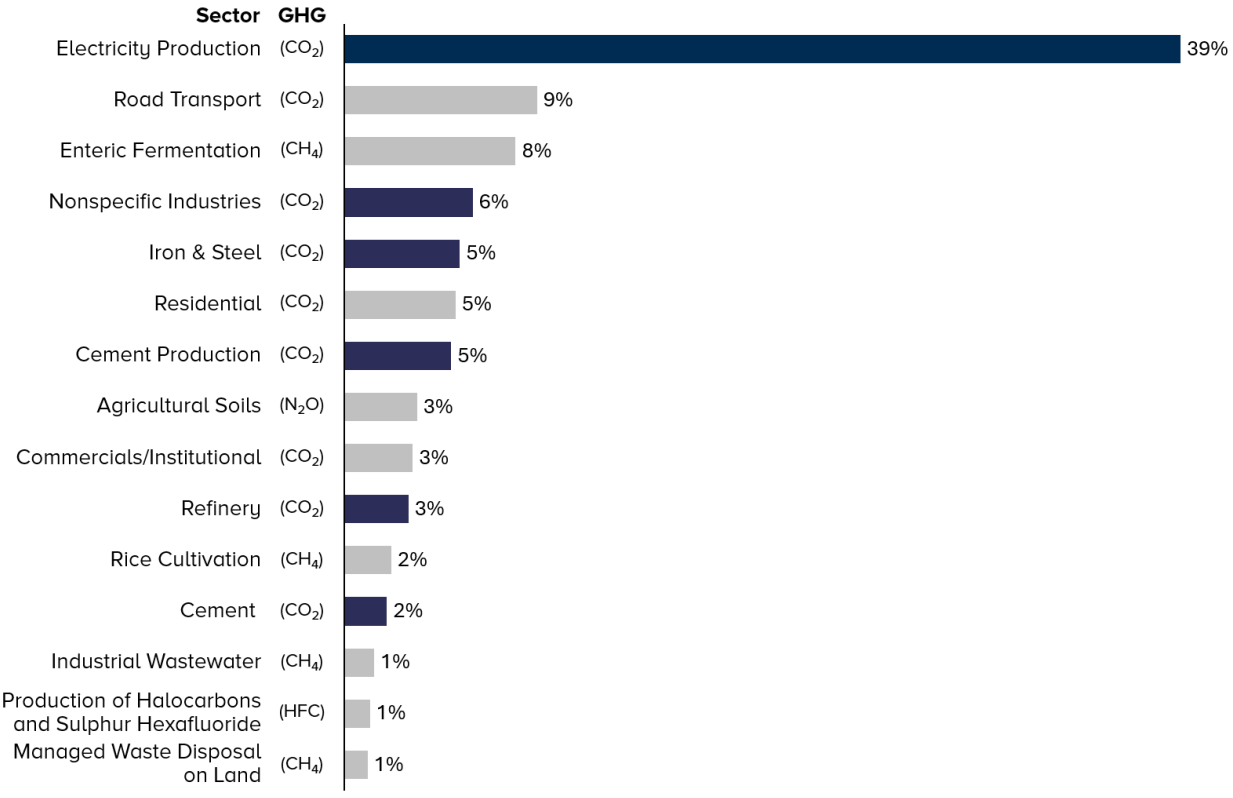


Figure 3. Percentage Share of Greenhouse Gas Emissions (GHG, CO_2e) by Category, 2020. Reproduced and adapted from Figure 2.5, reported by MoEFCC (2024) on page 75

*Blue shaded bars indicate sectors where CCS could potentially be applied, while grey shaded bars indicate sectors where CCS is unlikely to be applicable.

For this study, the sectors examined were power generation, natural gas processing, refining, cement and concrete, iron and steel, ammonia and fertiliser, and other chemicals production. These industries are known potential deployment sectors for CCS, with existing commercial facilities or pilots around the world (Global CCS Institute, 2024e; Pisciotta et al., 2024).

Power Generation

The Central Electricity Authority of India reported that in June 2025, installed electricity generation capacity reached a total of 484.82 GW, with the share of different power generation types shown in Figure 4 (Central Electricity Authority, 2025). The actual electricity generation in the year to June 2025 is shown in Figure 4 (INCED, 2025).

As shown in Figure 4, India's power generation capacity is nearly balanced between renewable and thermal generation capacity. However, the power that is generated and distributed to the electrical grid (Figure 5) remains heavily dependent on thermal power facilities, particularly coal-fired power generation, due to the variations in renewable output from solar, wind, and hydro systems as well as the availability of coal for generation purposes.

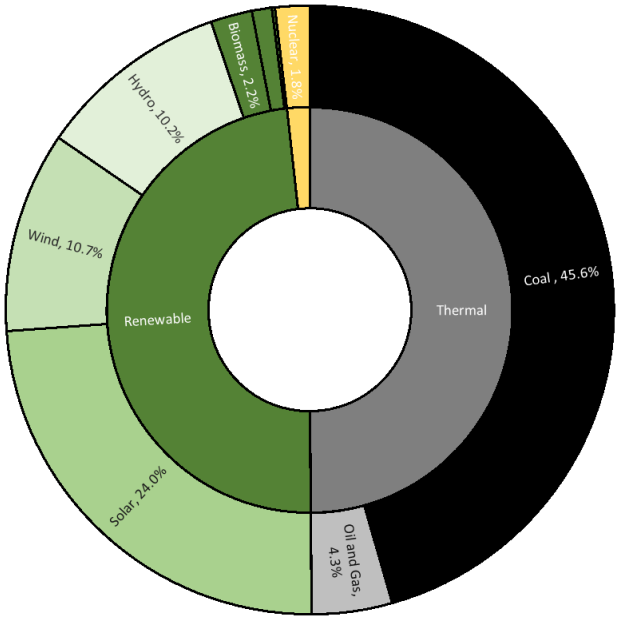


Figure 4. Summary of Installed Capacity of All Power Stations as of 30/06/2025 in India. (Source: Central Electricity Authority, 2025)

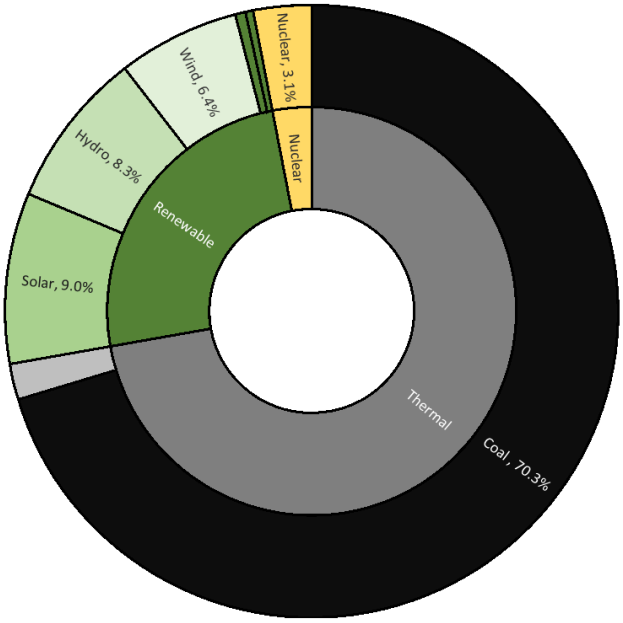


Figure 5. Source-wise Electricity Generation in India as of 30/6/2025. (Source: INCED, 2025)

Capacity Factor

Capacity factor, also known as the “utilisation rate” of a facility or “plant load”, refers to the total output of a plant compared with the maximum output possible over a given time period. It is especially important for power facilities as electricity demand is not constant. As such, the supply of power must fluctuate to meet demand and maintain grid balance. This fluctuation may result in certain power generators curtailing or even stopping power generation to maintain grid balance.

For fossil fuel facilities, when power generation is reduced or stopped, fossil fuels are not combusted, and as a result, CO_2 is not generated. For the consideration of potential CO_2 emissions volumes from a fossil fuel power generation point source, it is necessary to include the capacity factor as a part of the top-down calculation of CO_2 emissions.

Capacity factors for power stations were extracted from Central Electricity Authority data across the past four years to determine an average capacity factor for the plant. For plants that started operations less than four years ago, the calculation was adjusted to include only the time that the plant was operational. Equation 1 shows the formula used to calculate the capacity factor.

Equation 1. Capacity Factor Equation

$$\text{Capacity Factor (\%)} = \frac{\text{Actual Electricity Generated in MWh per Year}}{\text{Plant Capacity in MW} \times \text{Number of hours per Year}}$$

Coal Power Generation Facilities

Coal-based power facilities are a significant part of India’s power system, accounting for 70.3% of the generated power in the year to June 2025. Based on current governmental planning, they are expected to remain a mainstay of the system into the near future as well, considering the current expansionary plans for power capacity (Ministry of Power India, 2024) alongside the relatively long remaining economic lifetimes of existing coal-fired power generation, shown in Figure 6.

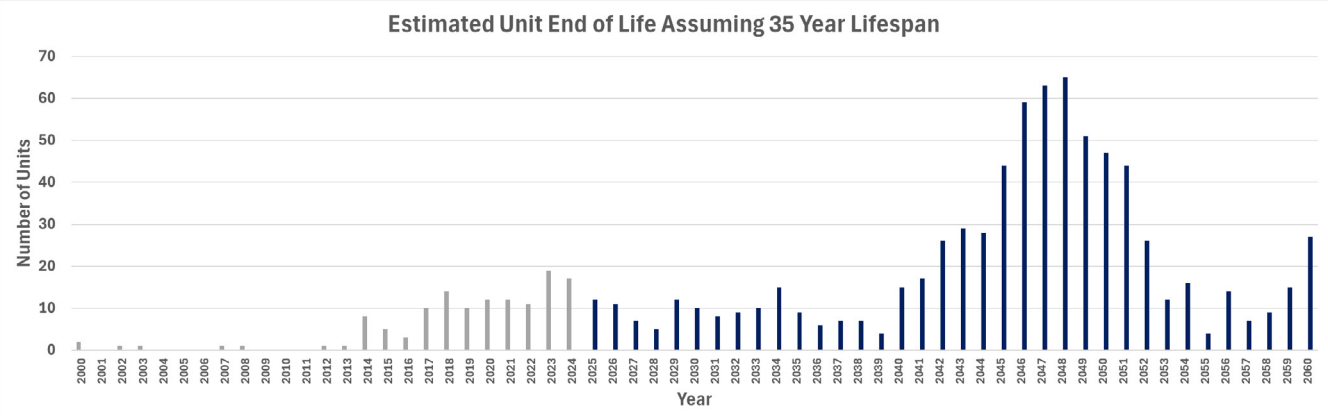


Figure 6. Estimated Unit End of Life, Assuming a 35 Year Lifespan. Note: Some units have already exceeded this lifespan

The capacity factor of coal power stations varies widely, with some stations at high capacity factors indicating baseload use, and other stations with significantly lower or even near-zero capacity factors, indicating use only during periods of high electricity demand.

Capacity factors were extracted from the Central Electricity Authority and mapped to named facilities, shown in Figure 7. Where facilities were identified through databases but not named, an average capacity factor of 56% was applied for the study.

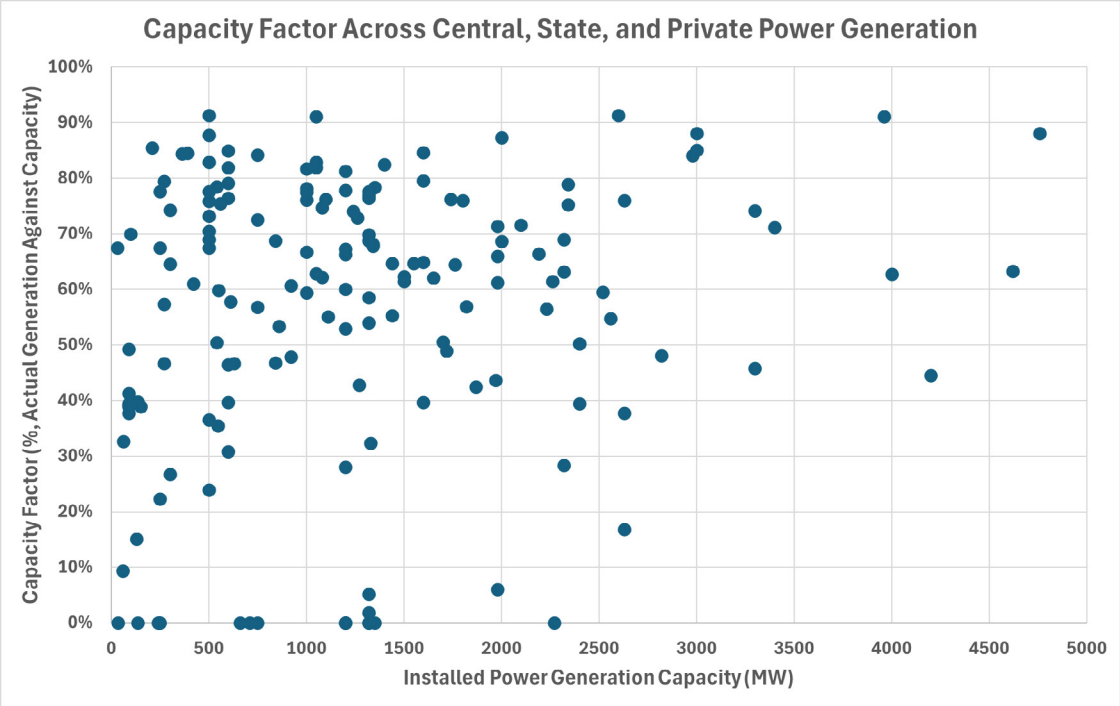


Figure 7. Power Plant Capacity Factor Average Across Four Years for Coal-Fired Power Generation Across the Central, State, and Private Sectors

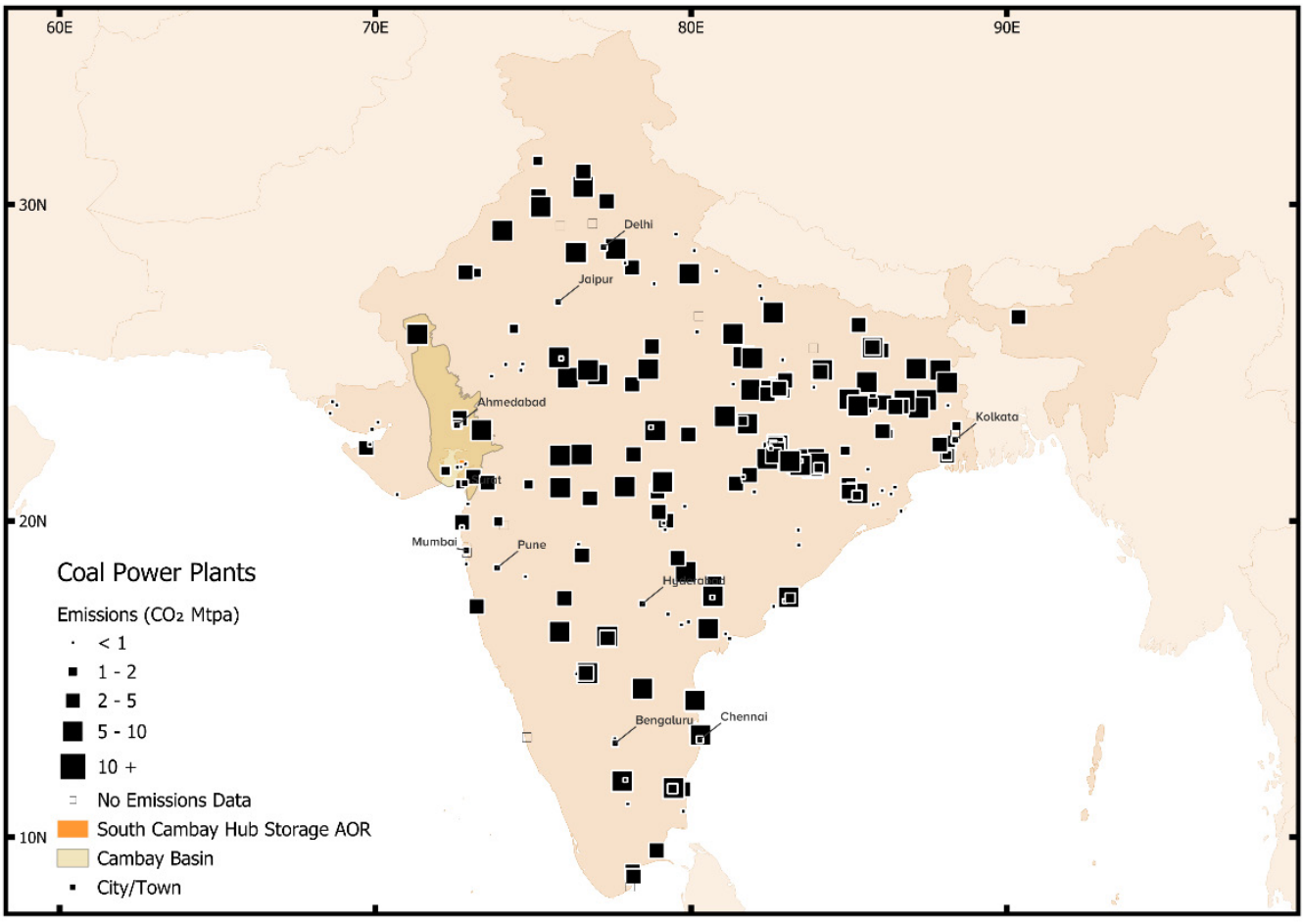


Figure 8. Location of Coal Power Plants in India

Natural Gas Power Generation

Natural gas-fired power generation facilities accounted for 1.9% of the total power generation in the year to 30 June 2025. Gas-fired power capacity expansion, and generation more generally, has been constrained by gas supply limitations, as India consumes more than it produces domestically. (IEA, 2025). Gas-fired power generation facilities are located as per Figure 9.

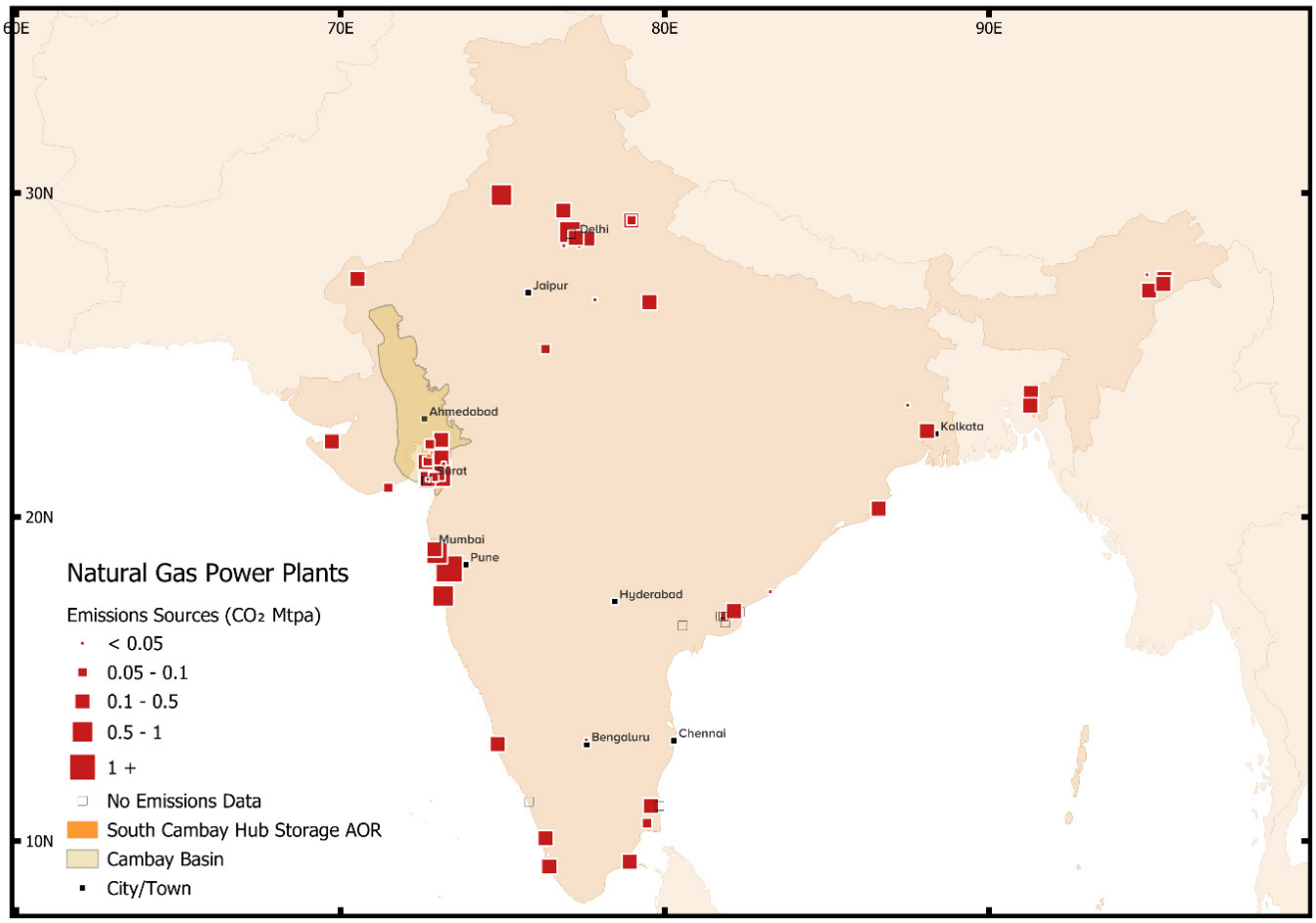


Figure 9. Location of Natural Gas Power Plants in India

Biomass Power Generation

Biomass power generation is a relatively small portion of India's grid capacity and generation, accounting for 0.5% of the total power generation in the year to 30 June 2025 (Central Electricity Authority, 2025). The locations of the plants are mapped per Figure 10.

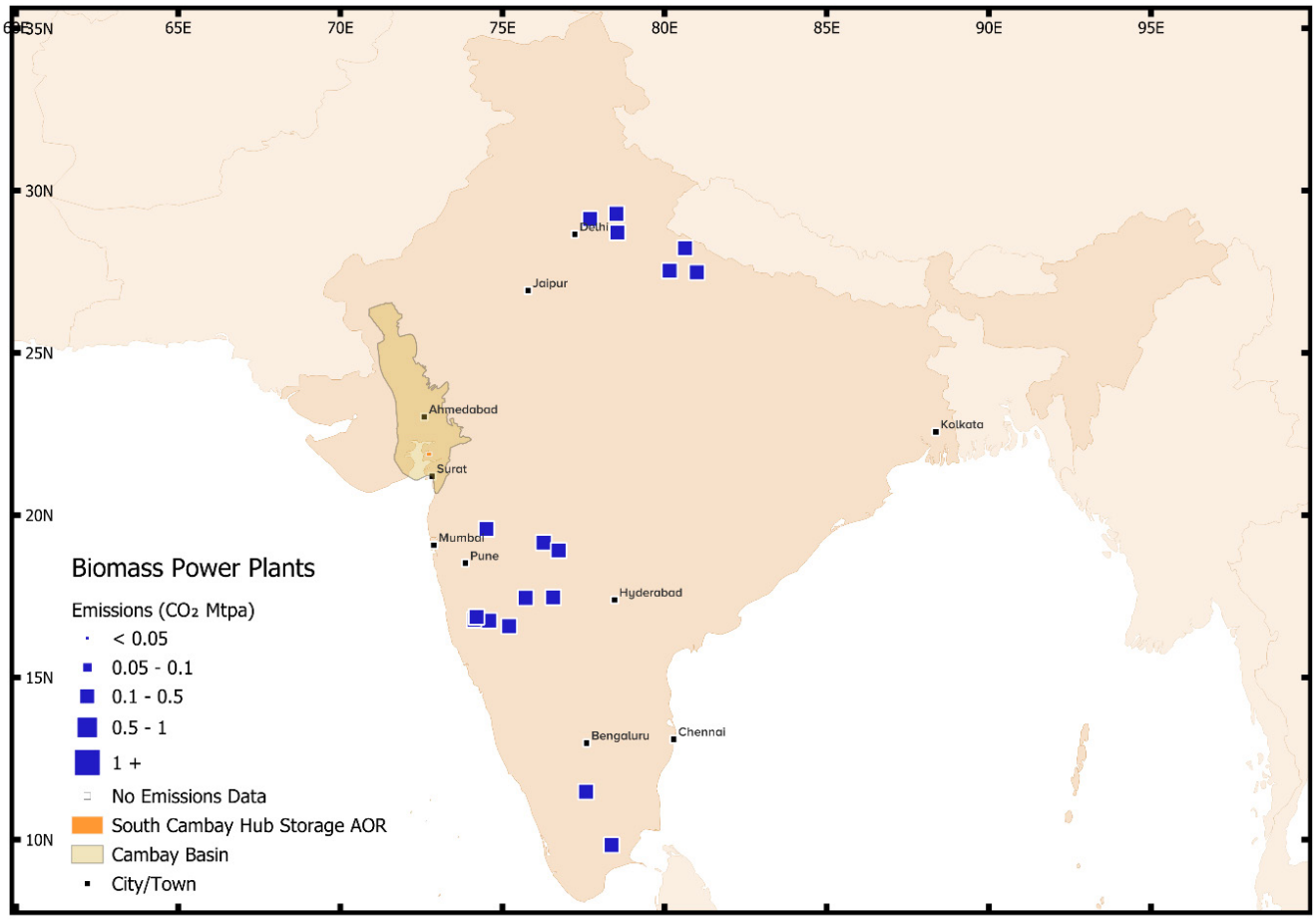


Figure 10. Location of Biomass Power Plants in India

Biomass power with CCS can be an attractive option for CO_2 sequestration, as the CO_2 captured is biogenic in origin. In this case, a power supplier may also be able to sell CDR credits to the voluntary carbon market, in addition to the sale of power generated, as CO_2 withdrawn from the atmosphere by biomass is then captured and stored underground.

Natural Gas Processing

India has 17 active, planned, or announced natural gas processing facilities located around the country, as per Figure 11 (GlobalData, 2025a). Natural gas processing facilities include facilities that treat raw well gas to produce on-specification natural gas, as well as regasification units that transform imported liquefied natural gas (LNG) into natural gas for distribution.

Information regarding CO_2 emissions from these facilities, reservoir gas or on-site power generation, is sparse and would benefit from further examination in collaboration with facility operators. One facility, the Hazira Natural Gas Processing facility, has been identified as a sour gas processing facility, and through estimations relating to inlet feed natural gas and sales specification natural gas (Maiti, n.d; Pandey, 2005), an estimate of 0.4 Mtpa of CO_2 emissions from the acid gas removal system has been calculated. All others are indicated in Figure 11; however, they are not included in the study due to the lack of available data.

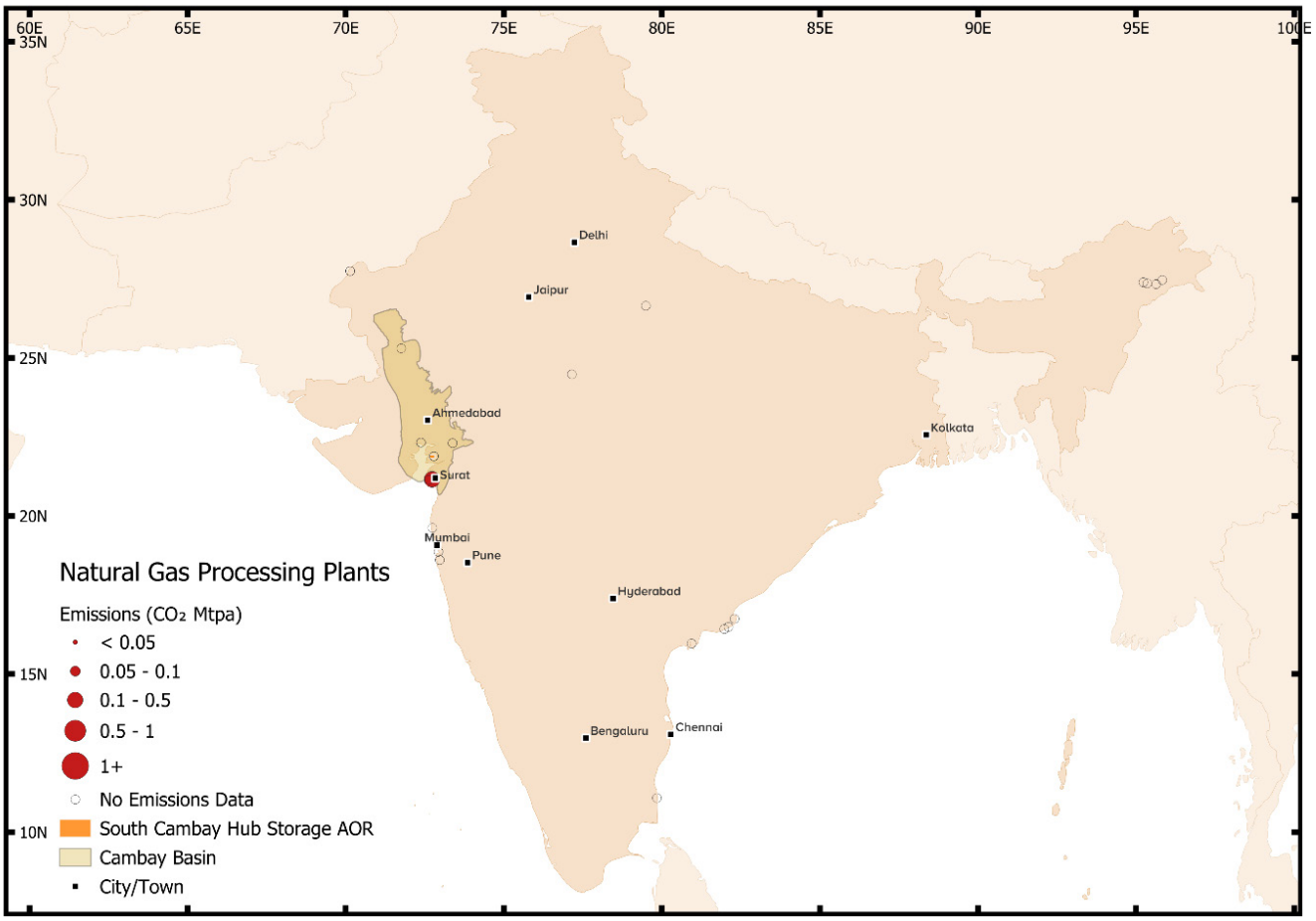


Figure 11. Location of Natural Gas Processing Plants in India

Oil Refining

India's oil refining capacity in 2025 was reported as 256 Mtpa (Ministry of Petroleum and Natural Gas India, 2025). This capacity was distributed across 19 combined refineries around the country, shown in Figure 13. Refineries include several point emissions sources on site, with four main categories primarily considered for CCS activities. The on-site furnaces & boilers, and the utilities systems can consist of several individual, physically separated, smaller systems located across a refinery at the various production units, which can make CCS for the refinery as a whole more challenging due to the wider area of sources to consider.

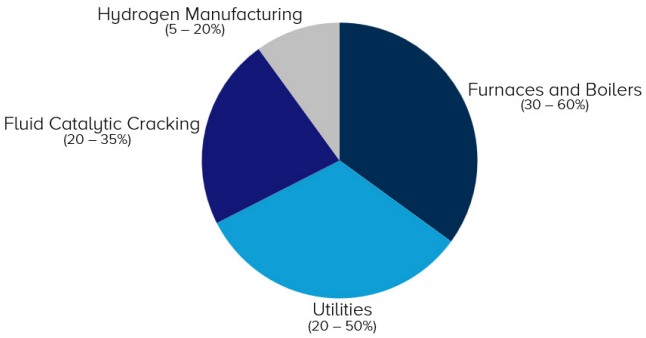


Figure 12. Primary Emissions Sources from Refineries (Source: Güleç, Meredith and Snape, 2020)

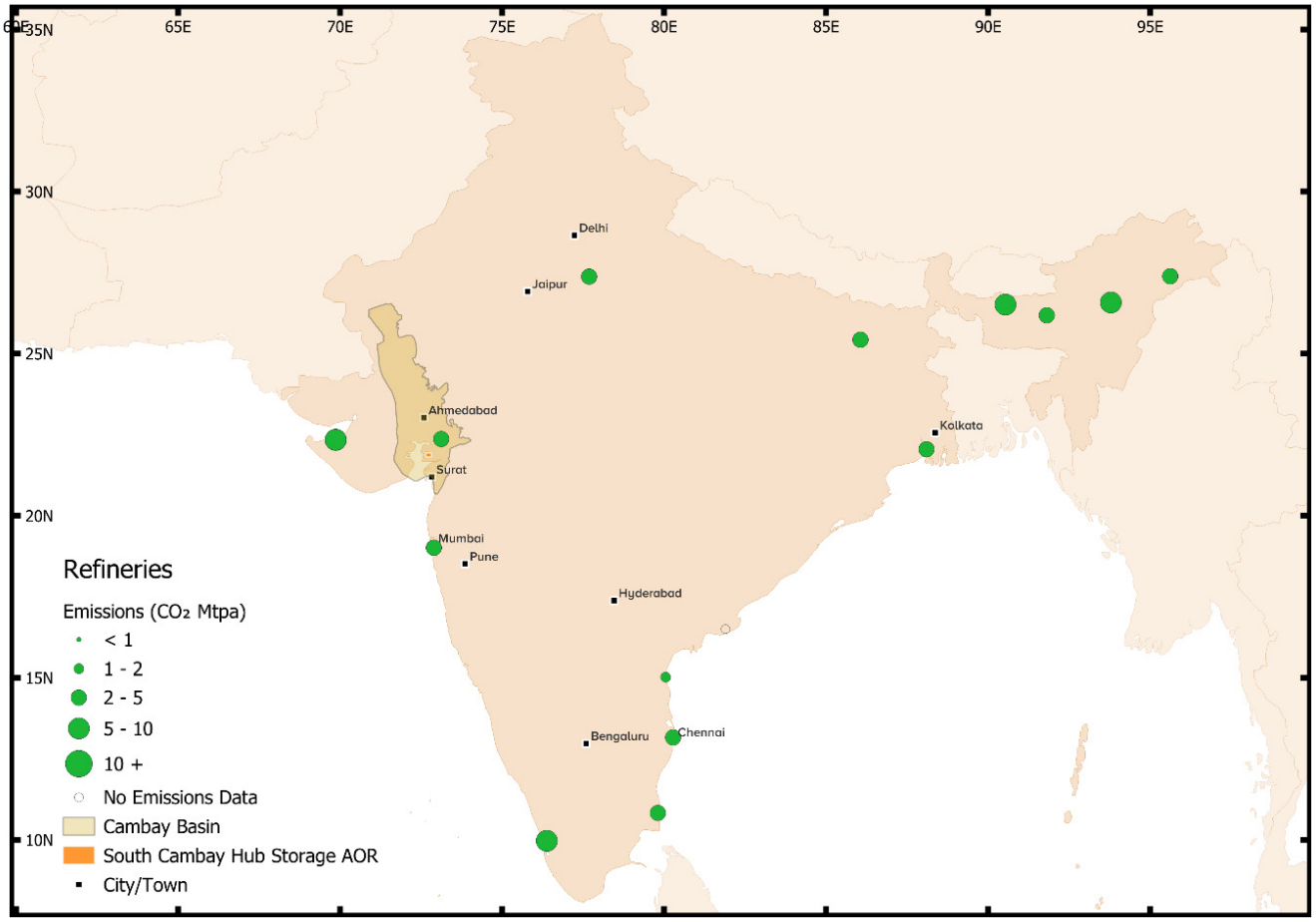


Figure 13. Location of Refineries in India

Cement and Concrete

Cement is one of the most critical raw materials in the construction industry, as a key component of concrete. Concrete itself is the most used manufactured item by mass in the world (Global Cement and Concrete Association, 2025). Cement is manufactured by blending raw materials, including limestone, silica, alumina, and iron, and then preheating to calcine the limestone into lime, followed by firing at a high temperature in a kiln. Cement is considered a hard-to-abate sector as the calcination process is an unavoidable part of the manufacturing process, which inherently generates CO_2, and CCS is one of the only ways to address this emissions source (Global Cement and Concrete Association, 2024).

Indian cement production capacity installed as of April 2024 sat at 553 Mtpa, though actual annual production in FY 2022-23 was estimated to be approximately 375 Mtpa (IBEF, 2025a). Production is primarily in the states of Andhra Pradesh, Rajasthan, Tamil Nadu and Gujarat (T E R I, 2013).

Cement plants across India have been identified and are shown in Figure 14. Some cement plants were identified without a corresponding capacity, and therefore emissions could not be estimated; these facilities are displayed on the map with an empty triangle, and are excluded from further analysis.

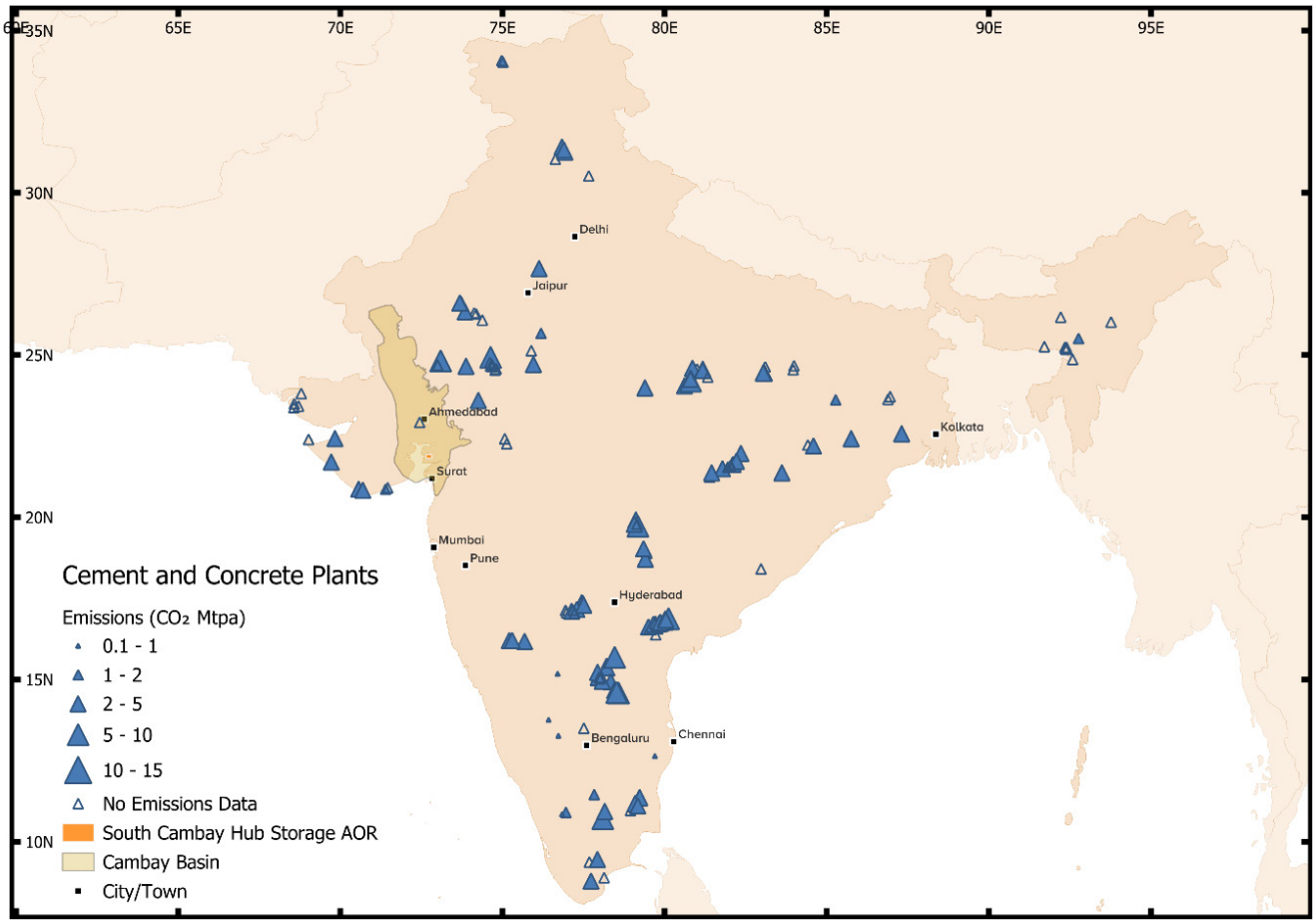


Figure 14. Location of Cement and Concrete Plants in India

Iron and Steel

The iron and steel industry in India has grown rapidly in recent decades to become the second largest producer of crude steel globally, with an installed capacity of 205 Mtpa in FY 2024-25 (Steel Radar, 2025) and a total production of 138 million tonnes (IBEF, 2025b). India also leads the world in direct reduction iron production (Midrex Technologies Inc., 2024). This production method reacts either natural gas or syngas from coal with iron ore and produces a high-pressure stream of top gas, from which it can be relatively easier to capture CO_2 compared with BF gas. An example of CCS on a DRI steel plant is commercially operated in Abu Dhabi (Clean Air Task Force, 2024b). Examples of carbon capture from DRI systems in India for utilisation are under consideration (S&P Global, 2025b).

The plants identified in the database search have primarily been BF and BOF production methods, which is consistent with the global production profile of iron and steel, where more than 70% of steel is produced via the BF/BOF method (World Steel Association, 2024).

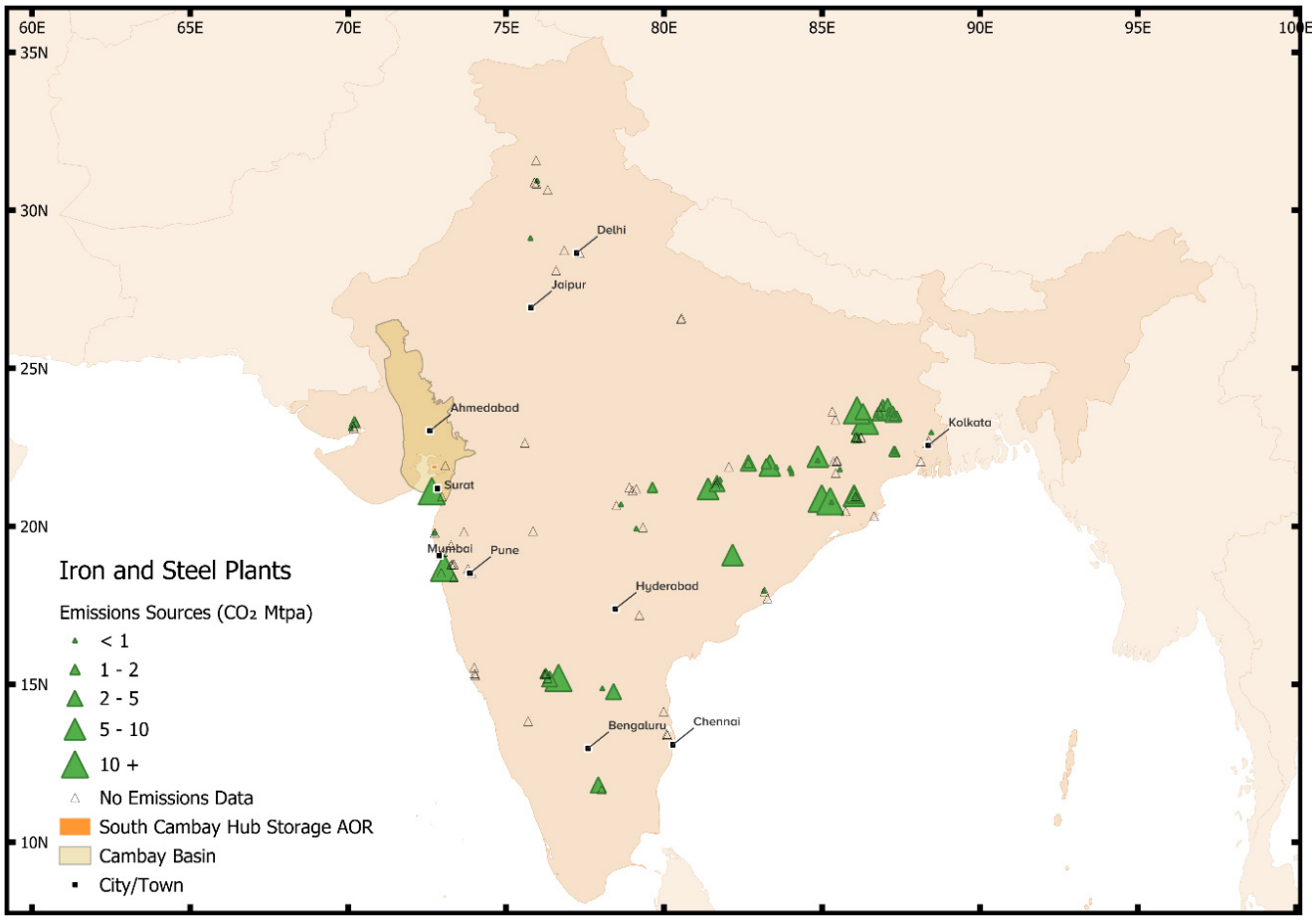


Figure 15. Location of Iron and Steel Plants in the Cambay Region

Ammonia and Fertiliser Production

India's ammonia production in 2024 was estimated to be between 17 and 19 million tonnes (Kothadiya, Hemant, and Deepak, 2024), used for the production of fertilisers. Ammonia production tends to be primarily for urea production, which also consumes some of the CO_2 generated by ammonia production facilities.

Ammonia production generally results in two streams of CO_2 produced:

1. A high-pressure and concentration stream of CO_2 from the CO_2 removal system upstream of the ammonia synthesis loop, and
2. A lower concentration stream of CO_2 from the reformer flue gas system.

CO_2 from the high-pressure removal system is often recycled for use to produce urea, the primary nitrogenous fertiliser used in India (IRENA & AEA, 2022). To account for this, any facility in the databases reviewed that also produces urea has a proportion of the CO_2 emissions from the ammonia production plant removed to account for the necessary CO_2 for urea production.

Petrochemicals

Petrochemical production in India extends beyond ammonia and urea to include a wider array of petrochemicals for various downstream uses. For this study, a select group of chemicals were chosen for further consideration from the datasets available. The selected chemicals tend to either have larger facilities to supply general production (feedstock) or have a production process where the generation of CO_2 is an inherent part of the process.

The selected chemicals for mapping and cluster analysis include:

- Ethylene Oxide (Inherent CO_2 generation from side reaction)
- PTA (Inherent CO_2 generation from side reaction)
- Methanol
- Ethylene Glycol
- Ethylene
- Propylene
- PET
- Polyethylene
- Xylene

The facilities and estimated emissions source sizes are shown in Figure 16.

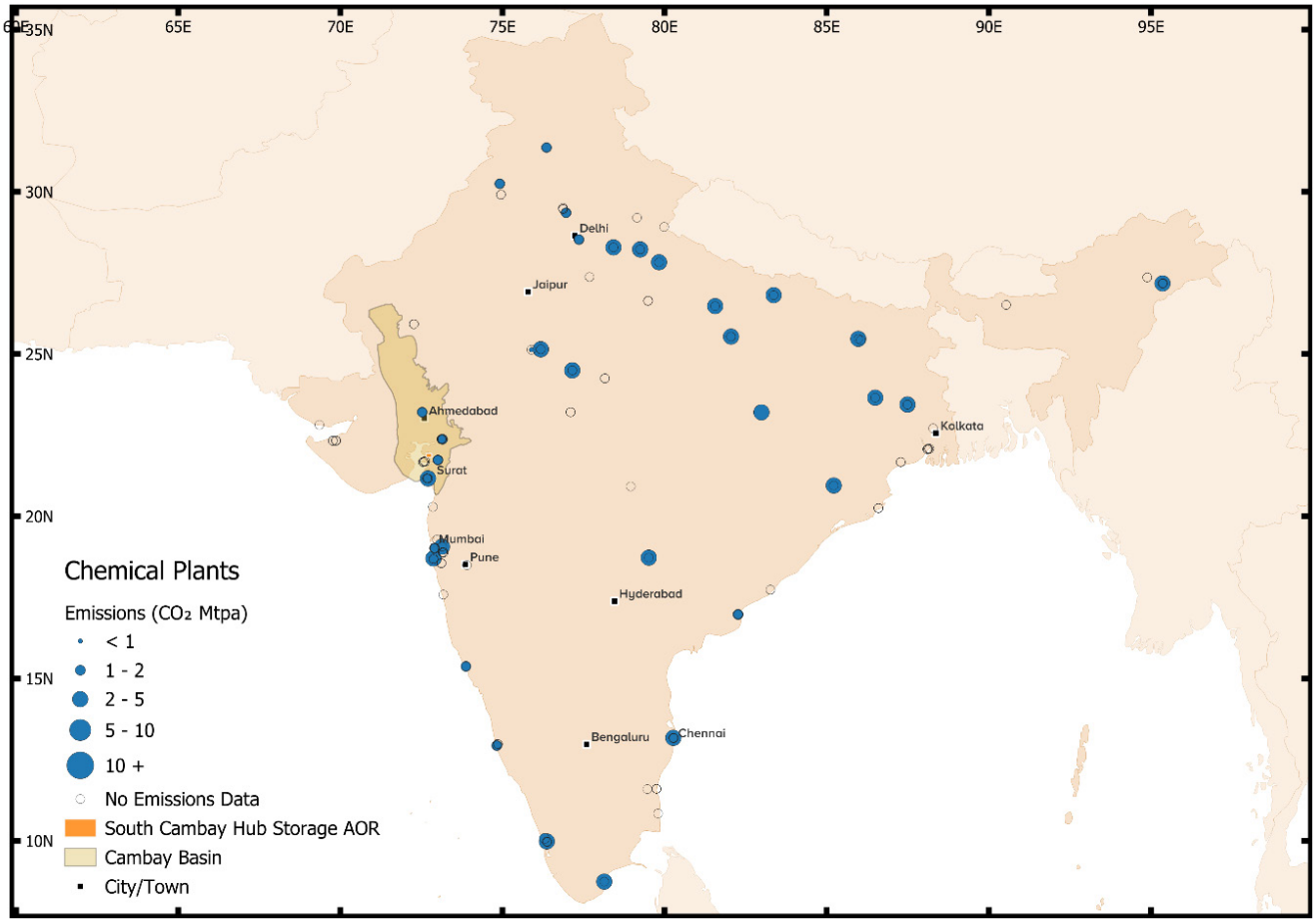


Figure 16. Location of Chemical Plants in India

21. Future Emissions Sources of Note

Future emissions sources were assessed based on known expansions and plant developments within the dataset studied. Generally, databases contained information on announced and known plant capacity expansions, and therefore likely emissions growth, out to 2030. Limited to no data was available beyond 2030, so this is used as the cutoff point for “Future Emissions” considerations.

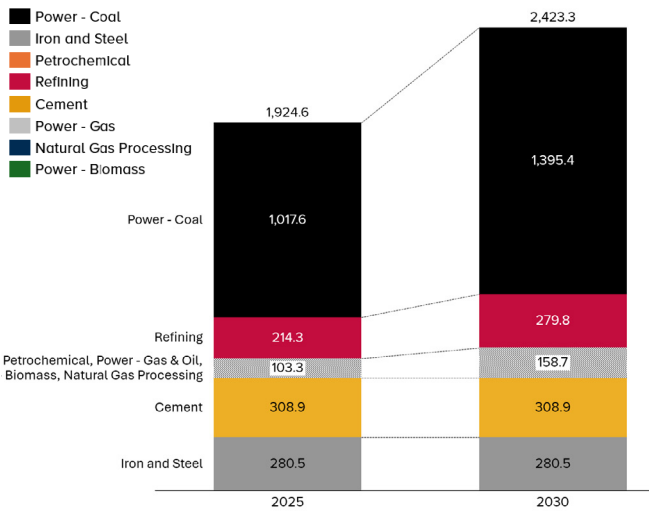


Figure 17. Estimated Emissions Totals for Select Sectors Based on Available Data for Existing (2025) and Future (2030) Sources

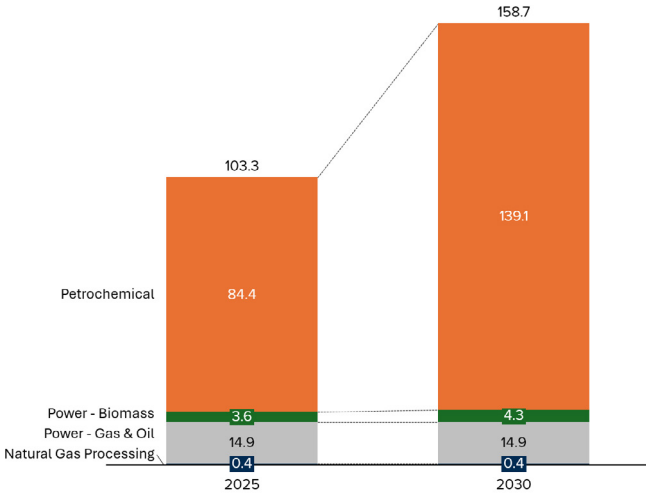


Figure 18. Estimated Emissions Totals for Select Sectors Based on Available Data for Existing (2025) and Future (2030) Sources, with a focus on Petrochemical, Power - Gas and Oil, Power - Biomass, and Natural Gas Processing

Figure 17 and Figure 18 show the identified sectors, the estimated existing total emissions, and the estimated future total emissions. These estimates were based on capacity and operational data for a range of individual plants; however, within each sector are units for which data is unavailable and have not been included in the analysis beyond identification of the area in which they are sited.

Refining capacity, petrochemical production capacity and coal power production capacity are anticipated to increase to 2030, in line with statements and guidance from the central government (Ministry of Power India, 2024; S&P Global, 2025a). The cement and iron & steel sectors have no indicated expansion plans in the data analysed, which aligns with the current gap between capacity and actual production output.

Projects tend to require between 4 and 6 years to move from the start of front-end engineering design to the completion of construction and start-up (International CCS Knowledge Centre, 2024; Worley, 2022). For any projects included in the hub study after Phase 1, the anticipated future emissions as of 2030 have been used to make design assessments.

Future Low-Carbon Hydrogen and Ammonia

A review of the upcoming projects in India was undertaken specifically for low-carbon hydrogen and ammonia, also referred to as “blue” hydrogen and ammonia. These projects refer to hydrogen production processes that use fossil fuels as a part of the manufacturing process and put in place abatement systems to address the CO_2 emissions from either combustion or process CO_2 sources.

A review of green hydrogen and ammonia (using hydrogen produced from renewable power and electrolysis) was not conducted as a part of this study; however, the Indian Government in 2022 approved a “National Green Hydrogen Mission” with several objectives to enhance the development and deployment of green hydrogen (Government of India, 2023).

Only one potential low-carbon hydrogen project was identified, the IOCL Koyali project in Gujarat. The details of this project are outlined in Table 17. No further proposed low-carbon (blue) hydrogen or ammonia sources have been identified from publicly available resources.

Table 17. Low-Carbon Hydrogen and Ammonia Projects in India

Project Name	Status	Proponents	Anticipated Project Capacity	CO_2 Destination	Source
IOCL Koyali	Feasibility	Indian Oil Corporation (IOCL), Oil and Natural Gas Corporation (ONGC), Dastur, Air Liquide and BEG for FEED	700 ktpa	Storage (EOR)	(Burgess, 2021; Business Wire, 2022; Roy, 2022)

22. Existing CCUS Projects in India

India has several CCS projects at the design and pilot stages. These are shown in Table 18. The most advanced CCS project is a study conducted by Dastur Energy, which would take CO_2 from the IOCL Koyali Refinery hydrogen production unit to the ONGC Gandhar Field. Several CCU projects are in operation and development as well.

Table 18. Existing Carbon Capture Projects in India for Either Storage or Utilisation

Project Name	Location	Type	Status	Proponents	Anticipated Project Capacity	CO_2 Destination	Source
IOCL Koyali	Gujarat	Capture	Feasibility	Indian Oil Corporation (IOCL), Oil and Natural Gas Corporation (ONGC), Dastur, Air Liquide and BEG for FEED	700 ktpa	Storage (EOR)	(Burgess, 2021; Business Wire, 2022; Roy, 2022)
Dastur Energy Blue Hydrogen CCS	Undisclosed	Capture	Announced	Dalstur Energy (Kolkata), Coal India (CIL), GTR	Undisclosed	Undisclosed	(The Economic Times, 2022)
Fugro Visakhapatnam	Andhra Pradesh	Full Chain	Feasibility	Fugro, Eco Carbon Engineering Solutions, Visakha Pharma City Limited, Environmental Geotechnology Laboratory	Undisclosed	Undisclosed	(Fugro, 2025)
South Cambay CCS Hub	Gujarat	Transport and Storage	Feasibility	Synergia	43 Mtpa full storage capacity	Undisclosed	(Argus Media, 2023; Synergia Energy, 2023)
IOCL Digboi Refinery	Assam	Full chain	Announced	Indian Oil Corporation, Oil India Limited	Undisclosed	Undisclosed	(Indian Oil, 2020)
JSPL Angul	Odisha	Capture	Announced	Jindal Steel and Power Limited (JSPL)	~1 Mtpa	Utilisation	(S&P Global, 2025b)
Tuticorin Alkali Chemicals and Fertilisers	Tamil Nadu	Capture	Operating	Tuticorin Alkali Chemicals and Fertilisers, Carbon Clean	60 ktpa	Utilisation	(Carbon Clean Solutions Limited, 2016)

Table 19. Existing Pilot and Demonstration Projects for Carbon Capture in India (Source: Gupta et al., 2024)

Project Name	Location	Type	Status	Proponents	Anticipated Project Capacity	CO_2 Destination	Source
TSL Jamshedpur Pilot	Jamshedpur	Capture	Operational	Tata Steel Limited (TSL), Carbon Clean	5 tpd	Utilisation	(Tata Steel, 2021)
HPCL Visakhapatnam CCS	Andhra Pradesh	Capture	Demonstration	Hindustan Petroleum Corporation Limited (HPCL)	24 ktpa	Undisclosed	(Hindustan Petroleum Corporation Limited, 2024)
JSW Vijayanagar	Karnataka	Capture	Announced	Jindal Vijayanagar Steel Limited (JSW), BHP, Carbon Clean	300 tpd	Utilisation	(South East Asia Iron and Steel Institute, 2024)
JSW Salav	Maharashtra	Capture	Announced	Jindal Vijayanagar Steel Limited (JSW), Carbon Clean	100 tpd	Utilisation	(South East Asia Iron and Steel Institute, 2024)
NTPC Vindhyachal	Madhya Pradesh	Capture	Operating	NTPC Energy Technology Research Alliance, Green Power International Pvt. Ltd, Carbon Clean	20 tpd	Utilisation (Methanol)	(Carbon Clean Solutions Limited, 2022; Patel, 2022)

2.3 Emissions Cluster Analysis

Point emission sources can be geographically grouped into regions known as “clusters”. These clusters offer opportunities for shared compression and transport systems, as well as economies of scale opportunities through aggregating CO_2 sources. To this end, emissions clusters were identified and then assessed on a qualitative basis to select one for further cost analysis.

23. Geographic Spread of Sources

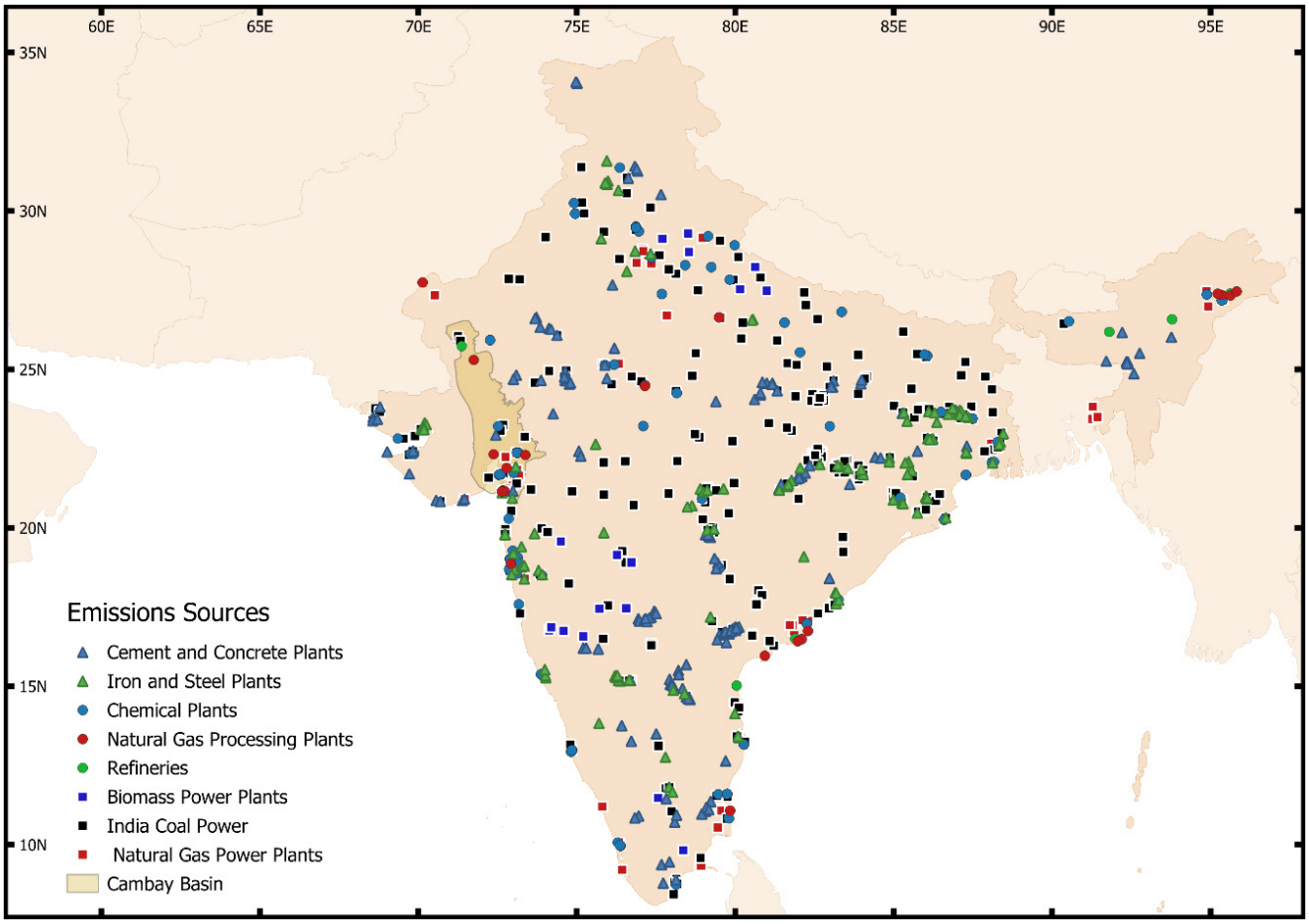


Figure 19. Location of all Identified Emission Sources across India

The emission sources in India of all the industries discussed in Section 2.2 are shown in Figure 19. There are several areas where there are larger numbers of point emission sources present, alongside higher volumes of CO_2.

24. Cluster Method

To understand hub development, various methods are employed to group emissions sources into clusters, each with its own distinct approach and suitability for specific applications. Clustering emissions sources by proximity optimises pipeline deployment, as geographically-close emissions reduce the pipeline infrastructure required.

The clustering method used in this analysis was the advanced DBSCAN (Density-Based Spatial Clustering of Applications with Noise) method, using a clustering algorithm well-suited for spatial data analysis. The DBSCAN algorithm is designed to discover clusters of varying shapes and sizes, and it is especially effective in dealing with noise and outliers in the data. The algorithm requires two parameters: the radius around a data point to search for neighbouring points, which in this study was 50 km, and the minimum number of emission sources for a cluster, which was two.

The results of the clustering method are shown in Figure 20. The clustering method resulted in 31 distinct clusters within the required parameters, which were then qualitatively analysed and ranked for further activities.

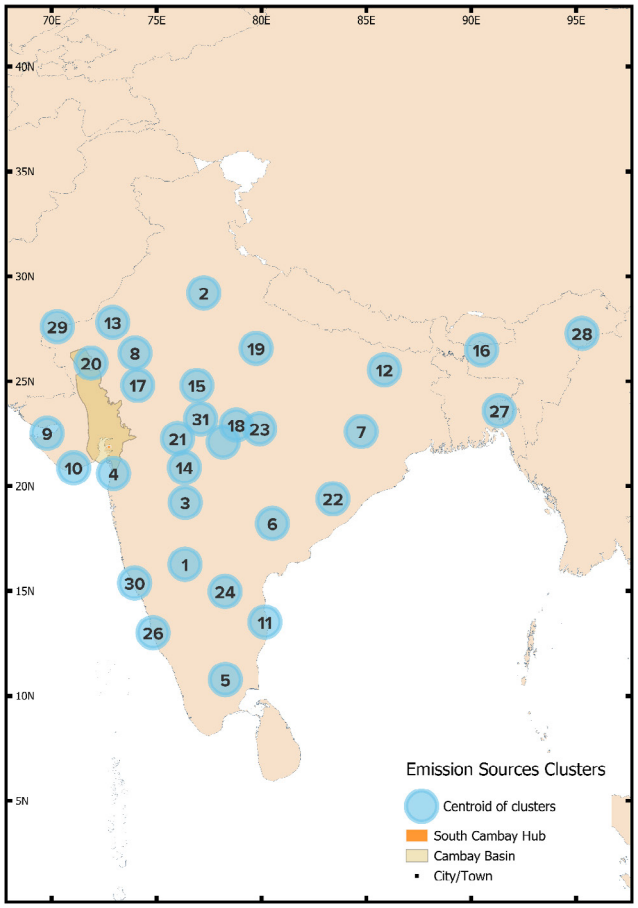


Figure 20. Identified Clusters Across India

25. Cluster Selection for Hub Design

Cluster selection was evaluated based on several factors, outlined below, in a qualitative analysis and ranking to complete the selection for further design.

Table 20 summarises how each of the individual factors was assessed, and then a score between 0, 1, and 2 was attributed.

Table 20. Cluster Selection Property Analysis

Property	Score		
	2	1	0
Distance To Storage	The cluster is less than 100 km from the nearest potential storage site.	The cluster is less than 250 km from the nearest potential storage site.	The cluster is more than 250 km from the nearest potential storage site.
Economies of Scale	The average size of emissions in the cluster is in the top 25% of all clusters assessed.	The average size of emissions in the cluster is in the top 50% of all clusters assessed.	The cluster is outside of the top 50% of clusters.
Current Emissions Size	The cluster is in the top 25% of clusters by current emissions size.	The cluster is in the top 50% of clusters by current emissions size.	The cluster is outside of the top 50% of clusters by current emissions size.
Timing of Emissions Growth	The cluster is in the top 25% of clusters by future emissions size by 2030.	The cluster is in the top 50% of clusters by future emissions size by 2030.	The cluster is outside of the top 50% of clusters by future emissions size by 2030.
Concentrations of Emissions Sources	The cluster has a significant proportion of emission sources in elevated concentration and partial pressure sources.	The cluster has a moderate proportion of emission sources in elevated concentration and partial pressure sources.	The cluster has a limited proportion of emission sources in elevated concentration and partial pressure sources.
Existing Pipeline Infrastructure	Significant pipeline infrastructure exists between likely CO_2 sources and storage locations.	Limited pipeline infrastructure exists between likely CO_2 sources and storage locations.	No existing pipeline structures between likely CO_2 sources and storage locations.
Subsurface Data Availability Regarding the Storage Area of Operations	Significant data is publicly available regarding the subsurface characteristics of the storage area of operations.	Limited data is publicly available regarding the subsurface characteristics of the storage area of operations.	No data is publicly available regarding the subsurface characteristics of the storage area of operations.
Existing CCS Activity in the Local Area	CCS activity is present in the local area.	Limited CCS activity is present in the local area.	No CCS activity is present in the local area.

Property	Score		
	2	1	0
Accessibility	Existing petroleum production facilities and workforces are present in the local cluster region.	A limited number of petroleum production facilities and workforces are present in the local cluster region.	No existing petroleum production facilities and workforces are present in the cluster region.

The parameters are defined as follows:

Distance to Storage: A relative measure of the distance between the closest storage basin and cluster.

Economies of Scale: Emissions Sources within the clusters were assessed to ascertain the scale of CO_2 sources. The ranking was then based on the average size of emissions in the source.

Timing of Emissions Growth: Areas where emissions were expected to grow were prioritised, as new CO_2 transport infrastructure may assist in decarbonising these newbuild facilities with long economic lifetimes ahead. Areas where emissions are expected to reduce due to alternative decarbonisation methods are ranked lower for CCS cluster priority, as alternative methods are already achieving the reductions necessary.

Concentrations of Emissions Sources: An assessment of the concentration and partial pressure of CO_2 within the cluster, generally correlated with the cost to capture from the source. Greater weight was given to clusters that have a higher proportion of emissions from sources such as natural gas processing, petrochemicals, cement, and refineries.

Existing Pipeline Infrastructure: A factor that assesses where new CO_2 pipelines could generally follow existing pipeline infrastructure (oil or natural gas), which can bring benefits such as existing right of ways, known terrain features, and already built access ways. There are no existing CO_2 pipelines in India, so the pipelines considered are solely petroleum and natural gas pipelines.

Data Availability Regarding the Subsurface: Subsurface exploration and data availability remain challenging in several of India's fields. As a result, screening exercises are constrained by the quality and quantity of data available. This parameter accounts for the data availability and how storage resources may be estimated. Further subsurface exploration data becoming available may change these assessments.

Existing CCS Activity or Development: Clusters where CCS activity has been identified were also given additional weighting to account for the existing engagement that has already been undertaken and that could be leveraged for future development. As indicated in Section 2.2 there are no currently active CCS projects in India, though there are several in various stages of development alongside CCU projects.

Accessibility: The development of CO_2 capture, transport, and storage facilities can be significantly accelerated by the availability and accessibility of existing subsurface infrastructure, such as drill pads, and existing skilled workforces in the region. This parameter accounts for existing infrastructure that may assist with the development of CO_2 capture, transport, and storage facilities.

Table 21 outlines the ranking assessment of the top 5 clusters against these properties.

Table 21. Qualitative Ranking System for Hub Selection, showing the Top 5 Clusters

Property	Cluster Number (Region)				
	Cluster #4 (South Cambay Hub, Gulf of Khambhat Eastern Shore)	Cluster #5 (Wider Tamil Nadu)	Cluster #9 (Gujarat, Gulf of Kutch)	Cluster #6 (Andhra Pradesh and Telangana)	Cluster #2 (Delhi and Surrounds)
Distance To Storage	2	1	2	1	2
Economies of Scale	0	0	1	2	0
Current Emissions Size	2	2	2	2	2
Timing of Emissions Growth	2	2	2	2	2
Concentrations of Emissions Sources	2	2	2	2	2
Existing Pipeline Infrastructure	2	2	2	1	2
Subsurface Data Availability Regarding the Storage Area of Operations	2	1	0	0	0
Existing CCS Activity in the Local Area	2	2	0	1	0
Accessibility	2	2	2	0	0
TOTAL (out of 18)	**16**	**14**	**13**	**11**	**11**

From the qualitative cluster ranking, it was indicated that Cluster 4 (South Cambay Hub (SCH); Gulf of Khambhat Eastern Shore) was the most suitable for CCS hub development and was selected for hub design. The primary reasons for this suitability include the proximity to the storage basin, the CO_2 volumes present, and the high concentration of existing CO_2 sources. Additionally, there is availability of suitable data for storage, existing CCS activities, and accessibility from existing petroleum activities.

Nearby Cluster 10 (Gulf of Khambhat Western Shore) was also included after consultation with the client due to the proximity of the emissions to the storage location and the hard-to-abate nature of the cement plants that made up the cluster. Cluster 10 was ranked 20th out of 31 clusters.

2.4 CCS Hub Design

The design of the SCH is completed with emissions sources from the selected clusters.

Cluster 4 – Eastern Shore, Gulf of Khambhat, consisting of petrochemical, natural gas processing, refining, and power plant emissions sources.

Cluster 10 – Western Shore, Gulf of Khambhat, primarily consisting of cement works and a coal-fired power plant.

The storage site was selected as the Gandhar Field, indicated on maps as “South Cambay Hub” or “South Cambay Hub Storage AOR”.

The Hub study and design have been completed as a high-level concept study to inform potential decarbonisation decision-making. As a result, there are uncertainties in the costs of capture and transport associated with each emissions source, both upside and downside. The band of cost uncertainty can be narrowed through further, more detailed engineering evaluation of each facility and the transport network.

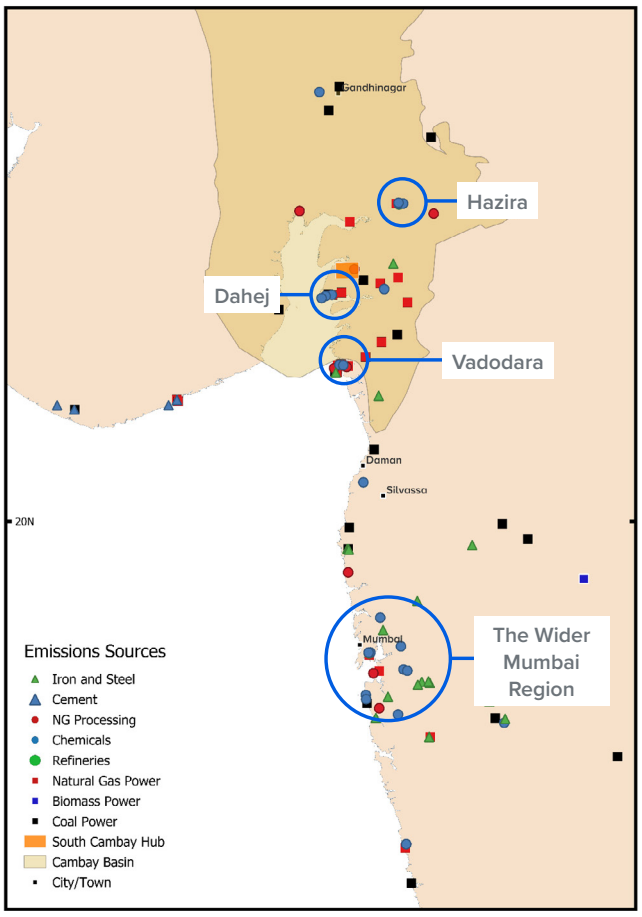
26. Selected Cluster Overview

The entire selected cluster consists of 125 facilities, with the following breakdown. As highlighted in Section 2.2 , this breakdown only includes the specifically identified sectors for CCS, and more point emissions sources will exist within the region that are not captured by this study.

Table 22. Cluster Facility Breakdown

Industry	Number of Facilities	Total Estimated Emissions Today	Total Estimated Emissions at 2030
Power	48	39.9 Mtpa	45.5 Mtpa
Refining	3 Complexes	16.0 Mtpa	16.43 Mtpa
Petrochemicals	22 Complexes 52 Units/Facilities	22.2 Mtpa	25.9 Mtpa
Iron and Steel	10	25.1 Mtpa	25.1 Mtpa
Cement	4	15.8 Mtpa	15.8 Mtpa
Natural Gas Processing	8	0.4 *(Note 1)*	0.4 *(Note 1)*
Total	125	119.3 Mtpa	132.0 Mtpa

Note 1 – As discussed under “Natural Gas Processing” in Section 2.2, only one natural gas processing facility has an emissions estimate; as such, the others are excluded from further analysis.



The emission sources are presented in Figure 21. Within the cluster, there are several key subclusters where emission sources are further concentrated. These sub-clusters include:

- Dahej
- Hazira
- Vadodara
- The Wider Mumbai Region

Figure 21. Overview Point Source Map of Cluster 4 (Gulf of Khambhat, Eastern Shore) and Cluster 10 (Gulf of Khambhat, Western Shore)

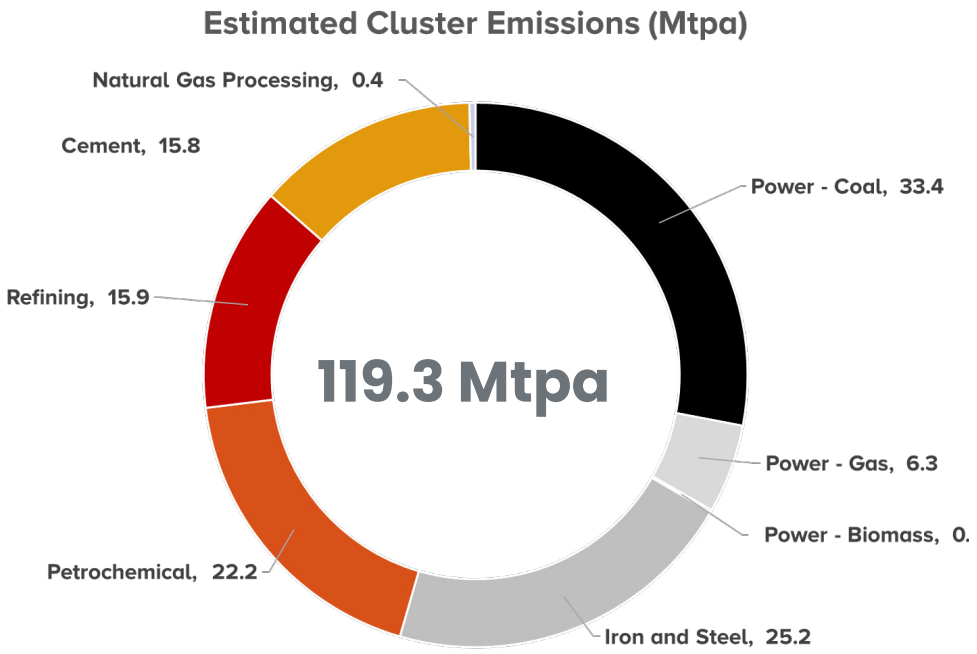


Figure 22. Breakdown of Estimated Existing Emission Sources in the Cluster by Sector

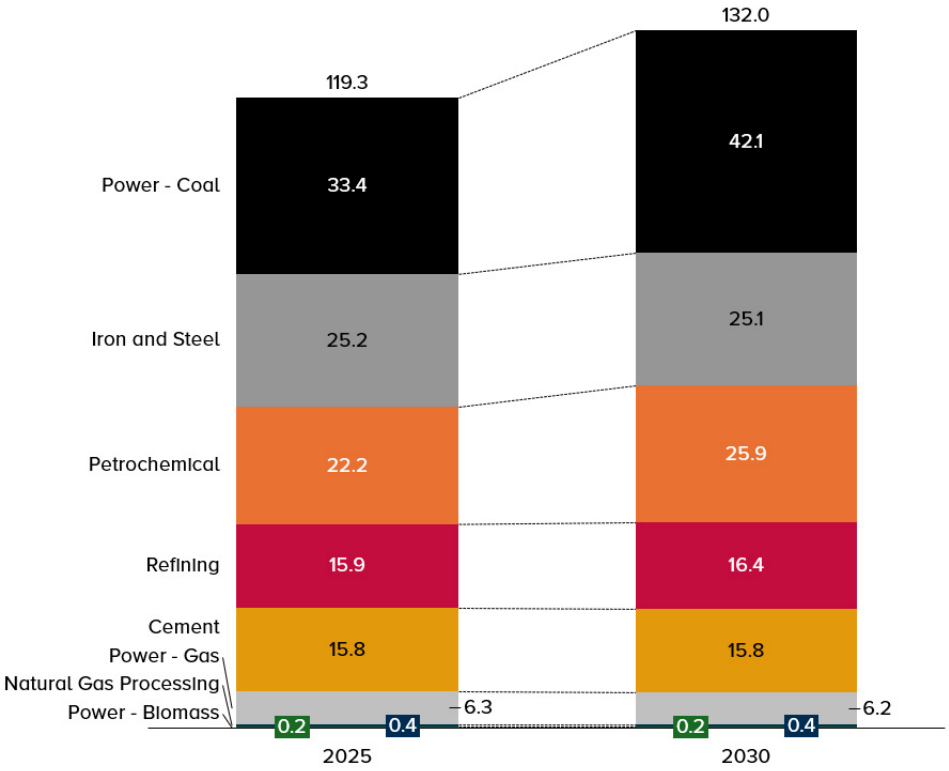


Figure 23. Development of Estimated Existing Emissions and Estimated Future Emissions at 2030 in the Cluster by Sector

The concentrations of the point emission sources considered are shown in Figure 23. This chart is an initial assessment of the possible CO_2 concentrations available, and site testing is required to validate. The concentrations shown are used for screening purposes only and are representative of other CO_2 sources found in each industry.

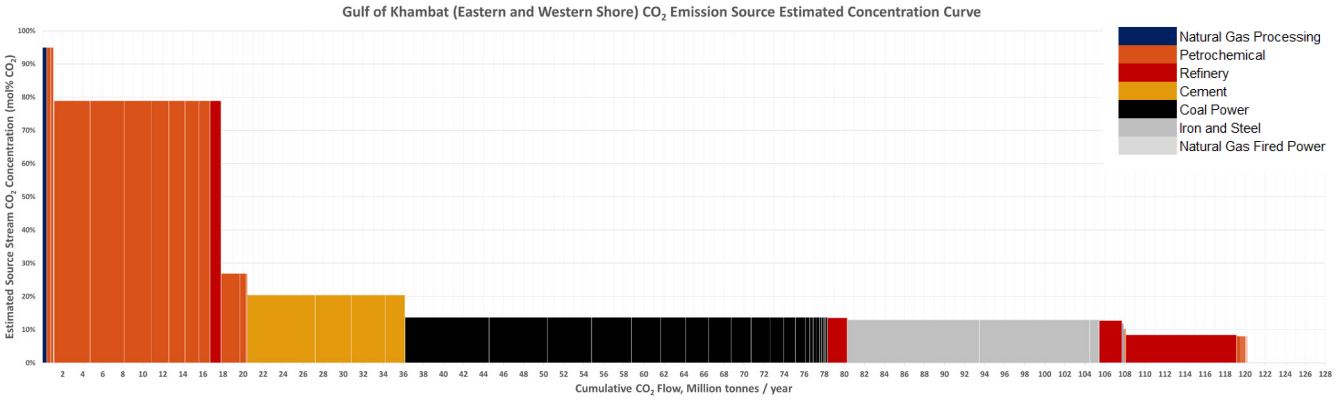
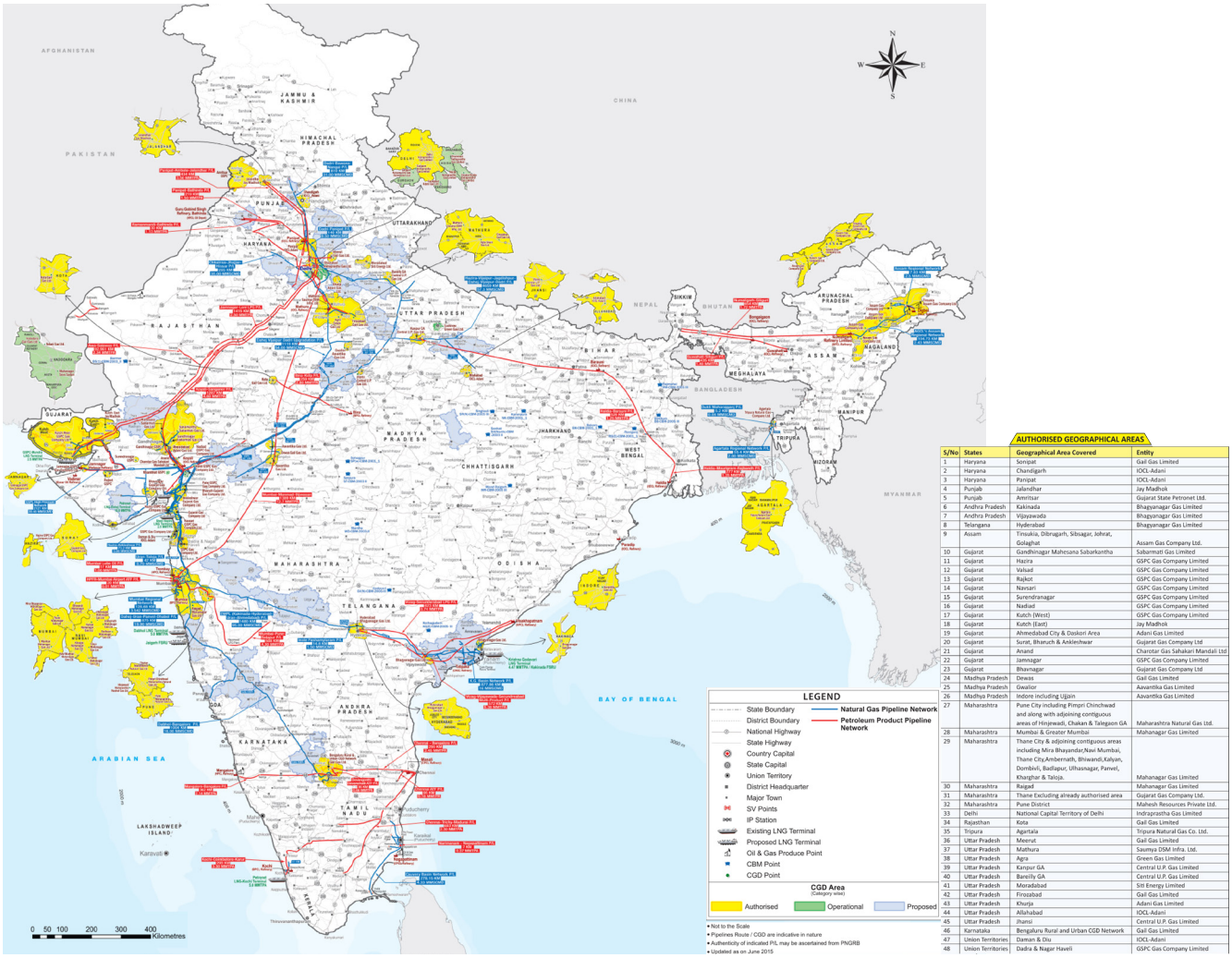


Figure 24. CO_2 concentrations of point emission sources in the Cambay area

27. CCS Hub Design Philosophy, Assumptions, and Constraints

The hub will be designed and implemented in phases to simplify the introduction of several complex engineering tasks, alongside the spreading of CAPEX over multiple years.

CO_2 pipeline pathways were generally routed to follow existing pipeline routes for oil and natural gas. A map of existing oil and gas pipelines can be seen in Figure 25. It is understood from prior engagement that the appetite for CO_2 pipelines is relatively limited due to the challenges of obtaining suitable easements and timelines for approvals. As such, making use of existing pipeline corridors is considered a top priority, and, where possible, these existing corridors have been followed in design.



AUTHORISED GEOGRAPHICAL AREAS

S/No	States	Geographical Area Covered	Entity
1	Haryana	Sonipat	Gail Gas Limited
2	Haryana	Chandigarh	IOCL-Adani
3	Haryana	Panipat	IOCL-Adani
4	Punjab	Jalandhar	Jay Madhok
5	Punjab	Amritsar	Gujarat State Petronet Ltd.
6	Andhra Pradesh	Kakinada	Bhagyanagar Gas Limited
7	Andhra Pradesh	Vijayawada	Bhagyanagar Gas Limited
8	Telangana	Hyderabad	Bhagyanagar Gas Limited
9	Assam	Tinsukia, Dibrugarh, Sibsagar, Johrat, Golaghat	Assam Gas Company Ltd.
10	Gujarat	Gandhinagar Mahesana Sabarkantha	Sabarmati Gas Limited
11	Gujarat	Hazira	GSPC Gas Company Limited
12	Gujarat	Valsad	GSPC Gas Company Limited
13	Gujarat	Rajkot	GSPC Gas Company Limited
14	Gujarat	Navsari	GSPC Gas Company Limited
15	Gujarat	Surendranagar	GSPC Gas Company Limited
16	Gujarat	Nadiad	GSPC Gas Company Limited
17	Gujarat	Kutch (West)	GSPC Gas Company Limited
18	Gujarat	Kutch (East)	Jay Madhok
19	Gujarat	Ahmedabad City & Daskori Area	Adani Gas Limited
20	Gujarat	Surat, Bharuch & Ankleshwar	Gujarat Gas Company Ltd
21	Gujarat	Anand	Charotar Gas Sahakari Mandali Ltd
22	Gujarat	Jamnagar	GSPC Gas Company Limited
23	Gujarat	Bhavnagar	Gujarat Gas Company Ltd
24	Madhya Pradesh	Dewas	Gail Gas Limited
25	Madhya Pradesh	Gwalior	Aavantika Gas Limited
26	Madhya Pradesh	Indore including Ujjain	Aavantika Gas Limited
27	Maharashtra	Pune City including Pimpri Chinchwad and along with adjoining contiguous areas of Hinjewadi, Chakan & Talegaon GA	Maharashtra Natural Gas Ltd.
28	Maharashtra	Mumbai & Greater Mumbai	Mahanagar Gas Limited
29	Maharashtra	Thane City & adjoining contiguous areas including Mira Bhayandar,Navi Mumbai, Thane City,Ambernath, Bhiwandi,Kalyan, Dombivli, Badlapur, Ulhasnagar, Panvel, Kharghar & Taloja.	Mahanagar Gas Limited
30	Maharashtra	Raigad	Mahanagar Gas Limited
31	Maharashtra	Thane Excluding already authorised area	Gujarat Gas Company Ltd.
32	Maharashtra	Pune District	Mahesh Resources Private Ltd.
33	Delhi	National Capital Territory of Delhi	Indraprastha Gas Limited
34	Rajasthan	Kota	Gail Gas Limited
35	Tripura	Agartala	Tripura Natural Gas Co. Ltd.
36	Uttar Pradesh	Meerut	Gail Gas Limited
37	Uttar Pradesh	Mathura	Saumya DSM Infra. Ltd.
38	Uttar Pradesh	Agra	Green Gas Limited
39	Uttar Pradesh	Kanpur GA	Central U.P. Gas Limited
40	Uttar Pradesh	Bareilly GA	Central U.P. Gas Limited
41	Uttar Pradesh	Moradabad	Sti Energy Limited
42	Uttar Pradesh	Firozabad	Gail Gas Limited
43	Uttar Pradesh	Khurja	Adani Gas Limited
44	Uttar Pradesh	Allahabad	IOCL-Adani
45	Uttar Pradesh	Jhansi	Central U.P. Gas Limited
46	Karnataka	Bengaluru Rural and Urban CGD Network	Gail Gas Limited
47	Union Territories	Daman & Diu	IOCL-Adani
48	Union Territories	Dadra & Nagar Haveli	GSPC Gas Company Limited

Figure 25. Map of City Gas Distribution, Petroleum Pipeline, and Natural Gas Pipeline Networks in India as of 2015 (Latest Version) (Petroleum and Natural Gas Regulatory Board of India, 2015)

Source Selection and Prioritisation

With the selected cluster, there is an estimated potential of more than 110 Mtpa of CO_2 emissions that could be addressed. According to the storage estimates for the selected site, a total of 341 Mt of CO_2 is estimated to be able to be stored over a 20-year lifetime in the chosen site, equating to 17 Mtpa. Balancing between the available CO_2 and the storage capabilities represents a more sustainable commercial and supply model compared with the maximum potential CO_2 addressable.

In this case, there is an oversupply of available CO_2 compared with storage resources. As such, the CO_2 sources selected would need to be prioritised to account for concentration (which aligns with indicative cost), distance from the storage complex, and the overall size of the emissions source. A qualitative assessment of further considerations, such as feasibility and technology readiness, overall mitigation potential, alternative decarbonisation options, and proximity to likely CO_2 transmission pipelines, is a necessary part of the decision process.

In the United States, the Kleinman Center for Energy Policy has developed a "US CCS Ladder for Industrial Decarbonisation" to assist with prioritisation (Pisciotta et al., 2024). This ladder lays out the role of CCS in specific industrial processes, and where CCS likely should be prioritised as a key decarbonisation lever to have the greatest impact, according to the Kleinman Center. Figure 26 shows the prioritisation laid out by the Kleinman Center for Energy Policy. As these are specifically related to heavy industry only, the ladder has been adapted in Table 23 to include further industries not mentioned in this ladder (including coal and natural gas-fired power generation). Facilities with higher concentrations and partial pressures of CO_2 or industries that are considered "hard-to-abate" due to inherent production emissions tend to be ranked towards the higher priority category ("A") such as cement, lime, ammonia, hydrogen, and ethylene oxide. These facilities are more likely to achieve commercial CCS and CCU operations first, and therefore will likely be critical for the development of CCS hubs.

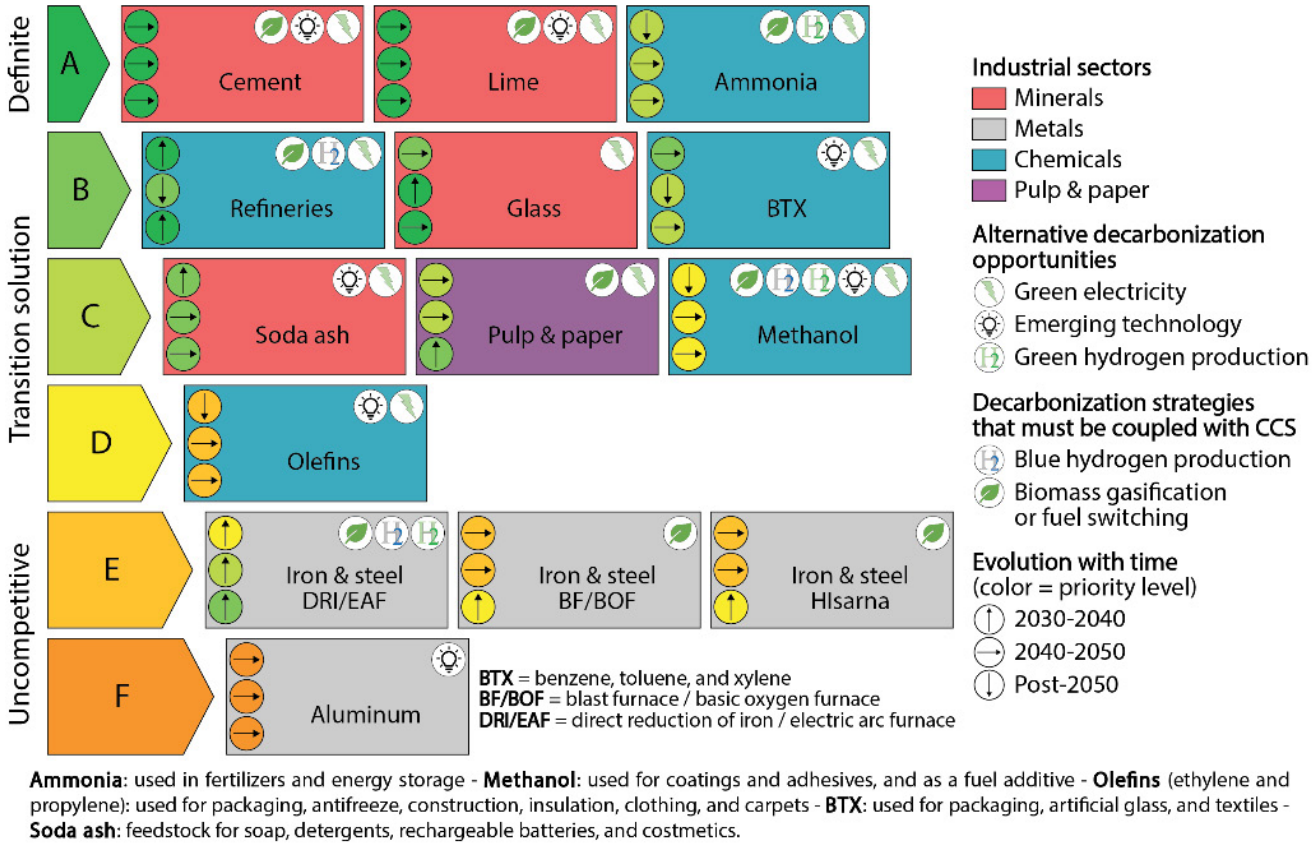


Figure 26. CCS Ladder from the Kleinman Center for Energy Policy (Pisciotta et al., 2024)

Table 23. CCS Ladder for Decarbonisation Prioritisation for This Study

Category	Industries				
A	Cement	Lime	Ammonia	Hydrogen	Ethylene Oxide
B	Refineries	Glass	BTX	PTA	Natural Gas Processing
C	Soda Ash	Pulp and Paper	Methanol	Natural Gas-Fired Power	
D	Olefins	Coal-Fired Power			

In this study, all sources within the cluster were first ranked based on the concentration of the source, the size of the source, and the partial pressure of the source. The rankings in each category were summed, and the emissions sources with the lowest total score were identified as priority sources for consideration.

These priority sources were then further examined for proximity to likely CO_2 transmission pipelines, existing CCS activities, and against the ladder shown in Table 23. The sources were then selected to achieve a total captured CO_2 volume in line with the 17 Mtpa constraint from storage conditions, with the chosen sources identified in Table 24.

Table 24. CO_2 Sources for the Phased Hub Design

CO_2 Source	Location	Size, Mtpa (2030 Size)	Qualitative Ranking	Ladder Tier
Reliance Industries Dahej Purified Terephthalic Acid (PTA) Plant 1, 2, 3	Dahej	1.9	1	B
Gujarat Narmada Valley Fertilizers & Chemicals Bharuch Ammonia & Urea Plant	Bharuch	1.4	2	A
IOCL Koyali Refinery	Vadodara	3.1	3	B
Gujarat State Fertilizers & Chemicals Vadodara Ammonia & Urea Plant 1 & 2	Vadodara	1.8	4	A
KRIBHCO Hazira Ammonia & Urea Plant 1 & 2	Hazira	3.6	5	A
Reliance Industries Dahej Ethylene Oxide Plant 1 & 2	Dahej	0.3	7	A
Bhavnagar Power Station	Western Gulf of Khambhat	1.2	8	D
UltraTech Cement Ltd - Gujarat Cement Works	Western Gulf of Khambhat	3.2	13	A
Hazira Natural Gas Processing Plant	Hazira	0.4	20	C
UltraTech Cement Ltd-Amreli	Western Gulf of Khambhat	1.2	28	A
DGEN Mega Combined Cycle power plant	Dahej	0.2	46	C
Total		**17 Mtpa**		

*In this study, only a partial amount of the total estimated CO_2 is captured from these plants, due to the storage constraints. For UltraTech Cement Ltd - Gujarat Cement Works, the total estimated CO_2 source size is 6.4 Mtpa, and for UltraTech Cement Ltd-Amreli, the total estimated CO_2 source size is 2.0 Mtpa.

28. Phase Design

PHASE 1

In Phase 1, two primary sources of CO_2 would be addressed from the Vadodara subcluster. These would be the IOCL Koyali Hydrogen production and Gujarat State Fertilisers and Chemicals Vadodara.

These two sources have been chosen as the primary sources for Phase 1:

1. IOCL Koyali has already expressed an interest in CCUS, completing a feasibility study with Dastur Energy in 2022 to capture and transport CO_2 to a Gandhar field for enhanced oil recovery (Business Wire, 2022; Roy, 2022).

2. Gujarat State Fertiliser and Chemicals Vadodara Ammonia and Urea Plant is a proximal high concentration source of CO_2 from the ammonia production process near IOCL Koyali.

As such, the first phase of this Hub would leverage existing relationships and work completed at IOCL Koyali by IOCL and ONGC, and further make use of the high concentration, relatively low cost of capture source nearby to the IOCL facility.

These sources were also chosen in place of the relatively nearer CO_2 sources at Dahej due to the following reasons:

1. The sources in IOCL Koyali and Gujarat State Fertiliser and Chemicals Vadodara have relatively larger point CO_2 sources by volume (Mtpa).

2. The sources in IOCL Koyali and Gujarat State Fertiliser and Chemicals Vadodara have relatively higher point CO_2 concentrations (mol%).

3. There is yet to be any publicly announced CO_2 capture activity from CO_2 sources in the Dahej area.

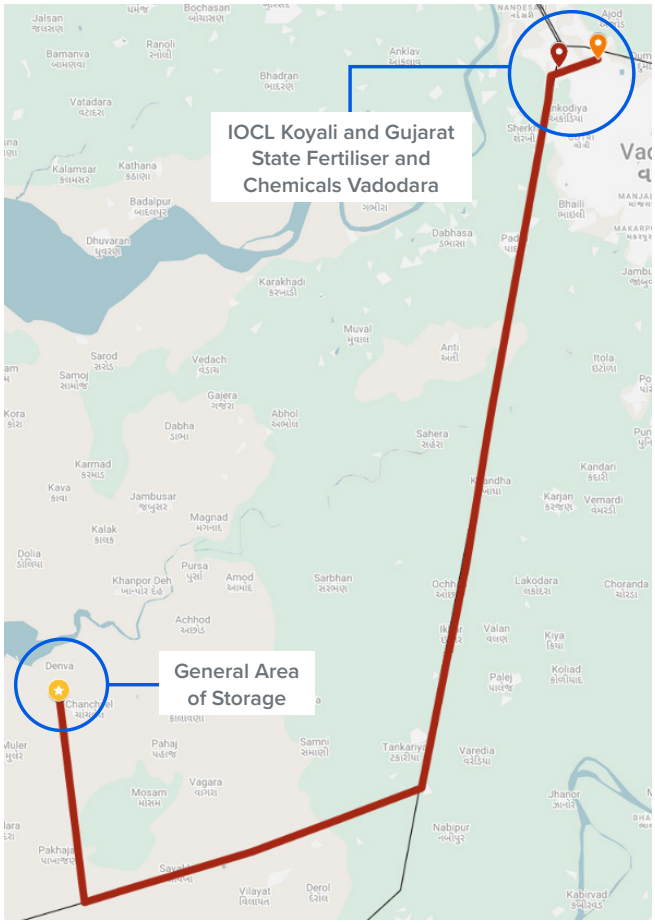


Figure 27. Map of CO_2 Emission Sources and Pipelines as of Phase 1, following existing petroleum and gas pipelines (thin black lines)

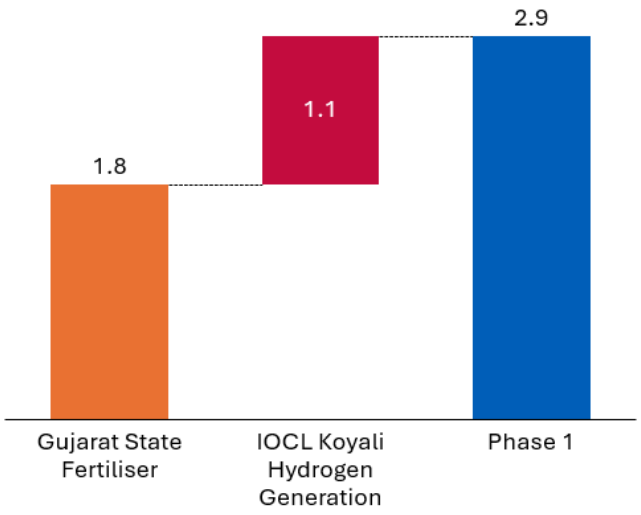


Figure 28. Waterfall Chart of the Emissions in Phase 1

PHASE 2

Phase 2 involves addressing several CO_2 sources around the eastern shore of the Gulf of Khambhat. There are two primary subclusters of note: Dahej and Hazira.

In the Dahej subcluster, the primary source of CO_2 is the Reliance Industries Dahej Ethylene Oxide facilities and the PTA production facilities. Additionally, the DGEN Power Station is located adjacent to the CO_2 trunk line that would transport CO_2 between the Reliance Dahej facility and the storage site. To act to decarbonise part of India's power sector, this source has been included in the modelling.

In the Hazira subcluster, the primary sources of CO_2 are the KRIBHCO Hazira Ammonia and Urea plant and the Hazira Natural Gas Processing Facility. The CO_2 pipeline also passes near the Gujarat Naramda Valley Fertilisers and Chemicals plant in Bharuch, where a tie-in can be placed to decarbonise this CO_2 production.

Phase 2 additionally includes CO_2 capture from the rest of the IOCL Koyali refinery, addressing the remaining emissions from the FCC, furnaces, and utility systems.

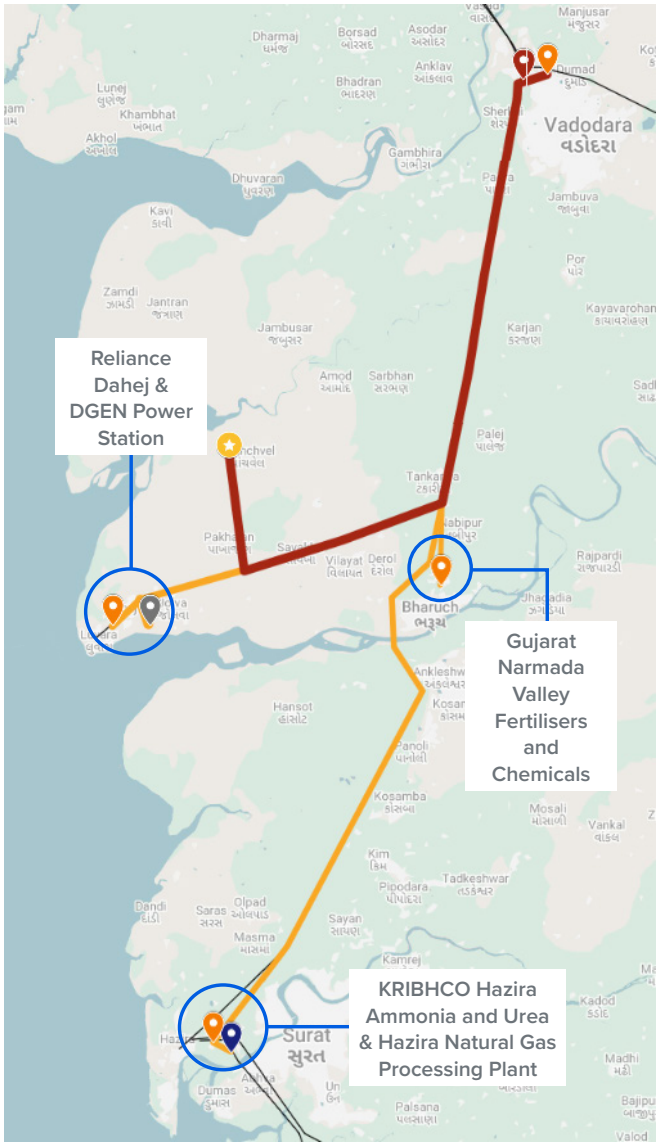


Figure 29. Map of CO_2 Emission Sources and Pipelines as of Phase 2, integrating the Dahej and Hazira subclusters, following existing petroleum and gas pipelines

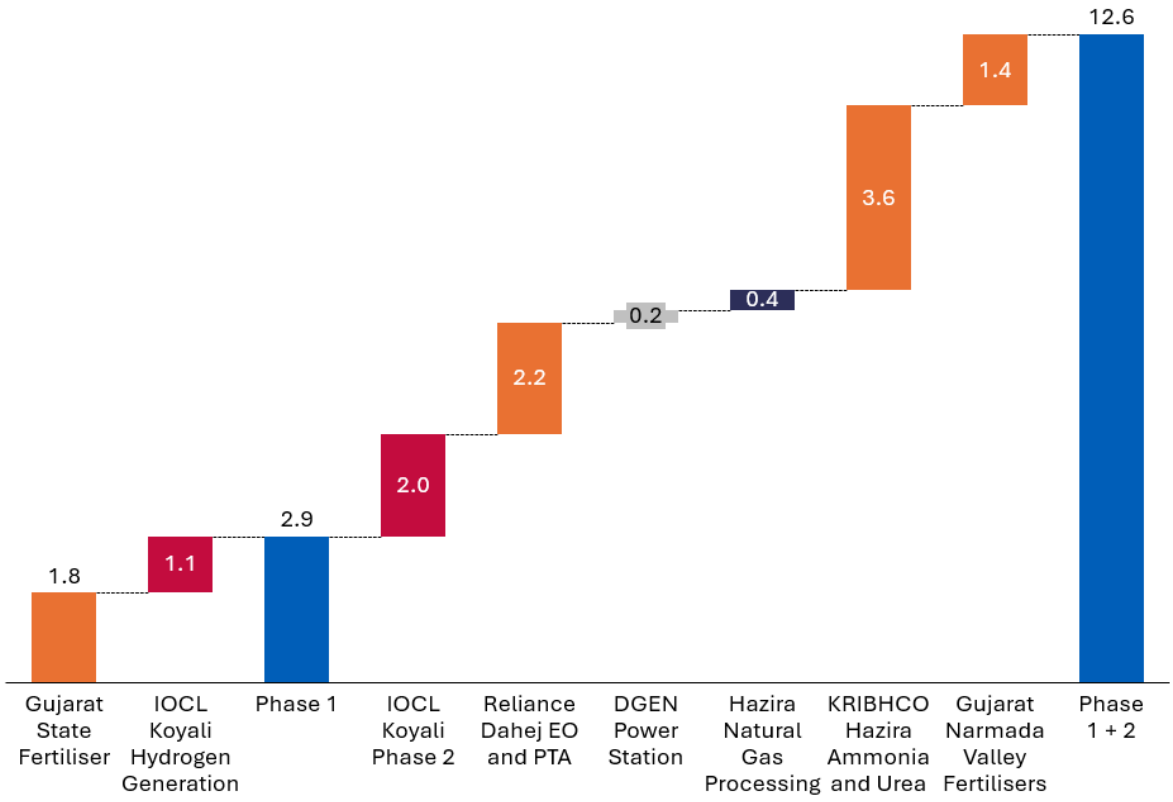


Figure 30. Waterfall Chart of Emissions Sources in Phase 2

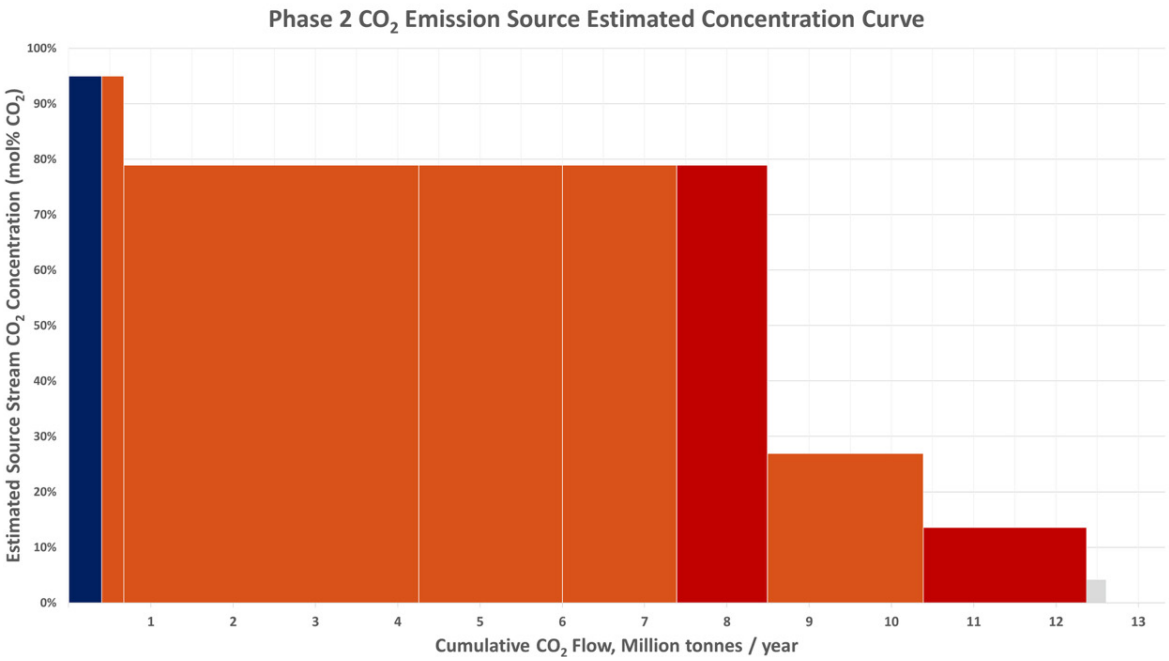


Figure 31. Estimated Concentration Curve for Cluster Phase 2 CO_2 Emission Sources

Additional CO_2 volumes are present in both Dahej and Hazira, which could be addressed by CCS if greater storage capacity were available. From the emissions source assessment, an additional 2.1 Mtpa could be captured at Dahej from primarily petrochemical sources, while 18.4 Mtpa could be captured at Hazira from petrochemical, iron and steel, and power emissions sources.

PHASE 3

Phase 3 involves addressing nearby cement facilities to the west of the Gulf of Khambhat. This is primarily for the Ultratech Gujarat Cement Works and Amreli facilities. On the pathway to the identified storage facility, the CO_2 pipeline passes close to the Bhavnagar Power Station, which is also included for the same reasons as the DGEN Power Station – the decarbonisation of on-route power sources.

In this phase, the CO_2 that can be addressed is constrained by the achievable storage injection rates. As such, only the process emissions related to the calcination process of lime into limestone are addressed, generally equivalent to between 60 to 65% of the total CO_2 emissions of a cement plant (Global Cement and Concrete Association, 2024). At Ultratech Amreli, all of these process emissions are targeted; however, only 80% of these process emissions are to be addressed at Ultratech Gujarat Cement Works.

The pipeline is also routed to cross the Gulf of Khambhat, from the Bhavnagar Power Station to the Dahej Tie-in Facility. This crossing makes use of the existing pipeline in place for the Dahej subcluster, and avoids an additional 200 km to follow the existing oil and gas pipelines routed to the north of the Gulf of Khambhat.

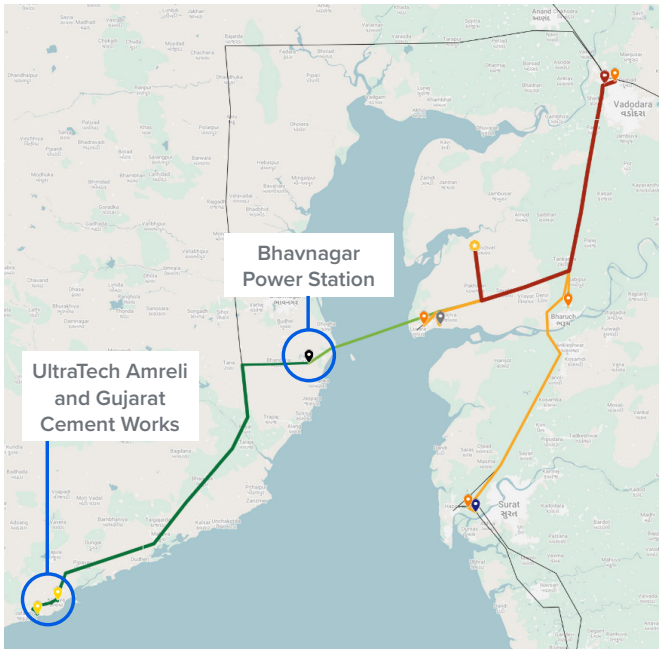


Figure 32. Map of CO_2 Emission Sources and Pipelines as of Phase 3, following existing petroleum and gas pipelines

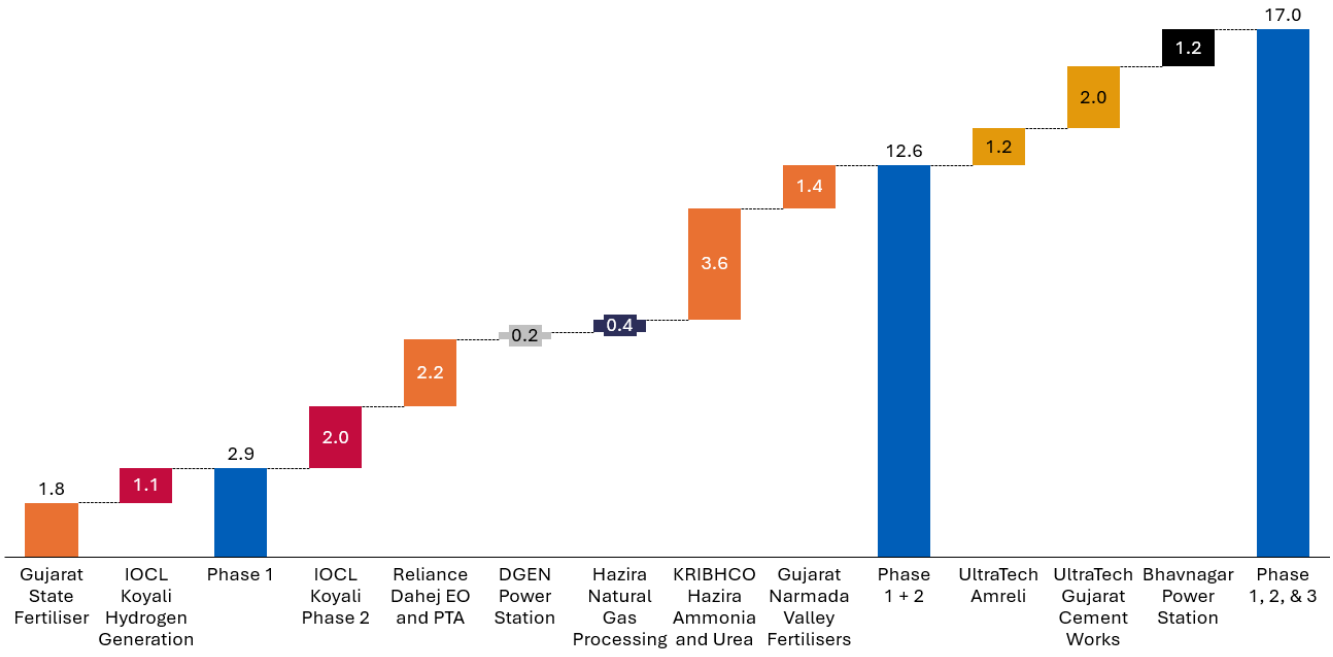


Figure 33. Waterfall Chart of Emissions Sources in Phase 3

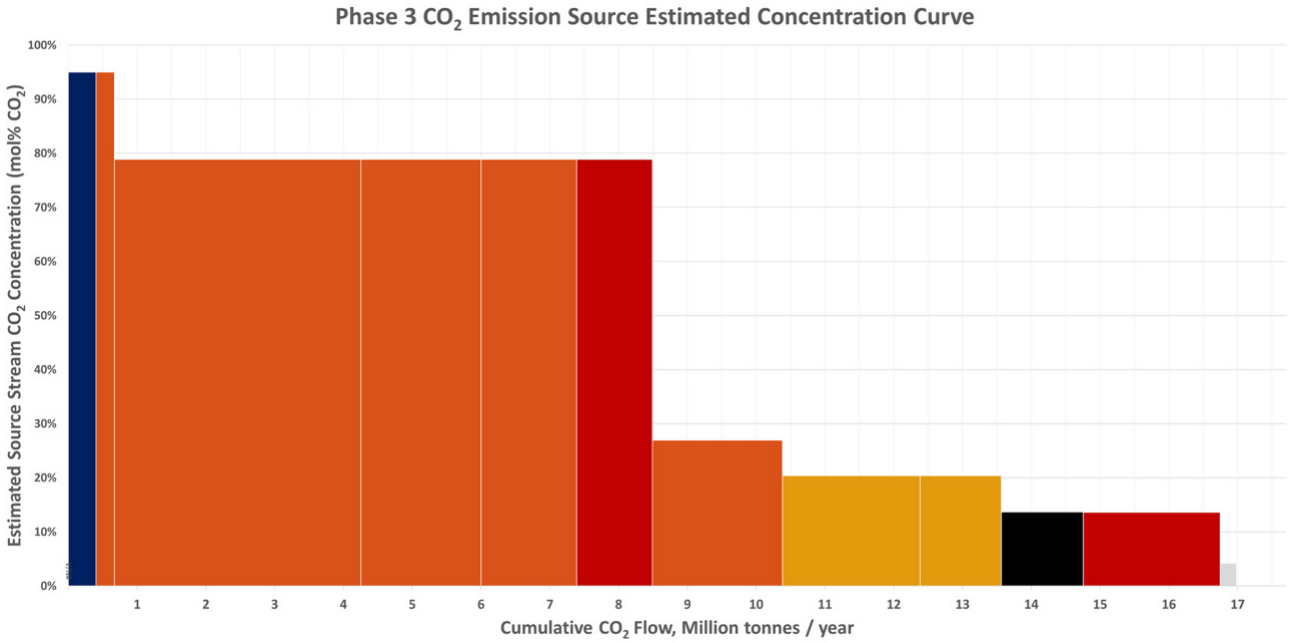


Figure 34. Estimated Concentration Curve for Cluster Phase 3 CO_2 Emission Sources

Additional CO_2 volumes are present along the western shoreline of the Gulf of Khambhat. The remaining emissions from the two cement plants captured are estimated at approximately 5.6 Mtpa, which is not planned to be captured due to the storage injection limits. Two additional cement plants, Ambuja Cements Ltd Gir Somnath and Gujarat Sidhee Cement, sit further west than Gujarat Cement Works and Ultratech Amreli, with an estimated CO_2 emissions volume of approximately 7 Mtpa, and some additional power plants that are estimated to potentially contribute another 0.5 Mtpa. These may be integrated into the hub network at a later date, provided that storage capacity can be increased.

2.5 CCS Hub Cost Analysis

The estimated costing for the identified CCS hub in US$ per tonne of CO_2 is presented below in a high-level, top-down manner for capture, compression, pumping, pipelines, and injection well.

29. Cost Assumptions and Model Parameters

As a part of the costing model used, utility pricing from the local region is included. Cost assumptions are shown in Table 25.

Table 25. Utility Cost Assumptions

	Utilities Pricing	Source
Power	$122/MWh	(GPP, 2025) (June 2025)
Natural Gas	US$6.99/ MMBTU	(MoP&NG, 2025) (June 2025)

All costs in this report were adjusted for cost inflation using the local Producer Price Index (PPI) and adjusted for location using Richardson location factors (Cost Data On Line, 2025).

Capital costs were annualised using a capital recovery factor (CRF) of 9.88%, based on a weighted-average cost of capital (i) of 7.6% and project life (n) of 20 years. The formula for CRF is given in Equation 2.

Equation 2. Capital Recovery Factor Formula

$$\mathrm{CRF} = \frac{\mathrm{i}((1+\mathrm{i})^{\mathrm{n}})}{(1+\mathrm{i})^{\mathrm{n}}-1}$$

CAPTURE COSTS

Capture costs for each source are estimated at the $/tonne level based on literature assessments for each sector, with decreasing estimates as the scale of the source of CO_2 rises. The relevant costs for the cluster are visualised in Figure 35 and presented in Table 26.

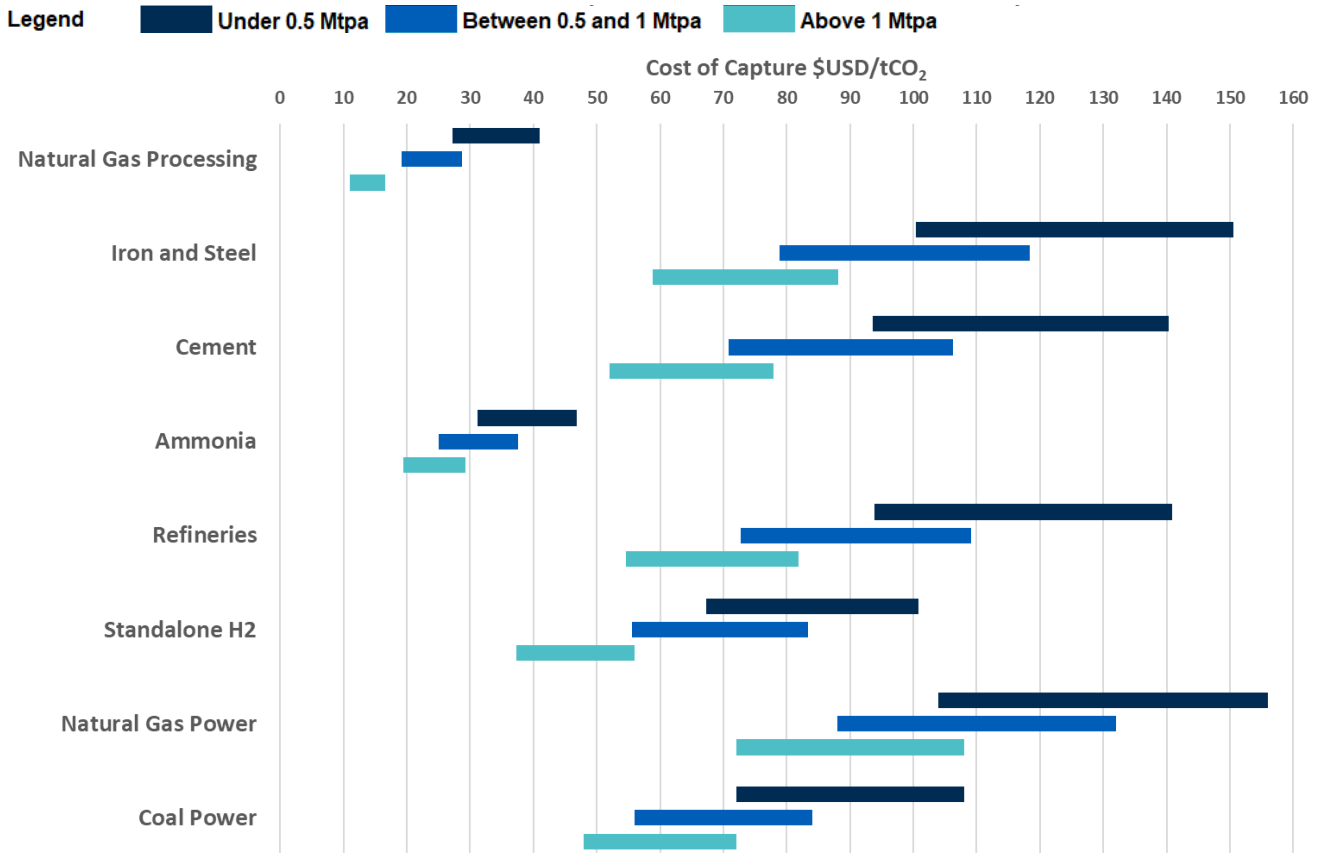


Figure 35. Rules of Thumb: Costs of Capture Across Industries Based on Joint Research Centre European Commission (2024); GCCSI (2025)

Table 26. Cost of Capture Values Used in this Analysis, based on the literature (Source: Joint Research Centre European Commission, 2024; GCCSI, 2025)

Capture Source Type	Cost of Capture ($US/tonne CO_2)		
	Under 0.5 Mtpa	Between 0.5 and 1 Mtpa	Above 1 Mtpa
Ammonia Production	31 – 47	25 – 38	19 – 29
Cement	94 – 140	71 – 106	52 – 78
Coal Power Generation	72 – 108	56 – 84	48 - 72
Hydrogen Production	67 – 101	56 – 83	37 – 86
Natural Gas-Fired Power Generation	104 – 156	88 – 132	72 – 108
Natural Gas Processing	27 – 41	19 – 29	11 – 17
Refineries	94 – 141	71 – 106	52 – 78

TRANSPORT COSTS

Pipeline

The pipeline system was modelled within Aspen HYSYS. All pipe is carbon steel. For each successive phase of the pipeline network, a separate model was run. These separate models represent the realistic pressure changes in the pipeline network as newer sections are added and the CO_2 flows through each pipeline network expansion. These pressures were used to estimate the pressure required from each capture plant's compression and pumping system. It was also to confirm the pipe sizing was adequate, without excessive pressure drop.

- Pipeline sizing was based on simple velocity criteria, which is appropriate for initial studies of this kind. The maximum flow velocity used is 20 m/s for gas and 2 m/s for liquid/dense/supercritical CO_2 for all phases (Peletiri et al., 2018; Sinnott & Towler, 2022). The next standard diameter size above that determined by maximum velocity was selected.

- Heat exchange from the pipeline to the surrounding ambient conditions was included in the model, alongside elevation and wall thickness effects.

- Steel ASME B36.10M Schedule 160 pipe was selected for supercritical service. Pipe schedule sets the wall thickness for pipe, as well as the mass of pipe per metre of length surface area (for paint cost). Schedules were selected for sufficient Maximum Available Working Pressure (MAWP) for the service in question.

- The basis for estimating pipeline cost was this set of component costs as described by Core Energy Group (2015). These are summarised in Table 27.

Table 27. Pipeline Cost Components (Source: Core Energy Group, 2015)

Economic Variables	Costs in AUD (2015)
Steel pipe	$2,500/tonne
Coating	$45/m^2
Construction	$30,000/inch-km
Other (includes insurance, engineering, legal costs)	15%
Contingency	10%
Offshore Pipe Cost Factor	200%

Compression and Pumping

Each captured CO_2 stream must be compressed to dense phase conditions before entering the pipeline network. The assumed system to do this for each facility is:

- Centrifugal compressor to bring CO_2 to the critical pressure of 73.8 bar.
- Aftercooler reduces CO_2 temperature following each compression stage.
- Knockout pots remove liquid water that condenses after each stage.
- Remaining water vapour is removed after the third compression stage.
- The final step uses a pump to boost dense phase CO_2 to the required pressure to enter the pipeline network. This pressure is determined by backpressure calculations in HYSYS, with the CO_2 arriving at the delivery point at 100 bar.

The cost of CO_2 compressors and pumps was estimated using formulae in McCollum and Ogden (McCollum & Ogden, 2006). The cost of compressors and pumps for each CO_2 source stream was included in the analysis. However, spur lines (from capture plant to CO_2 compressor and from compressor to trunk line) were not included in the costing where the distance was less than 1 km, and are assumed to be included within the existing costs of capture value.

30. Cost Results

The CO_2 network is structured as a three-phase development. Costs are presented on a per-phase basis. Transport costs shown for each phase represent incremental capital and operating expenditures incurred during that phase only, excluding costs from earlier phases. Aggregate transport costs for the full network build-out are presented separately.

As a phased development, the incremental costs (capital and operating) incurred in each phase are of interest. As such, spending in previous phase(s) is not included in the summaries below.

CAPTURE COSTS

As the network develops with additional phases, capture costs are not expected to decline, as there would be no change to the capture facility itself. If the capture facility is expanding in a new phase, however, there may be a reduction in costs due to the increased size of the facility or the use of pre-existing systems. Based on the cost ranges outlined in Table 26, the following capture cost breakdown emerges:

Phase 1

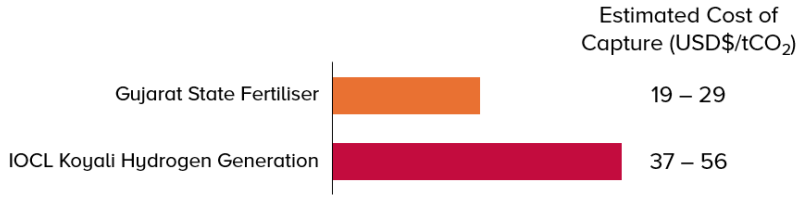


Figure 53 - Estimated Cost of Capture for Sources in Phase 1

In Phase 1, the hydrogen production sources of Gujarat State Fertiliser and IOCL Koyali are integrated into the network. Gujarat State Fertiliser is an ammonia plant, and must remove practically all CO_2 as a part of the production process, while IOCL Koyali has a somewhat more dilute stream, hence the difference in costs.

Phase 2

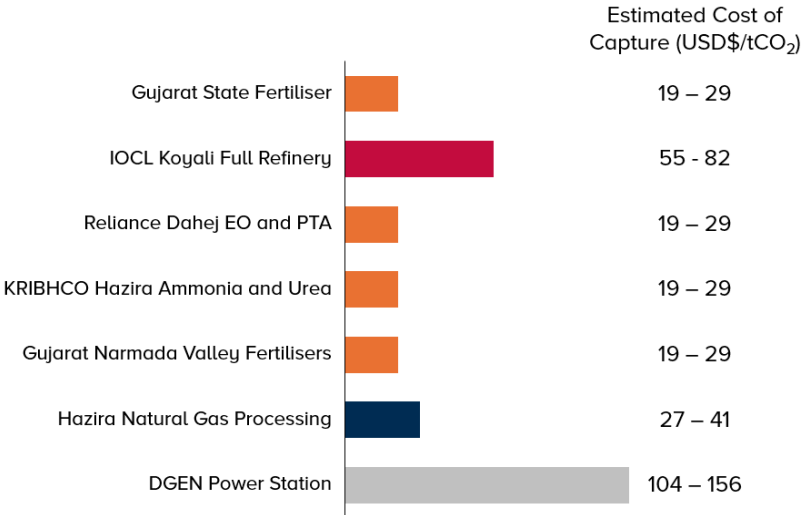


Figure 54 - Estimated Cost of Capture for Sources in Phase 2

In Phase 2, the selected sources from Dahej, Hazira, and the remaining sources from the refinery are integrated. CCS at IOCL Koyali expands to address the full refinery emissions, resulting in costs that are higher, as additional, more dilute streams from across the refinery are addressed.

Phase 3

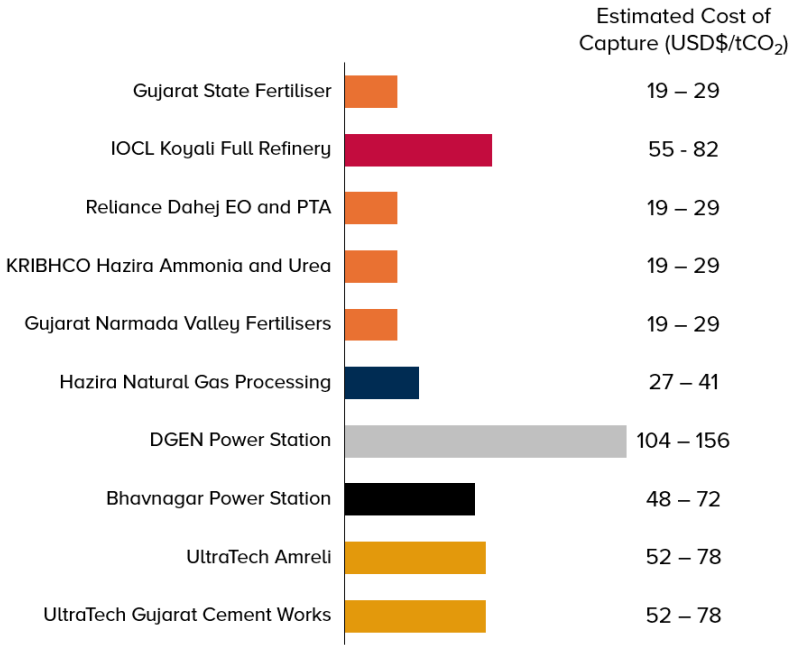


Figure 55 - Estimated Cost of Capture for Sources in Phase 3

In Phase 3, the sources from the western shore of the Gulf of Khambhat are added, including two cement plants (partial capture of all CO_2 available) and a coal power plant en route to the South Cambay hub storage site.

TRANSPORT COSTS

Compression Costs for Each Point Source

CO_2 from each capture plant needs to be boosted to dense phase pressures for pipeline transport. This requires a compression system and pump as described in Section 2.2. Compression costs for point sources are summarised in Table 28.

Compression cost is dominated by energy OPEX in all cases. As compression energy scales linearly with flow rate, the estimated midpoint cost of compression is within a relatively narrow range for all sources, regardless of scale ($12.9-$18.1 per tonne).

The CO_2 transport network consists of pipeline segments and a CO_2 injection pumping facility at the storage site. As the project progresses through each phase, the volumes of CO_2 being stored rise from 2.85 Mtpa (Phase 1), 12.62 Mtpa (Phase 1 and 2), up to 17.0 Mtpa (Phase 1, 2 and 3). The pumping facility would be expanded with additional pumps in each phase to provide the necessary capacity, and energy consumption for the pumps rises accordingly.

Table 28. Estimated Point Source CO_2 Compression Costs

Point source	CO_2 Flowrate	Phase	CAPEX	Annualised Capital Costs	Energy OPEX	Other OPEX	Total Annualised Compression Costs	Estimated Midpoint Cost of CO_2 Avoided
	Mtpa		MM$	MM$/year	MM$/year	MM$/year	MM$/year	$/tCO$_2$
Gujarat State Ferilisters	1.8	1	36.5	3.1	21.9	1.5	26.5	15.1
IOCL Koyali (Phase 1 and 2)	3.1	1 & 2	49.3	4.2	38.6	2.0	44.8	14.5
Reliance Dahej PTA and EO	2.2	2	35.6	3.1	23.5	1.4	28.0	12.9
DGEN Power Station	0.2	2	13.9	1.2	2.6	0.6	4.3	18.1
Hazira Natural Gas Processing	0.4	2	17.3	1.5	4.4	0.7	6.6	16.5
KRIBHCO	3.6	2	73.5	6.3	44.4	2.9	53.7	15.0
Gujarat Narmada Valley Fertilisers and Chemicals	1.4	2	29.9	2.6	15.5	1.2	19.3	13.9
UltraTech Amreli	1.2	3	30.7	2.6	15.2	1.2	19.1	16.2
Ultratech Gujarat Cement Works	2.0	3	40.4	3.5	25.9	1.6	31.0	15.4
Bhavnagar Power Station	1.2	3	28.7	2.5	13.9	1.2	17.5	14.7

Pipeline Costs For the Network

The pipeline system was developed and designed with the philosophies outlined in Section 27 and Section 29. The pipeline routes and their sizes are shown in Figure 35. The rollout of the pipeline network is summarised in Table 29. Each segment was sized for the maximum flow expected over the full project life cycle, which meant that, in early phases, some pipelines were significantly larger than needed at the point of first use. This pre-investment is necessary to avoid having to unnecessarily duplicate capacity in later phases.

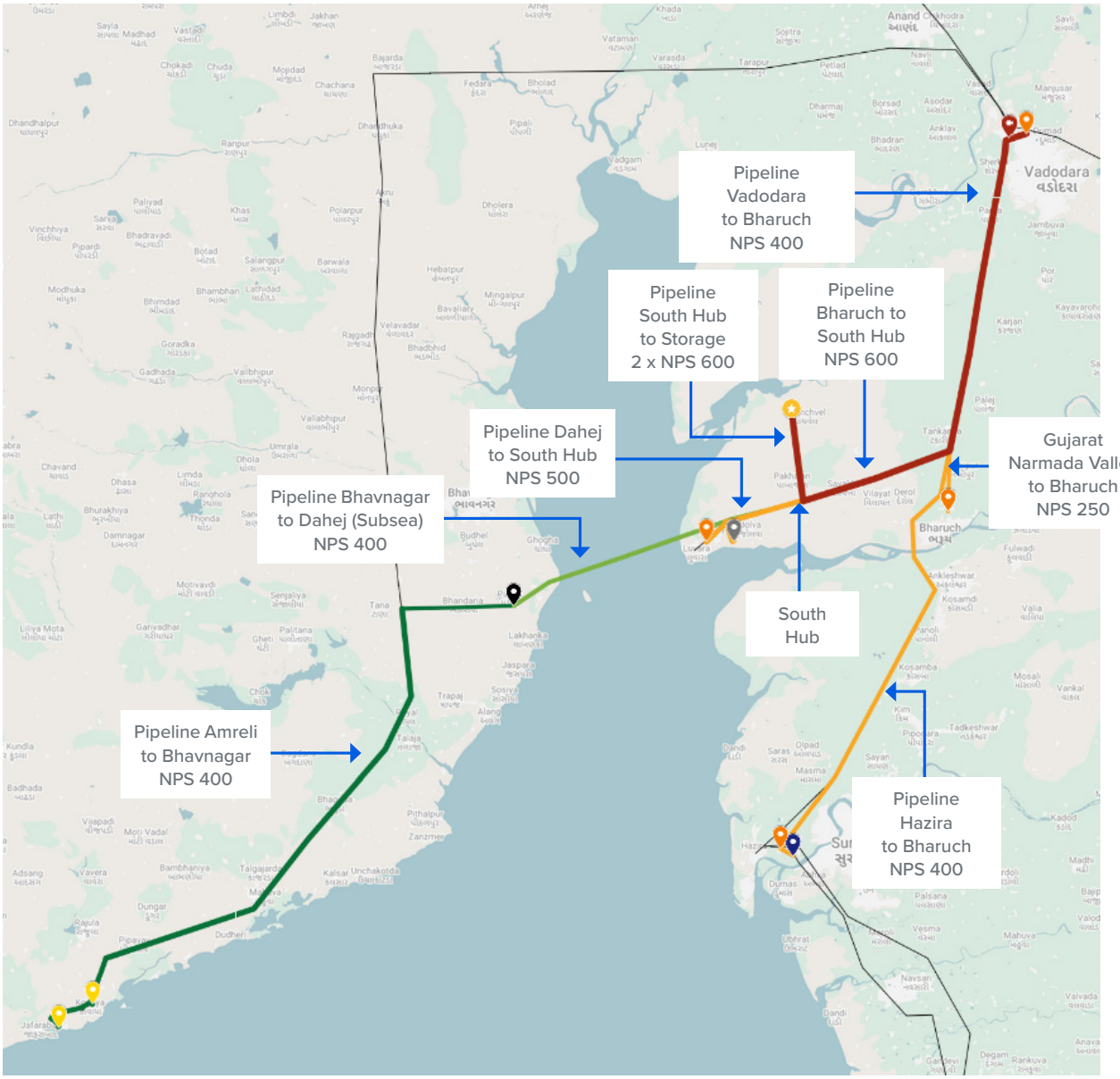


Figure 36. Pipeline Network with Pipe Identification and Sizing

Table 29. Pipeline Segments by Stage. Bold figures are newbuilds in each stage

	Phase 1				Phase 1 & 2				Phase 1, 2 & 3			
Pipeline Network Segment	**Flow (Mtpa)**	**# of pipelines**	**DN (mm)**	**Length (km)**	**Flow (Mtpa)**	**# of pipelines**	**DN (mm)**	**Length (km)**	**Flow (Mtpa)**	**# of pipelines**	**DN (mm)**	**Length (km)**
Pipe Vadodara to Bharuch	2.9	1	400	60	4.8	1	400	60	4.8	1	400	60
Pipe Bharuch to South Hub	2.9	1	600	29	10.2	1	600	29	10.2	1	600	29
Pipe South Hub to Storage	2.9	1	600	18	12.6	2*	600	18	17.0	2	600	18
Pipe Dahej to South Hub					2.4	1	500	86	6.8	1	500	86
Pipe Hazira to Bharuch					4.0	1	400	86	4.0	1	400	86
Pipe Amreli to Bhavnagar									3.2	1	400	126
Pipe Bhavnagar to Dahej									4.4	1	400	43

* South Hub to Storage pipeline is duplicated in Phase 2 (i.e. one DN600 pipeline is built in Phase 1, a second is built in parallel in Phase 2 to accommodate the additional CO_2 from the local source).

Pipe network costs were estimated for each pipeline segment and for the CO_2 injection pump at the storage site. The flow and cost results for each phase have been presented as incremental, both for flow (i.e. how much additional flow is seen in each phase) and cost (over and above spend in previous phases). These are summarised in Table 30. Overall ("TOTAL") pipeline costs to the end of Phase 3 are summarised in Table 33.

Table 30. Incremental Flows and Pipeline Network Costs for Each Phase of the Project

Pipeline network costs	Phase 1						Phase 2						Phase 3					
Flows and costs represent incremental flow/spend from that phase only	Flow	Capex	Annualised Capex	Opex	Total Annualised Segment Costs	Cost of CO_2 Transport	Flow	Capex	Annualised Capex	Opex	Total Annualised Segment Costs	Cost of CO_2 Transport	Flow	Capex	Annualised Capex	Opex	Total Annualised Segment Costs	Cost of CO_2 Transport
	Mtpa	$MM	MM$/ year	MM$/ year	MM$/ year	$/t$CO_2$	Mtpa	$MM	MM$/ year	MM$/ year	MM$/ year	$/t$CO_2$	Mtpa	$MM	MM$/ year	MM$/ year	MM$/ year	$/t$CO_2$
Pipe Vadodara to Bahruch	2.9	132.1	13.1	1.3	14.4	5.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pipe Bahruch to Southhub	2.9	123.1	12.2	1.2	13.4	4.7	7.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pipe Southhub to Storage	2.9	74.3	7.3	0.7	8.1	2.8	9.8	74.3	7.3	0.7	8.1	0.8	4.4	0.0	0.0	0.0	0.0	0.0
Pipe Dahej to Southhub							2.4	270.4	26.7	2.7	29.4	12.2	4.4	0.0	0.0	0.0	0.0	0.0
Pipe Hazira to Bahruch							4.0	189.4	18.7	1.9	20.6	5.2	0.0	0.0	0.0	0.0	0.0	0.0
Pipe Amreli to Bhavnagar													3.2	277.5	27.4	2.8	30.2	9.5
Pipe Bhavnagar to Dahej													4.4	189.4	18.7	1.9	20.6	4.7
Storage injection pump	2.9	4.0	0.4	2.6	3.0	1.0	9.8	14.2	1.4	9.4	10.8	1.1	4.4	5.3	0.5	3.5	4.0	0.9
TOTAL	**2.9**	**333.5**	**33.0**	**5.9**	**38.8**	**13.6**	**9.8**	**548.2**	**54.2**	**14.8**	**68.9**	**7.1**	**4.4**	**472.2**	**46.7**	**8.2**	**54.9**	**12.5**

*In Table 30, the incremental costs for the pipelines are presented. As the Phases progress, existing pipelines that do not get duplicated (such as South Hub to Storage in Phase 2) see no new spending. Additional flow through pipelines also does not result in increases in spending, as the additional energy expended to increase flow (and therefore additional cost) is accounted for in Table 28 and in Table 31 through Table 33.

Table 31. Overall Transport Project Costs at the End of Phase 1

Overall Project Costs at the End of Phase 1	Flow	CAPEX	Annualised CAPEX	OPEX	Total Annualised Segment Costs	Cost of CO_2 Transported
	Mtpa	$MM	MM$/year	MM$/year	MM$/year	$/tCO$_2$
Source Compression	2.9	85.9	8.5	63.9	72.4	25.4
Pipelines	2.9	329.5	32.6	3.3	35.9	12.6
Delivery Pump	2.9	4.0	0.4	2.6	3.0	1.0
TOTAL	2.9	419.3	41.4	69.8	111.3	39.0

Table 32. Overall Transport Project Costs at the End of Phase 2

Overall Project Costs at the End of Phase 2	Flow	CAPEX	Annualised CAPEX	OPEX	Total Annualised Segment Costs	Cost of CO_2 Transported
	Mtpa	$MM	MM$/year	MM$/year	MM$/year	$/tCO$_2$
Source Compression	12.6	256.0	25.3	151.0	176.3	14.0
Pipelines	12.6	863.5	85.4	113.5	198.9	15.8
Delivery Pump	12.6	18.2	1.8	1.0	2.8	0.2
TOTAL	12.6	1,137.7	112.4	265.5	378.0	30.0

Table 33. Overall Transport Project Costs at the End of Phase 3

Overall Project Costs at the End of Phase 3	Flow	CAPEX	Annualised CAPEX	OPEX	Total Annualised Segment Costs	Cost of CO_2 Transported
	Mtpa	$MM	MM$/year	MM$/year	MM$/year	$/tCO$_2$
Source Compression	17.0	355.7	35.2	220.3	255.5	15.0
Pipelines	17.0	1,330.4	131.5	13.3	144.8	8.5
Delivery Pump	17.0	23.5	2.3	15.5	17.8	1.0
TOTAL	17.0	1,709.6	169.0	249.1	418.1	24.6

In Phases 1 and 2, a reduction in the levelised cost of transport and injection is indicated as the buildout of CO_2 pipelines makes use of existing pipeline infrastructure in the network, alongside expanding the network to make better use of economies of scale. In Phase 3, as entirely new CO_2 pipeline infrastructure is

built on the Western Shore of the Gulf of Khambhat, the levelised cost for the pipeline network increases, but the increased volumes of CO_2 result in further economies of scale, reducing the overall levelised cost of transport outlined in Table 36 through to Table 38. Further hard-to-abate sources of cement production CO_2 exist further west of the end of the Phase 3 trunkline, which could be considered in future analyses if storage capacity estimates increase.

The overall final midpoint levelised cost for the source compression and pipelines to the storage site is estimated at US$24.6, with a likely range of US$19.7 to US$29.5. Nearly two-thirds of this cost is source compression at the inlet points of the network.

31. Overall Hub Cost of Capture and Transport

The overall hub costs of capture and transport are presented in Figure 37, Figure 38 and Figure 39.

Phase 1

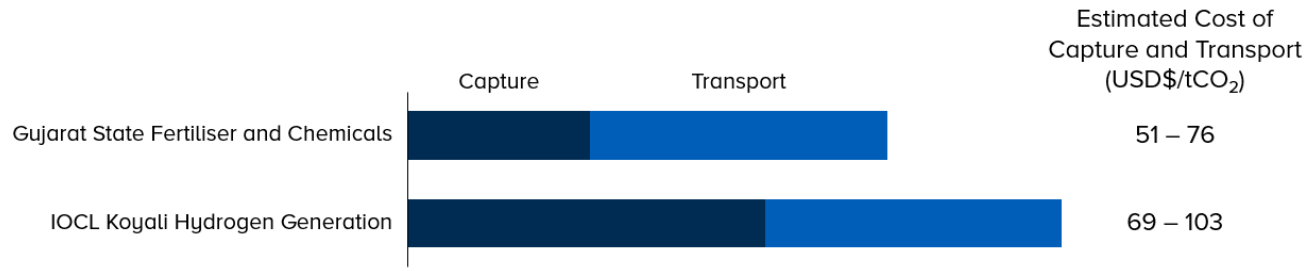


Figure 37. Estimated Cost of Capture and Transport for Phase 1

In Phase 1, the relatively smaller volumes of CO_2 result in transport being a larger proportion of the overall costs to capture and transport CO_2.

Phase 2

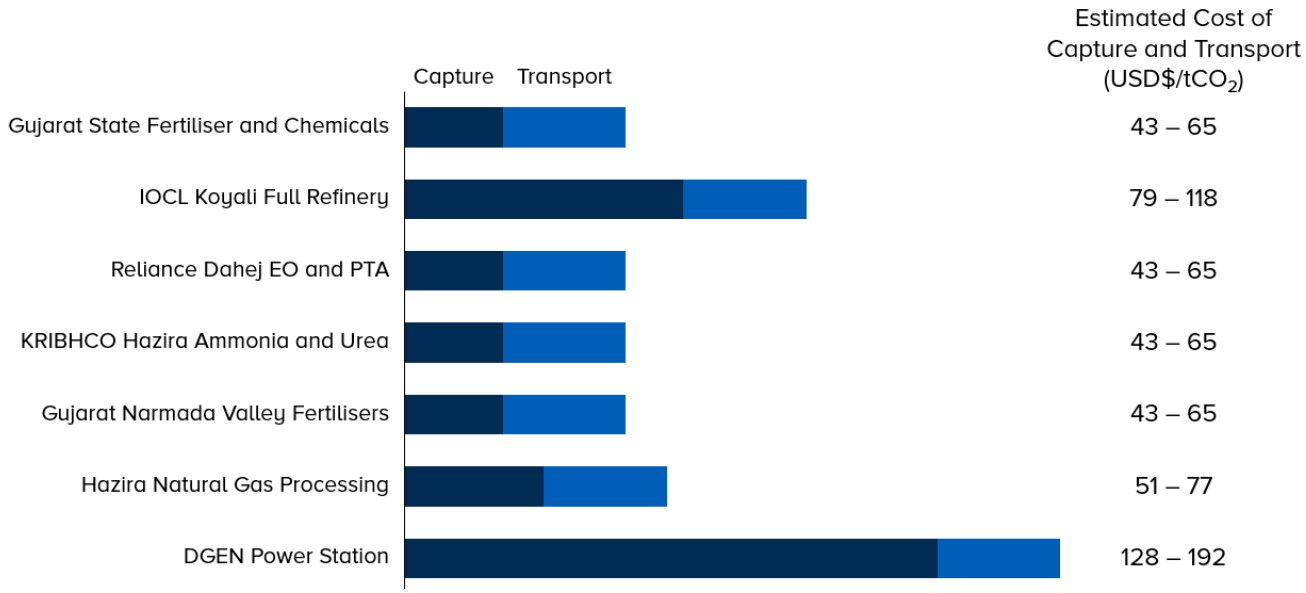


Figure 38. Estimated Cost of Capture and Transport for Phase 2

In Phase 2, integrating the Dahej, Hazira, and remaining Vadodara sources enables economies of scale that bring down the costs of capture and transport for some of the Phase 1 sources; however, the addressing of more sources from IOCL and the resultant increase in cost of capture outweigh the impact at this stage. The higher concentration and pressure sources of ammonia and natural gas processing introduce further lower-cost and effective abatement opportunities. DGEN Power Station, as a smaller natural gas power emission source, shows the impact of lower pressure, lower concentration, and smaller-sized impacts on costs. The proximity of the emissions source to the pipeline is the primary reason for inclusion.

Phase 3

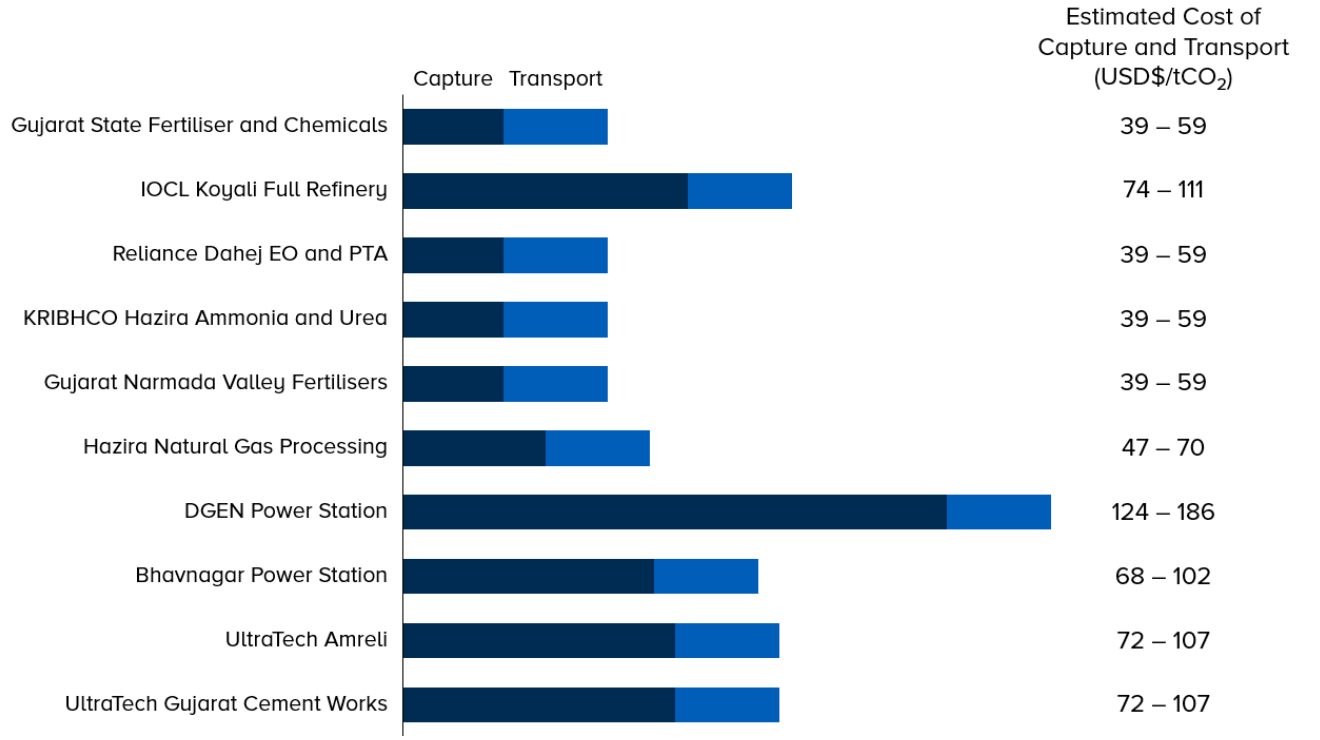


Figure 39. Estimated Costs of Capture and Transport for Phase 3

In Phase 3, the final added sources from the western shore of the Gulf of Khambhat, two cement plants and a coal power plant, make up the remainder of the capacity of CO_2 that can be stored in the storage facility. As with Phase 2, transport costs for sources that were integrated in earlier phases are further reduced with enhanced economies of scale, reducing the overall estimated cost of capture and transport.

The overall levelised cost for capture and transport of CO_2 to the storage site is estimated to be in the range of US$39 to US$59 on the low end, to US$124 to US$186 on the high end, though that high range is for a smaller, low concentration and low pressure source. The rest of the sources within the cluster have estimated costs of capture and transport that fall between US$39 and US$111, depending on the source characteristics.

03

CO_2 Storage and Infrastructure Review

Photo: Adobe Stock

3. CO_2 Storage and Infrastructure Review

3.1 Key Messages

The Southern Cambay Hub appears, based on this screening analysis, to be a potential first-of-a-kind CO_2 storage opportunity for further assessment in the Ankleshwar Formation storage complex with 341 $MtCO_2$ theoretical storage resources at costs of US$1.4-87.5 per tonne of CO_2. The wide cost range reflects uncertainty in key reservoir properties, which strongly influences the number of injection wells required to achieve the target rates in each hub development phase. Reducing this uncertainty through improved data availability and targeted appraisal would help narrow cost estimates and accelerate investment decisions. India needs large-scale CO_2 storage for industrial decarbonisation, and the Southern Cambay Hub is one of the country's most technically and economically viable early opportunities.

Storage Site Selection

The Ankleshwar Formation storage complex (Eocene Hazad Member reservoir and Kanwa Shale regional seal) is one of the most suitable amongst Indian storage prospects due to its proven reservoir-seal system, onshore location, extensive existing data from over 500 wells, suitable depth of 1.0-1.5 km, established infrastructure, clear permitting pathway, and accessibility. The economics of an onshore location reduce costs by up to 50% compared to offshore alternatives, while existing petroleum operations provide social licence and infrastructure foundation.

Resource and Injectivity Estimates

Storage resources: 341 $MtCO_2$ (P50 estimate), ranging from 180-585 $MtCO_2$ across stacked sand reservoirs, enabling an injection rate of up to 0.1-1.5 Mtpa, depending on reservoir quality, requiring 12-171 wells for full development. The injection strategy involves migration-assisted trapping, with initial injection on the flanks of the Gandhar structure, followed by migration towards the Gandhar Oil Field.

The approach could be phased, with preliminary analysis indicating an approach with Phase 1 targeting 2.85 Mtpa, Phase 2 targeting 9.77 Mtpa, and Phase 3 targeting 4.38 Mtpa.

Cost Analysis

Storage costs range from US$1.4 to US$28.7/tCO_2 (high injectivity) to US$8.5 to US$87.5/tCO_2 (low injectivity), with Phase 1 CAPEX ranging from US$130 to US$1,057 million. The primary cost driver is injection rates, with higher injectivity rates dramatically improving project economics. Phase 1 carries the highest unit costs due to upfront capital spread across smaller initial volumes. The reuse or abandonment of wells was not considered.

Critical Challenges

The Southern Cambay Hub has many significant challenges, which, in this high-level analysis, were not addressed and require further work. These include:

- Reservoir challenges: Multi-layered sands exhibit significant lateral discontinuity and compartmentalisation that could limit injection efficiency and CO_2 storage capacity.
- Legacy wells: Over 500 existing wells require integrity assessment and potential re-completion to prevent CO_2 leakage.
- Data gaps: India's restricted subsurface database severely limits detailed site characterisation, forcing reliance on high-level assumptions.

Next Steps to Enable Further Development

1. Priority 1: Establish ONGC partnership for data access and complete systematic well audit within 12-24 months.
2. Priority 2: Progress from analytical assessments to full 3D geological and reservoir modelling to more accurately quantify storage capacity, injection-well requirements, and phase-specific costs, while optimising injection strategies within 6-12 months of data access.
3. Priority 3: Advance regulatory approvals and stakeholder engagement while implementing monitoring protocols.

The opportunity: Southern Cambay Hub is one of India's most straightforward paths to large-scale CO_2 storage with manageable risks, provided data access and reservoir characterisation challenges are systematically addressed

3.2 Introduction: Cambay Basin

The Cambay Basin is a predominantly onshore intra-cratonic rift basin covering an area of 50,000 km^2 on the western margin of India (Figure 41). The basin is a highly prolific and mature oil basin with few gas fields.

The basin is divided into several structural blocks, with the Jambusar-Broachblock of the South Cambay basin being the focus of this study, as it hosts the Gandhar Field and is the primary depocentre of the Ankleshwar Formation (Middle Eocene), the storage complex for this analysis. (Figure 40).

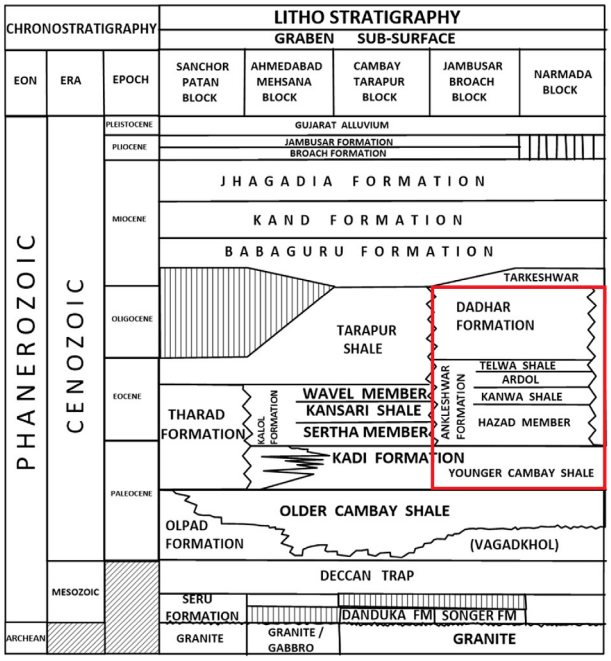


Figure 40. Generalised Stratigraphy of the Cambay Basin. (Source: Vishal et al., 2025)

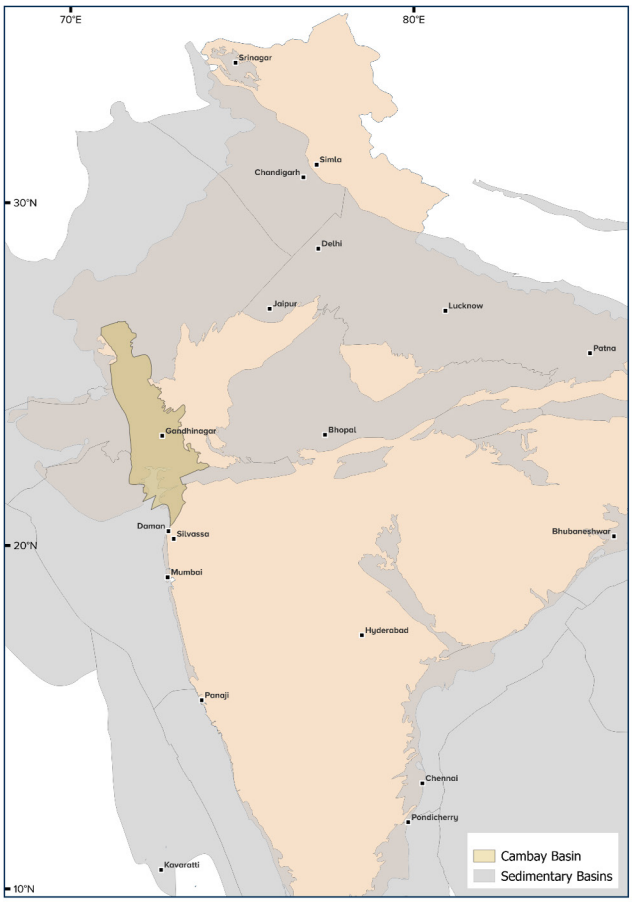


Figure 41. Location of the Cambay Basin and other basins of India. Source of basins: CGG Robertson (2020)

32. Cambay Basin Selection

The Cambay Basin is the basin selected for the OGCI CCS Hub analysis. Specifically, the Eocene Ankleshwar Formation storage complex has the highest potential for CO_2 storage servicing a CCUS Hub – herein referred to as the Southern Cambay Hub (SCH). The Ankleshwar Formation and, in particular, the Hazad Member are the oil-bearing reservoirs of the Gandhar Oil Field.

The SCH ranked highest because of the following factors[1]:

1. CO_2 storage suitability: the Ankleshwar Formation meets the high-level criteria for a CO_2 storage complex:
    - Multiple, proven reservoirs and seals, as evidenced by an active petroleum system
    - Depth greater than 800 m
    - Existing subsurface data
2. Onshore: Onshore CCUS Hubs are lower in cost and logistically simpler in terms of surface infrastructure (transport and storage) compared to offshore. In a reservoir of moderate quality, these costs can be doubled according to the internal CO_2 costs analysis of the Institute.
3. Previous studies: Several studies confirm that the Ankleshwar Formation, the Gandhar Field, and the Southern Cambay Basin, more broadly, are consistently identified as suitable for CO_2 storage (Global CCS Institute, 2024c; Ministry of Petroleum and Natural Gas, 2022; Vishal, Chandra, et al., 2021; Vishal et al., 2024b; Vishal, Verma, et al., 2021) (Figure 26).
4. Data: The Gandhar Field is a mature oil field hosting hundreds of wells and seismic data. This data enables characterisation and resource calculation of the Ankleshwar Formation.
5. Enhance oil recovery (EOR) potential: Although EOR is out of scope of this analysis. The India CCS Roadmap identified the field as a potential EOR field, providing a future revenue or cost offset (Ministry of Petroleum and Natural Gas, 2022)
6. Permit: According to the National Data Repository of India (Ministry of Petroleum and Natural Gas, 2025) website, the field is under a petroleum licence. Having permitting in place to access the subsurface and oil and gas activities provides a strong enabler for permitting of CO_2 storage exploration.
7. Accessibility: According to the National Data Repository of India (Ministry of Petroleum and Natural Gas, 2025 and the World Database on Protected Areas (UNEP-WCMC and IUCN, 2025), the region is not designated as a protected area.
8. Social Licence: The SCH area is an operating oil field with related infrastructure, including drill pads, pipelines and processing plants. Gough et al. (2018) state that establishing an industrial presence creates familiarity and trust that extends to new projects, including CCS. The Institute recognises that social licence to operate is an often-overlooked or late-stage consideration for CO_2 storage projects.

1 Note: policy, permitting and regulatory frameworks were not considered.

3.3 Previous studies and CCS projects

Several studies identify the Cambay Basin as a suitable storage basin with high potential (Bakshi, 2023; Global CCS Institute, 2024c; Holloway, 2008; Ministry of Petroleum and Natural Gas, 2022; OGCI, 2025; Vishal et al., 2024b; Vishal, Verma, et al., 2021). The oil and gas maturity of he sedimentary basins of India was summarised by Ministry of Petroleum and Natural Gas (2022) (Figure 42). Although not a direct indicator, the maturity of a basin in terms of oil and gas production is a broad indicator of the suitability for CO_2 storage potential, with mature basins (producing and exploited oil and gas fields) hosting properties favourable for CO_2 storage, including proven reservoirs and seals, available data, geological characterisation and accessibility. Specifically on CO_2 storage potential, the Cambay Basin is found to have very high potential (Vishal, Verma, et al., 2021) (Figure 43).

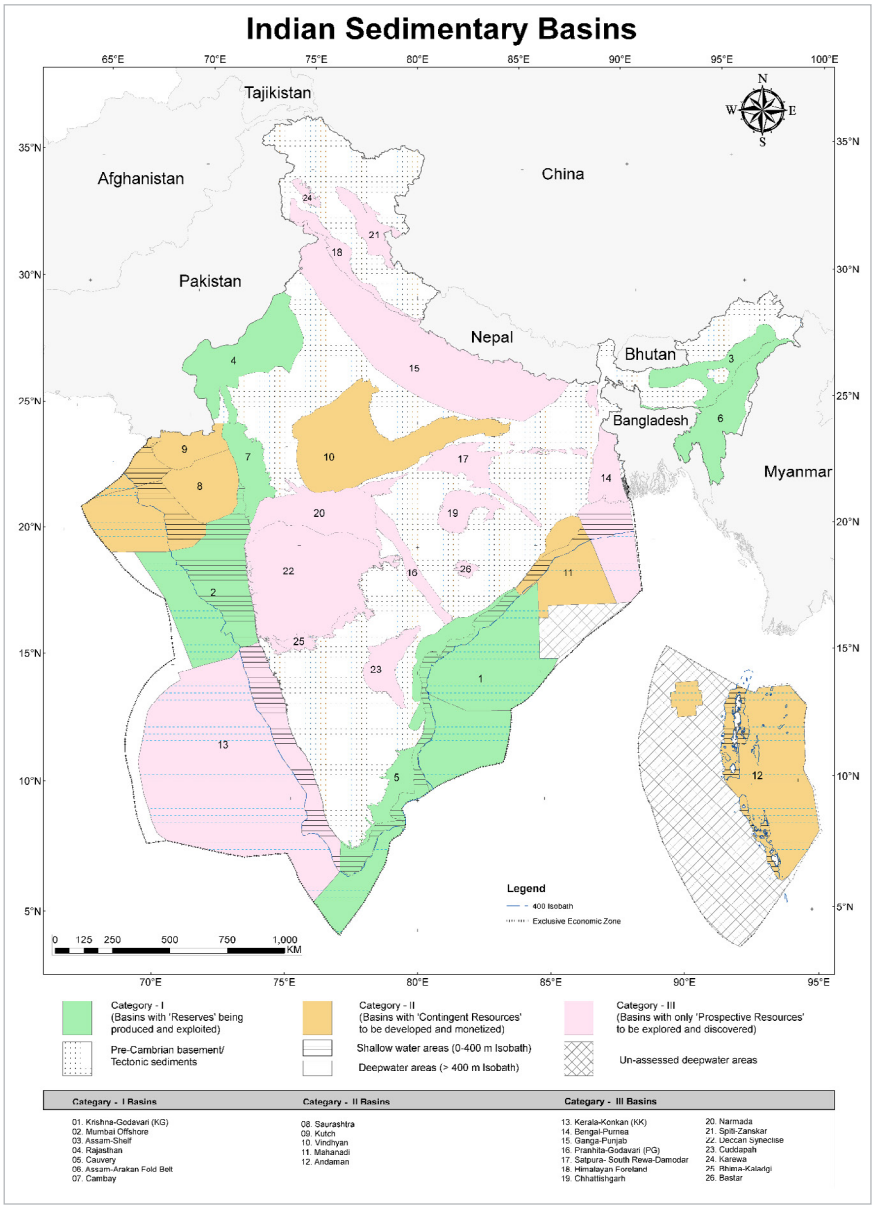


Figure 42. The sedimentary basins of India ranked according to their oil and gas maturity. The oil and gas maturity of a basin is a broad indicator of the suitability for CO_2 storage potential, with mature basins (producing and exploited oil and gas fields) hosting properties favourable for CO_2 storage. Source: Ministry of Petroleum and Natural Gas (2022)

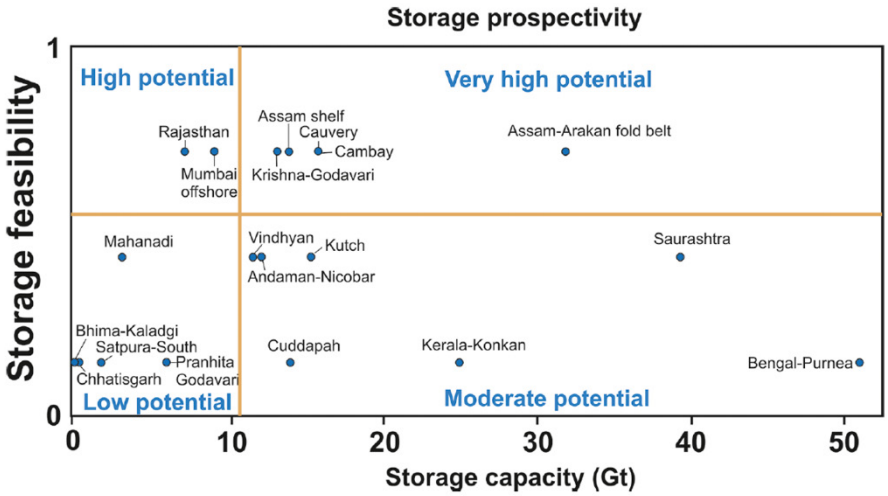


Figure 43. Storage prospectivity of major Indian basins by feasibility vs capacity, highlighting the Cambay Basin as "very high potential". Source: Vishal et al. (2021)

OGCI CCUS Hubs

The OGCI CCUS Hub website identifies the Ahmedabad (called Ahmadabad by OGCI) depleted oil and gas reservoir CCUS Hub (located in the Cambay basin) with a total storage potential of 156 $MtCO_2$ (OGCI, 2025). Although the authors do not publicly disclose the methodology and data behind the analysis, it is assumed that the hub encompasses all hydrocarbon fields and bases its estimate on the total resources and reserves of these fields.

The OGCI CCUS Hub website also identified a second CCUS Hub in the Cambay Basin, the Ahmedabad saline aquifer formation, with a total storage resource of 5,600 $MtCO_2$ (OGCI, 2025). Once again, the methodology and data behind the analysis are not known. The assumption for this study is that this represents an aggregation over a broader area, rather than a specific formation, given the significant value.

India Cement Study

The Global CCS Institute (2024) also studied the CO_2 storage potential of the Cambay Basin as part of a comprehensive study across India. The basin-scale analysis utilises the DOE (Goodman et al., 2011) method, modified for basin-scale assessments and Monte Carlo simulations. This volumetric approach, conducted under open-boundary calculations, assumes that the basin hosts a series of deep saline formations that enable a percentage of CO_2 storage. Net resources of the Cambay were 1,790 $MtCO_2$ (P10), 9,830 $MtCO_2$ (P50), and 48,060 $MtCO_2$ (P90), with the onshore portion being 8,980 $MtCO_2$ (P50) (Global CCS Institute, 2024c). There was no attempt to define individual formations or their reservoir properties.

The study also evaluated the CO_2 storage resources of conventional oil and gas fields, as well as those planned and announced for production. The study identified the Cambay Basin as hosting 68 conventional oil fields and 16 conventional gas fields. The analysis did not include the SCH's Gandhar Field due to the lack of data provided for the study at the time. The largest field by CO_2 resource in Cambay was the Gujarat Field, located around 100 km southeast of the Gandhar Field. The storage resource of the Gujarat Field was 52 $MtCO_2$ (P50) (Global CCS Institute, 2024c). The total storage resources of the Cambay and the three other key basins in India, for comparison, are listed in Table 34.

Based on this analysis, the producing and depleted fields of the Cambay Basin were also not considered as standalone storage complexes, as they are all too volumetrically small to be considered as hubs. The Gandhar Field is incorporated into the Ankleshwar storage complex and SCH more broadly.

The largest hydrocarbon fields in the Global CCS Institute (2024) were the Mumbai High oil field (P50:

300 Mt CO_2) and the Bassein Gas Field (P50: 696 Mt CO_2), both located offshore in the Mumbai Basin (Global CCS Institute, 2024c). These fields are currently producing, with no near-term timeline for the end of their production. According to GlobalData (2025), the expected production from the Bassein Field extends until 2057. For this current analysis, the offshore part of the Mumbai Basin was excluded, as onshore storage was prioritised over offshore in the initial screening of potential storage sites for hubs.

Table 34. CO_2 Storage Potential of Hydrocarbon Fields in India. (Source: Global CCS Institute, 2024)

Basin	Field Type	P10 ($MtCO_2$)	P50 ($MtCO_2$)	P90 ($MtCO_2$)
Cambay	Oil	45.99	61.89	83.44
	Gas	14.87	18.41	22.74
Mumbai Offshore	Oil	251.89	338.47	455.94
	Gas	579.05	722.43	888.49
Assam-Arakan	Oil	84.49	111.97	148.91
	Gas	94.89	119.09	148.39
Krishna-Godavari	Oil	17.56	23.63	31.93
	Gas	391.18	486.20	597.46

33. Projects

The Cambay Basin is the site of two commercial CCS projects, according to the Institute's CO_2RE database (Global CCS Institute, 2025a).

Koyali refinery

Indian Oil Corporation Ltd. (IOCL) Koyali refinery, located in Vadodara, Gujarat, plans to store its CO_2 emissions at the Gandhar Field as part of a CO_2-EOR operation. IOCL plans to transport the CO_2 via a 110 km pipeline. IOCL has entered into a Memorandum of Understanding (MoU) with Oil and Natural Gas Corporation (ONGC), and was the only project identified in the 2030 Roadmap (Ministry of Petroleum and Natural Gas, 2022).

Cambay CCS Project

Synergia Energy is assessing the northern Cambay Basin for CO_2 storage (Synergia Energy Ltd, 2023). Synergia will target the formation of the company's Cambay PSC fields, located to the north of the Gandhar Field. Synergia Energy estimates storage resources of over 500 $MtCO_2$.

3.4 The Gandhar Field

The SCH includes the Gandhar Oil Field, which has been in production since 1986. The oil reservoir is the Hazad Member, the focus of this study's SCH. Oil accumulates in low-relief structural highs, with strati-structural traps formed by reactivated normal faults (Saha et al., 2004). Water injection began in 1991, with no evidence that it has ceased. Details include:

- Area: 645 km^2 (Ministry of Petroleum and Natural Gas, 2025)
- Depth varies from about 1700 m in the centre of the field to about 3000 m towards the southeast (Aswal et al., 2015; A. Kumar et al., 2004)
- Reservoir pressure ranges 30-34 MPa (Vishal et al., 2024a)
- Oil: Low sulphur, light oils with 38-55 API (Varanasi et al., 2022)
- Oil Production 29.6% with an average water cut of 80.3%.(Varanasi et al., 2022)
- 560 wells (number of production vs. injection wells not specified) (S. K. Dhar, 2006)
- Water injection since 1991 (S. K. Dhar, 2006)

34. SCH: Ankleshwar Storage Complex

The Ankleshwar Formation is the storage complex of the SCH and comprises the Eocene Hazad Member reservoir and Kanwa Shale regional seal. Tectonic rifting, volcanism, and the deposition of the Deccan Traps, as well as basement faults, controlled the deposition of the Ankleshwar Formation (Vishal et al., 2024a). The deposition of the Hazad Member reservoir, and in particular, higher-quality sands, focuses on the southern Cambay Basin, called the Gandhar-Jambusar blocks. This area is on the northwestern rising flank of the Broach depression, which created accommodation space for the deposition of the Hazad Member sands. In this area, the deltaic environment, formed by the Proto-Narmada and Dadhar river systems, resulted in the deposition of the Hazad Member sands.

The Hazad Member formed during an overall transgressive event. The onset of the high stand resulted in a progradational delta buildout. The delta deposited tide-influenced, delta-front to delta-plain sands in the form of a series of distributary channels, mouth bars and sand-rich channel-lobes (Figure 45). The Hazad Member is informally subdivided into 12 sand units, called Gandhar Sands (GS0-GS12), including four parasequences (GS0 to GS2, GS3, GS4 to GS6, and GS7 to GS9) separated by flooding surfaces (Figure 45; Figure 46). The flooding surfaces, combined with the high sediment supply and limited accommodation space, resulted in vertical and horizontal heterogeneity of thin, moderate to poor-quality reservoir sands.

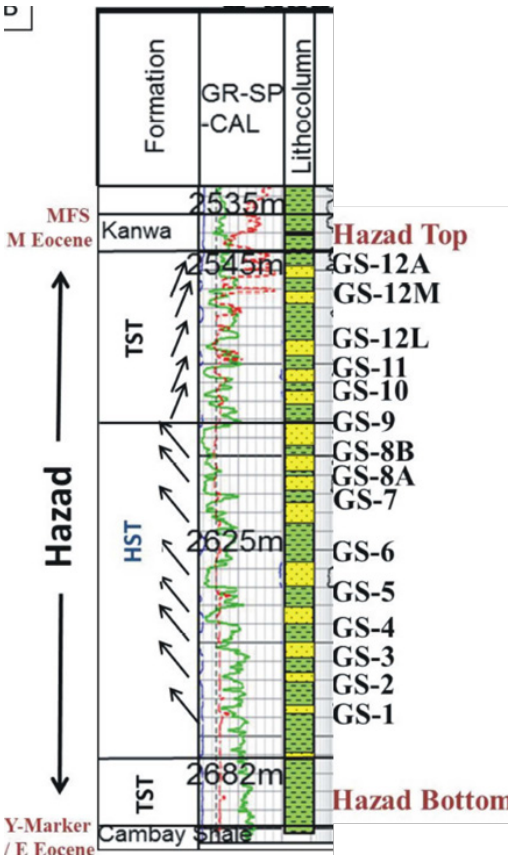


Figure 44. Well Log Profile and Sequence Stratigraphy of SCH's Hazad Member. Note: Well name unknown. (Source:Aswal et al. (2015))

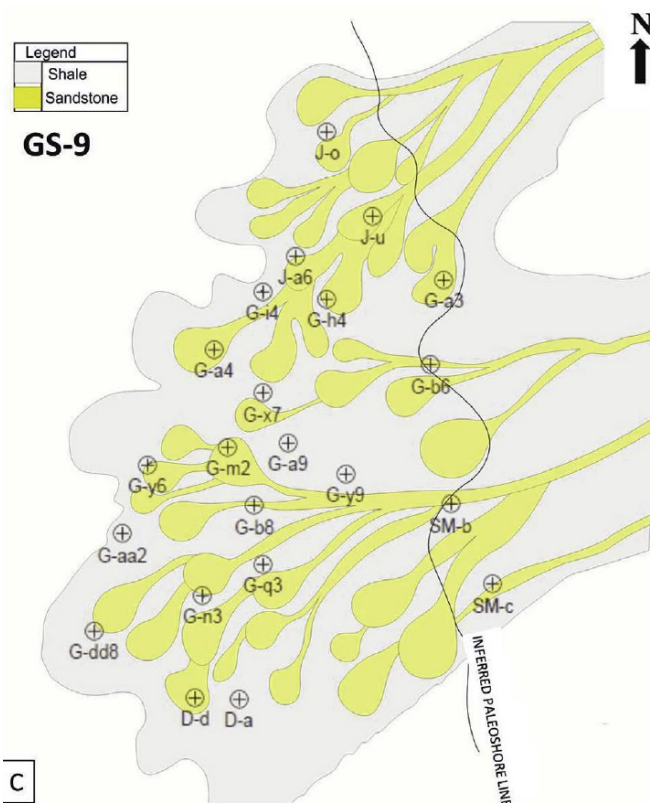


Figure 45. Depositional Model of the Hazard Member of the GS-09 Sand. Source:Aswal et al. (2015). Note: the well names shown do not correspond to actual well names.

The deposition of the Hazad Member was ultimately terminated by the regional seal of this study, during a maximum flooding surface due to a late Eocene uplift event (Atiq et al., 2015; Jaiswal et al., 2018; Jaiswal & Bhattacharya, 2018). The Kanwa Shale is deemed suitable as a caprock for CO_2 storage (Ganguli et al., 2017).

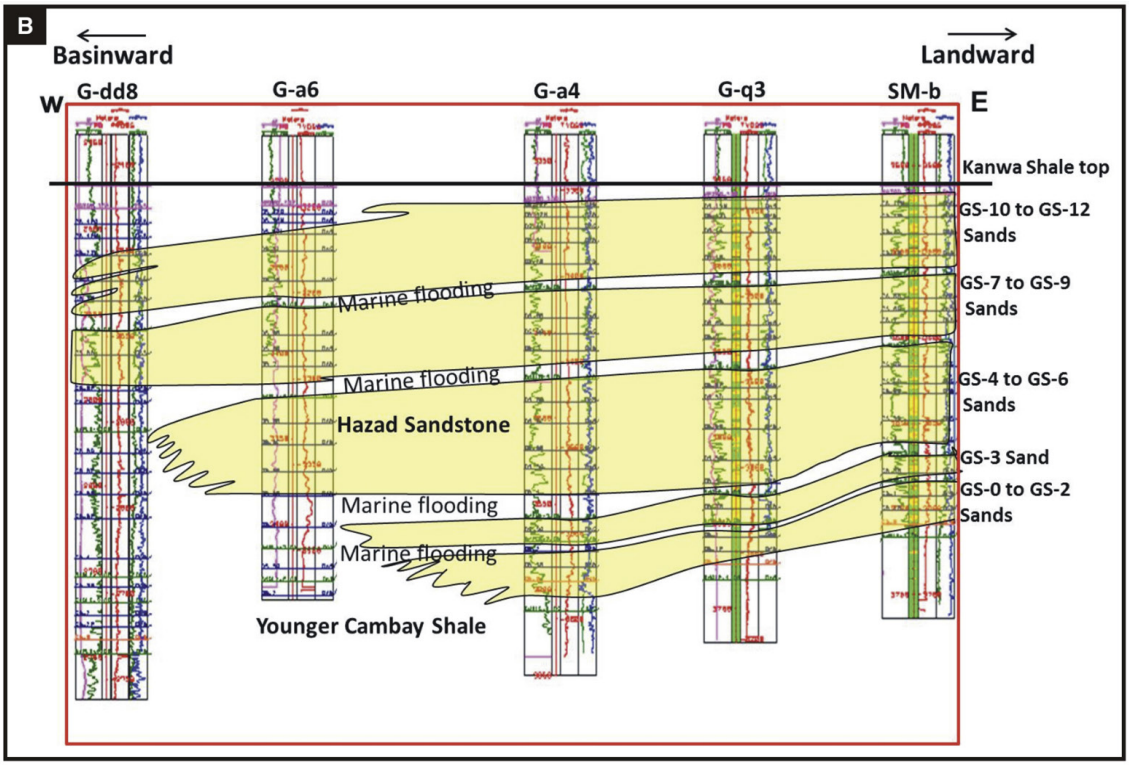


Figure 46. Hazad Member Distribution and Different Facies (GS-0 - 12 sands). Source: Jaiswal & Bhattacharya (2018)

CO_2 Storage in the Hazad Member Reservoir

Based on the limited literature and data available on the Hazad Member from a CO_2 storage perspective, the Hazad Member as individual units show substantial variation in their potential to store CO_2 from low to very high (Aswal et al., 2015; Atiq et al., 2015; Jaiswal et al., 2018; Jaiswal & Bhattacharya, 2018; Vishal et al. 2024b; Vishal et al., 2025),

The least favourable units for CO_2 storage are GS0, GS1 and GS12, which are thin, clay-rich, and tidally influenced, with discontinuous sand bodies and low net-to-gross, potentially limiting injectivity and overall capacity. GS10 is also low quality, being thin, patchy, tidally dominated, and prone to cementation.

Moderate-quality units are GS2-3, GS9, and GS11. These units have cleaner sands locally, with effective sand thicknesses ranging from ~2 to 9 m, but suffer from lateral restriction, tidal heterogeneity, or compartmentalisation due to argillaceous facies (Figure 44). In CO_2 storage terms, these could serve as secondary injection targets or pressure-management intervals in a stacked development scheme.

The highest-quality, most prospective units are GS4-8. GS4-5 offers laterally extensive mouth-bar/channel sands with good sorting, albeit with higher clay margins. GS6 marks the onset of main delta progradation, characterised by stacked upward-coarsening cycles, high net-to-gross ratios which offer both high injectivity and capacity (Figure 44). GS7 and GS8 continue this trend with even greater thickness and lateral continuity, dominated by mouth-bar facies with minimal tidal reworking. Among these sand units, only GS7 has been previously assessed and identified as highly prospective for CO_2 storage due to its clearly delineated clean sand, high porosity, and extensive areal continuity (Vishal et al., 2025).

From a CO_2 storage perspective, GS6-GS8 align well with the needs for large-volume injection: they occur in central Gandhar-Jambusar corridors, have favourable reservoir continuity, and are likely pressure-connected to existing oil fields. GS4-5 can serve as supplementary storage layers, adding stacked capacity and operational flexibility.

Based on these findings, this study focused only on GS4-GS12. However, the reservoir properties for every unit use the areal extent and porosity data from GS7 due to limited data availability for the other units. The analysis does not account for oil in place in some units because of insufficient data.

3.5 Storage Resources

Theoretical storage resources refer to the maximum volume of CO_2 that can be stored within a geological formation, calculated solely based on fundamental physical and geological properties. This estimate does not account for practical, technical, or regulatory constraints that would apply in a real-world project, such as CO_2 supply, injectivity limits, pressure buildup, containment risks, well placement, or access to infrastructure.

Theoretical storage assessments typically represent the upper bound of storage resource estimates. While they provide a valuable basis for screening and comparing formations, the actual usable storage resource in practice is often considerably lower. The degree of uncertainty in theoretical storage estimates can be substantial, owing to variability in subsurface data quality, limited knowledge of reservoir continuity and properties at depth, and simplifications made in the absence of detailed site-specific information.

It is also important to note that theoretical storage resources are progressively refined as more information becomes available. As projects move from site screening to site-specific investigations, additional factors — such as dynamic reservoir behaviour, pressure management, and containment risks — are considered, resulting in more realistic (typically lower) resource estimates.

In this study, the method used to estimate theoretical CO_2 storage resources is presented, with a focus on open boundary (where pressure can dissipate beyond the formation boundaries), assuming the Hazad Member Sands (GS) units are regionally extensive, laterally persistent saline units with clean, well-sorted sands and minimal internal shales — favourable for lateral hydraulic connectivity. The methodology is shown in Storage Resource Calculation, including all the data inputs and assumptions.

To quantify the uncertainty inherent in these storage resource estimates, the Monte Carlo simulation technique is employed. By sampling across the plausible ranges of key geological parameters — such as reservoir thickness, porosity, and the in-situ density of CO_2 — Monte Carlo analysis provides probabilistic distributions of storage resources rather than single-point estimates. This approach allows us to more accurately represent the uncertainty associated with subsurface heterogeneity and limited data availability, and to report a range (e.g., P10, P50, P90) of potential storage outcomes for each scenario.

Figure 47 to Figure 56 illustrate the theoretical storage resources estimated for each unit under the most optimistic scenario. This scenario assumes:

- Extensive lateral continuity (75% of the studied region, 750 km^2),
- Effective porosity values at the upper end of the assumed ranges, and
- Open boundary conditions with full pressure support.

Even under such assumptions — which effectively represent a conservative upper bound — the estimated storage resources of individual units remain modest. The largest potential is associated with GS7 (including the GS7+8 interval).

When considering the P50 (most likely) case, the results suggest that each unit could at best accommodate small to medium-scale storage projects, most likely in a stacked development setting. The estimated cumulative P50 storage across all units is ~341 $MtCO_2$.

Table 35. Storage Resources of the Hazad Member Sands (GS)

Unit	P10 Average ($MtCO_2$)	P50 Average ($MtCO_2$)	P90 Average ($MtCO_2$)
GS4	9	18	31
GS5	19	35	61
GS6	11	21	37
GS7	51	96	165
GS8	18	33	57
GS9	20	38	66
GS10	15	29	50
GS11	20	38	65
GS12	17	32	54
Total	**180**	**341**	585

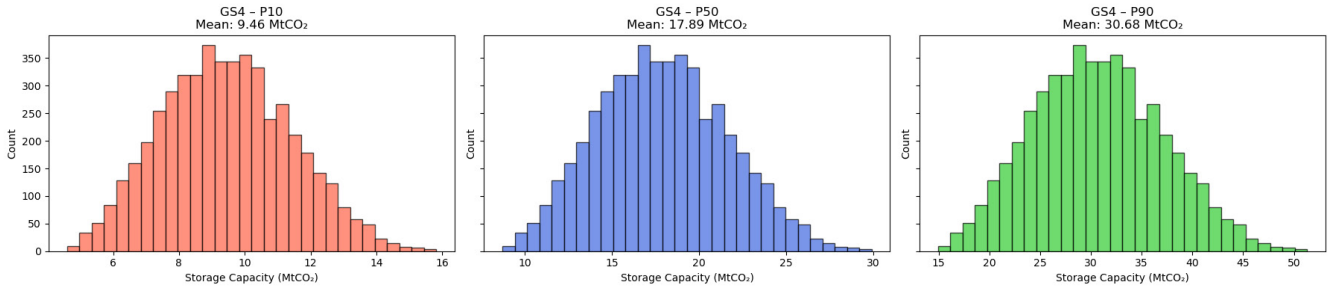


Figure 47. Histogram of estimated CO_2 storage resources for GS4, shown for P10, P50, and P90 efficiency factors

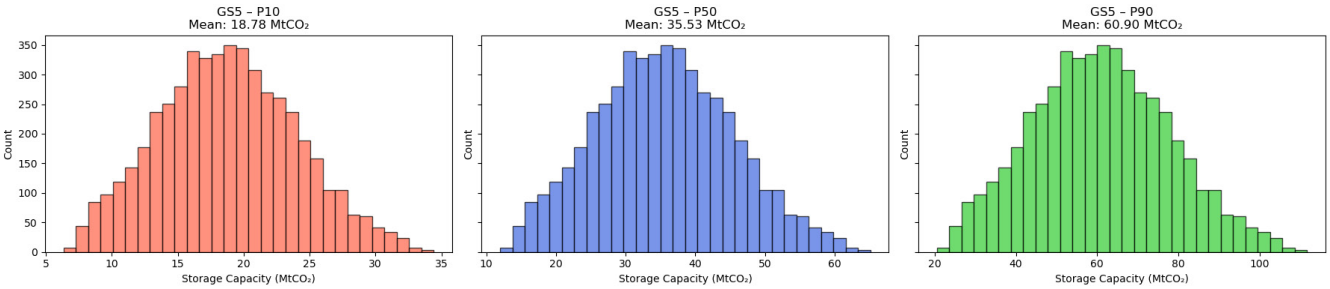


Figure 48. Histogram of estimated CO_2 storage resources for GS5, shown for P10, P50, and P90 efficiency factors

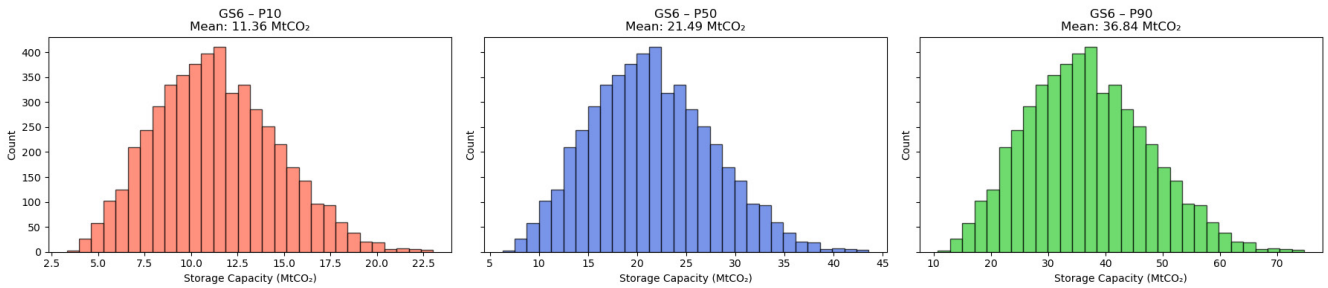


Figure 49. Histogram of estimated CO_2 storage resources for GS6, shown for P10, P50, and P90 efficiency factors

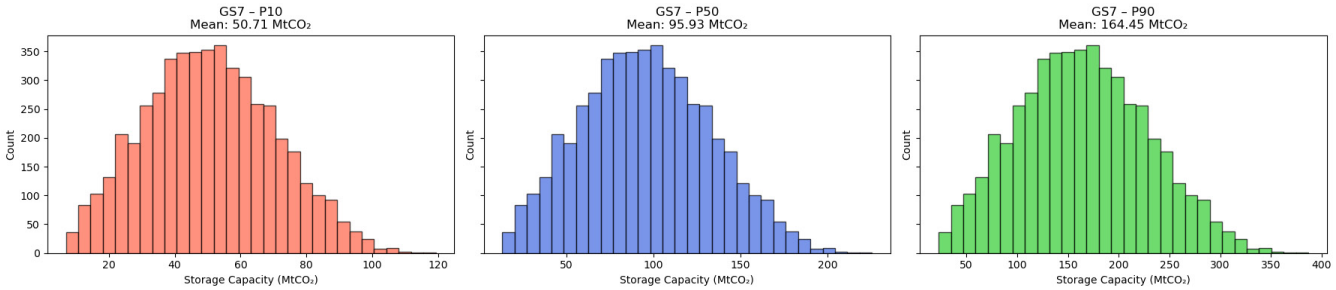


Figure 51. Histogram of estimated CO_2 storage resources for GS7, shown for P10, P50, and P90 efficiency factors

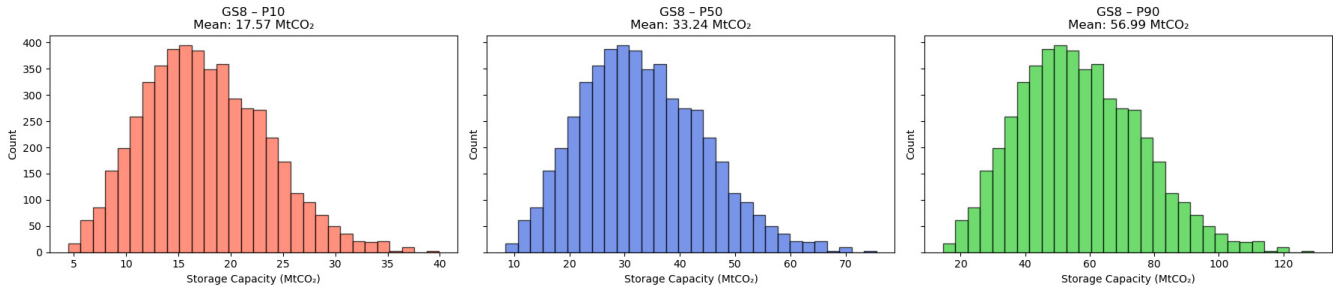


Figure 52. Histogram of estimated CO_2 storage resources for GS8, shown for P10, P50, and P90 efficiency factors

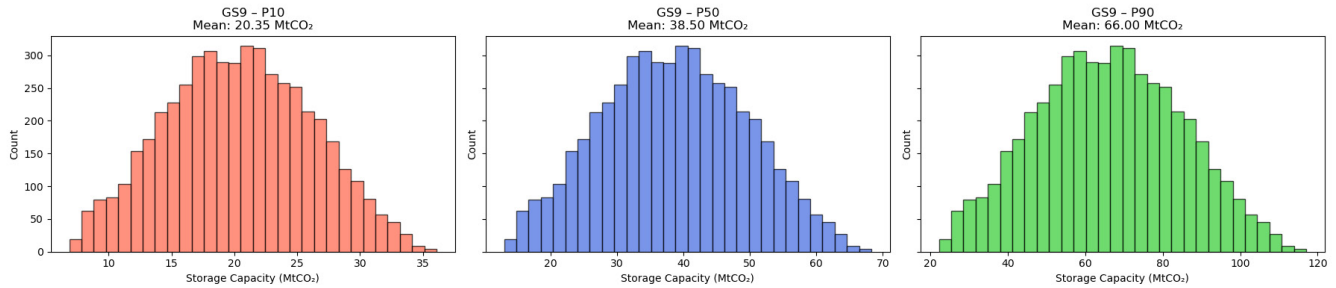


Figure 53. Histogram of estimated CO_2 storage resources for GS9, shown for P10, P50, and P90 efficiency factors

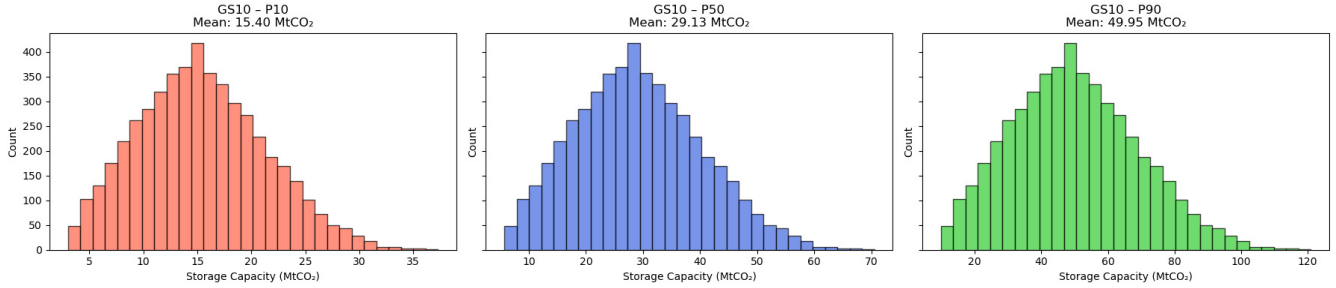


Figure 54. Histogram of estimated CO_2 storage resources for GS10, shown for P10, P50, and P90 efficiency factors

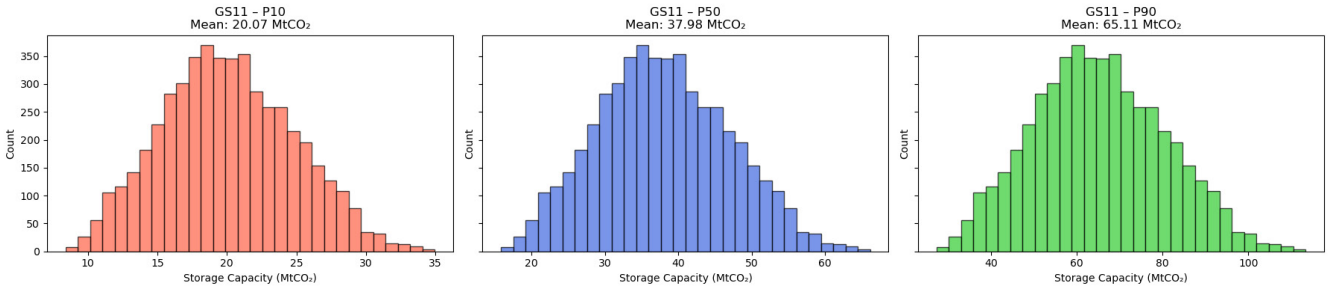


Figure 55. Histogram of estimated CO_2 storage resources for GS11, shown for P10, P50, and P90 efficiency factors

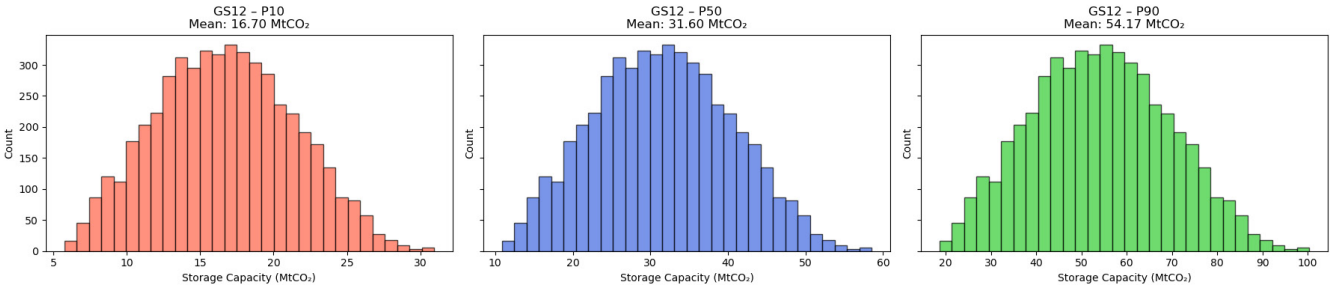


Figure 56. Histogram of estimated CO_2 storage resources for GS12, shown for P10, P50, and P90 efficiency factors

3.6 Injectivity Results

Injectivity measures the resevoir's capacity to accept injected fluids and is a key parameter in assessing CO_2 storage feasibility. It is typically expressed as injected volume or mass per unit pressure increase at the wellbore. . High injectivity indicates that large volumes of CO_2 can be injected with relatively small increases in wellbore pressure, thereby reducing the number of injection wells required and improving overall project economics.

The data and methodology for this section are in Injectivity Estimation. Based on the injectivity analysis, the high-quality reservoir case (permeability 577.5 mD, thickness 22 m) can accommodate all assessed rates (0.5, 1.0, and 1.5 Mtpa CO_2) without exceeding the maximum allowable bottomhole pressure (BHP) (90% of the fracture pressure). The medium-quality case (permeability 200 mD, thickness 12 m) likewise supports up to 1.5 Mtpa under the same constraint. However, it requires a higher BHP, and therefore a higher wellhead pressure (WHP) than the high-quality case. 1.5 Mtpa per well is adopted for both High and Mid cases in Table 3 and used to estimate the number of wells required to meet the total target injection rate reported there.

In contrast, for the low-quality case (permeability 32 mD, thickness 2 m), none of the tested rates are achievable without exceeding the maximum allowable BHP. For this case, the maximum feasible rate at the maximum allowable BHP is calculated and reported in Table 36. Table 36 also reports the total number of injection wells required for each case to achieve the P50 storage requirement of 341 Mt over a 20-year injection period.

Table 36. Result of the Injectivity Calculation

Reservoir Properties	Unit	Low	Mid	High
Injectivity index	Mt/year/psi	6.678E-05	2.466E-03	1.305E-02
Max feasible rate per well (capped at 1.5 Mtpa)	Mtpa	0.1	1.5	1.5
Required BHP	psi	6200	5249	4756
Required WHP	psi	3017	1668	1276
Total injection capacity (P50)	Mt	341	341	341
Total no. of injector wells	Number	171	12	12

Phased Development

Phase development	Unit	Low	Mid	High
Phase 1: Target injection rate	Mtpa	2.85	2.85	2.85
Phase 1: No. of injectors	Number	29	2	2
Phase 2: Target injection rate	Mtpa	9.77	9.77	9.77
Phase 2: No. of injectors	Number	98	7	7
Phase 3: Target injection rate	Mtpa	4.38	4.38	4.38
Phase 3: No. of injectors	Number	44	3	3

3.7 High-Level Costs of Storage

The cost of CO_2 storage is an important factor in assessing the overall feasibility and competitiveness of CCS projects. While capture and transport typically represent the largest share of CCS costs, storage economics can materially influence project design and investment decision-making.

Detailed information on scope Exclusions, Assumptions and Components that underpin modeling in this section, can be made available upon request.

Storage costs were estimated for each injectivity case (low, medium and high) across the phased development of the SCH project, reflecting an increasing number of emission sources transporting and storing CO_2 at the site (Figure 19). This approach reflects the development sequence of the SCH project. The generation of the estimates uses the Global CCS Institute CO_2 Storage Cost Model (GCOST), providing a structured framework for evaluating storage costs at screening and pre-feasibility levels. For each case (low, mid, and high injectivity), both minimum and maximum cost estimates capture the uncertainty associated with reservoir performance, well count, and infrastructure requirements (Table 37). This range highlights the sensitivity of storage cost components, as informed by the literature and actual projects.

Table 37. Cost of Storage for Each Phase and Cases

Category	Phase 1 (EMISSIONS 2.85 Mtpa)						Phase 2 (9.77 Mtpa)						Phase 3 (4.38 Mtpa)					
Cases	Low		Mid		High		Low		Mid		High		Low		Mid		High	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
CAPEX US$ Million	226	1,057	131	524	131	524	379	2,062	56	268	56	268	178	948	32	139	32	139
OPEX US$ Million	138	1,308	42	243	42	243	397	4,189	74	600	74	600	218	2,072	73	455	73	455
ABEX US$ Million	19	130	5	50	5	50	56	308	7	39	7	39	26	141	4	19	4	19
Total Cost US$ Million	383	2,494	177	817	177	817	831	6,559	136	907	136	907	422	3,160	109	613	109	613
Total Cost with Contingency	766	4,989	354	1,634	354	1,634	1,662	13,119	273	1,813	273	1,813	844	6,320	218	1,226	218	1,226
Cost per tonne with contingency US$/$tCO_2$	13.4	87.5	6.2	28.7	6.2	28.7	8.5	67.1	1.4	9.3	1.4	9.3	9.6	72.1	2.5	14.0	2.5	14.0

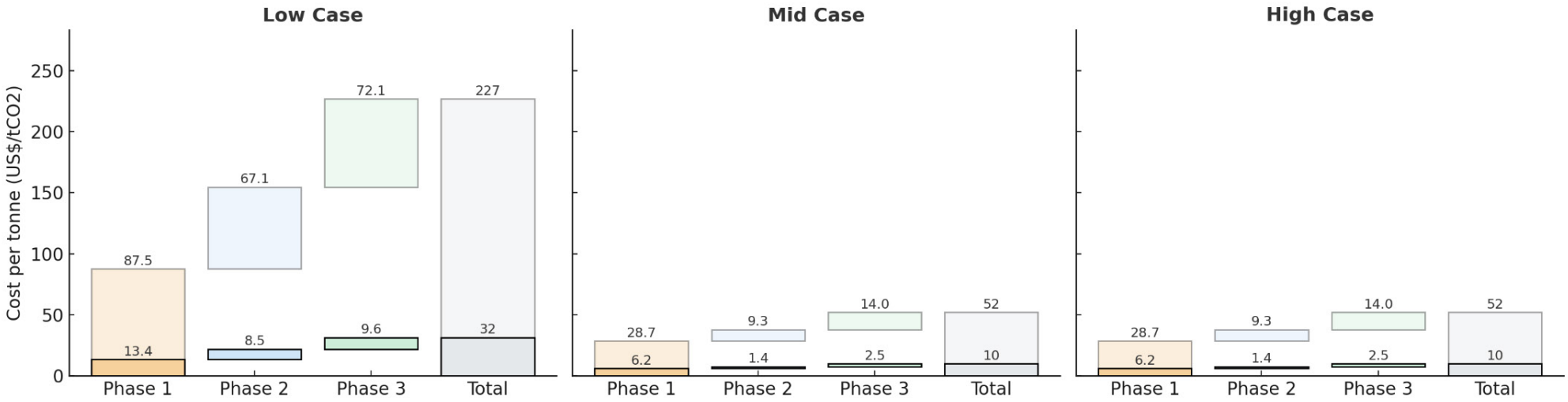


Figure 57. Cost of Storage According to Cases and Phases. Minimum cost ranges are shown in a solid colour, and Maximum cost ranges are shown in a faded colour

The analysis shows that Phase 1 carries the upfront burden, as early capital investment is spread across relatively small injection volumes. Phase 3 reflects the post-closure portion, where costs continue even as injection has ceased.

- Low Case: Total storage cost ranges from US$8.5-87.5/$tCO_2$. The wide spread is driven by high well counts in Phases 2 and 3, making this outcome the most expensive scenario and economically challenging.
- Mid and High Cases: Costs for the High and Mid cases are effectively the same because both scenarios use the same well count and, without numerical simulation, apply an identical plume footprint/monitoring area. The cost ranges from US$1.4 to US$28.7/tCO_2, with Phase 2 still contributing the largest share, but at improved efficiency. These cases present a more balanced distribution of costs.

3.8 Ankleshwar Storage Complex Issues

There is a limited availability of publicly accessible, high-quality subsurface data in India, which constrains detailed site screening and characterisation. For example, access to the National Data Repository for Petroleum Data remains technically challengining, and many datasets are not readily usable for integrated reservoir analysis Until more detailed geological and reservoir datasets are accessible, robust, site-specific CO_2 storage assessments in India will remain subject to material uncertainty.

The two most significant issues identified with the SCH Ankleshwar storage complex are the high level of heterogeneity in the sands and the fact that the SCH is an active, mature oil field. The issues identified below do not encompass policy, regulatory, or social aspects, which are outside the scope of this part of the overall study.

35. Reservoir Architecture and Sand Body Geometry

The Ankleshwar storage complex comprises multi-layered sandstone units (GS-1 to GS-12) deposited in a deltaic environment during the Middle Eocene period. These sand bodies exhibit lenticular, isolated geometries with a discrete nature of occurrence. The depositional environment led to rapid lateral facies changes and the formation of isolated sand lobes, separated by interdistributary mudstones. The intervening mudstone layers act as barriers to fluid flow, creating a compartmentalised reservoir system rather than a continuous storage formation. This heterogeneity is so pronounced that rock properties and fluid properties can change significantly over short distances within sand bodies (S. K. Dhar, 2006; Rath et al., 2013). The discrete nature of the sand bodies makes large-scale injection of CO_2 challenging, reducing overall injectivity and capacity due to the small size of the sand bodies, pressure variations, channelling, and decreased sweep efficiency.

36. Mature Gandhar Field

A mature oil field can be an optimal target for CO_2 storage; however, it also presents inherent issues. The primary issue is the large number of production and injection wells drilled over the project's lifetime, which remain active. According to Dhar (2006), there are over 500 wells, which is comparable to our estimates. The large number of wells over a relatively small area provides additional evidence of significant reservoir heterogeneity and limited lateral continuity across many of the units.

These wells will need to be re-completed to ensure they do not provide a leakage pathway out of the storage complex. However, as a benefit, they could be recompleted as injector and monitoring wells.

In addition to the wells, mature oil fields face a second challenge: the occupation of pore space by residual hydrocarbons. In depleted oil and gas reservoirs, significant volumes of hydrocarbons remain trapped after primary and secondary recovery operations. Furthermore, reservoirs containing oil, water, and CO_2 exhibit three-phase flow, which creates unprecedented complexity compared to simple CO_2-water systems. Overcoming these issues through optimised injection strategies is possible.

37. Information Gaps

While the development pathway is clear, several critical information gaps remain that may limit progression beyond appraisal and pilot testing. These gaps relate primarily to data availability and stakeholder engagement.

Reservoir Characterisation

The present storage resource estimates rely heavily on data from the GS7 unit, which has been used as a proxy for other Hazad sand intervals (GS3-GS8). This introduces significant uncertainty, as site-specific data for the remaining units are lacking. Furthermore, dynamic multiphase flow modelling, including CO_2-water-hydrocarbon interactions and pressure build-up under continuous injection, has not yet been undertaken.

Similarly, the fracture gradient and overall geomechanical behaviour of the storage complex under sustained CO_2 injection are poorly constrained. Addressing these gaps through new appraisal drilling, core acquisition, and laboratory testing is critical to refining storage estimates and de-risking full-scale development.

Injectivity and Reservoir Performance

A key uncertainty in progressing the storage complex is the absence of direct well test data to validate current injectivity assumptions. The absence of pilot-scale injection data is a critical gap: until step-rate tests and early injection trials are performed, it is uncertain whether the reservoir can sustain commercial rates without rapid pressure buildup, heterogeneity-driven channelling, or earlier-than-expected capacity limitations.

Well Conversion and Integrity

The Gandhar Field, which incorporates the Ankleshwar storage complex, contains an estimated 500-600 legacy wells, which could represent a substantial opportunity for reuse as CO_2 injectors or monitoring wells. However, their current condition and long-term integrity remain unassessed. A complete well inventory and systematic integrity audit — including cement bond logs, casing pressure tests, and barrier verification — will be necessary to evaluate reuse potential.

Where wells meet integrity standards, strategic conversion could significantly reduce new drilling costs and shorten project timelines. Conversely, wells found to be unsuitable for reuse will contribute to decommissioning liabilities, which could be factored into the overall project economics and closure planning.

Cost Definition

The present estimates are based on Class 5 screening-level data and are therefore subject to a wide uncertainty range (−50% to +100%). Progression to Class 3 or better will require detailed engineering, vendor quotes, and site-specific inputs on well design, drilling costs, and monitoring systems.

04

CCS in India's Net Zero Pathway: Energy System Modelling Analysis

Photo: Adobe Stock

4. CCS in India's Net Zero Pathway: Energy System Modelling Analysis

Please note, a high level summary of findings has been provided here. Further detailed analysis may be made available upon request.

4.1 Key findings from the scenarios

- **Restricting India to domestic-only carbon storage may create economic penalties through increased trade costs.** When India cannot access international CO_2 storage, scenarios achieve lower internal cumulative system costs but incur substantial trade expenses by forcing costly imports of low-carbon fuels and industrial commodities.

- **Judicious use of international storage access may deliver net zero at a relatively small cost premium above baseline.** The most cost-effective pathway with international storage access achieves net zero at just 8.8% above baseline costs without net zero policy, indicating that international cooperation economically would be essential despite requiring CO_2 transport infrastructure investment.

- **Net zero action generates substantial economic benefits when consequential climate damages are considered.** Under the modelling, unmitigated climate change impacts India's GDP, while coordinated climate action with international CCS can enable achieve nearly a doubling of GDP compared to unmitigated climate change.

- **In the modelled cases, industrial bioenergy with CCS (BECCS) becomes the most consistent carbon capture application across all pathways.** Regardless of storage constraints, all net zero pathways deploy industrial BECCS by 2065, providing negative emissions to offset hard-to-abate sectors while generating useful energy.

- **Power sector carbon capture deployment depends on international storage availability.** Pathways with international storage access deploy substantial electricity generation CCS by 2065, while domestic-only storage pathways result in virtually zero power sector CCS and instead rely on expensive renewable-to-hydrogen-to-electricity conversion for dispatchable generation.

4.2 Introduction and methodology

The transition to net zero emissions requires a portfolio of decarbonisation technologies that extend beyond renewable electricity generation and energy efficiency measures. CCS technologies become economically viable when implemented alongside comprehensive policies designed to achieve carbon neutrality by specific target years. This analysis examines how CCS fits within India's broader decarbonisation strategy and the conditions under which these technologies become cost-effective compared to alternatives such as renewable electricity, hydrogen production, biomass, biofuels, and synthetic fuels.

The modelling approach employs the GENZO model, a comprehensive global energy system optimisation model developed by the Global CCS Institute, that encompasses 36 regions worldwide, including a dedicated India region.

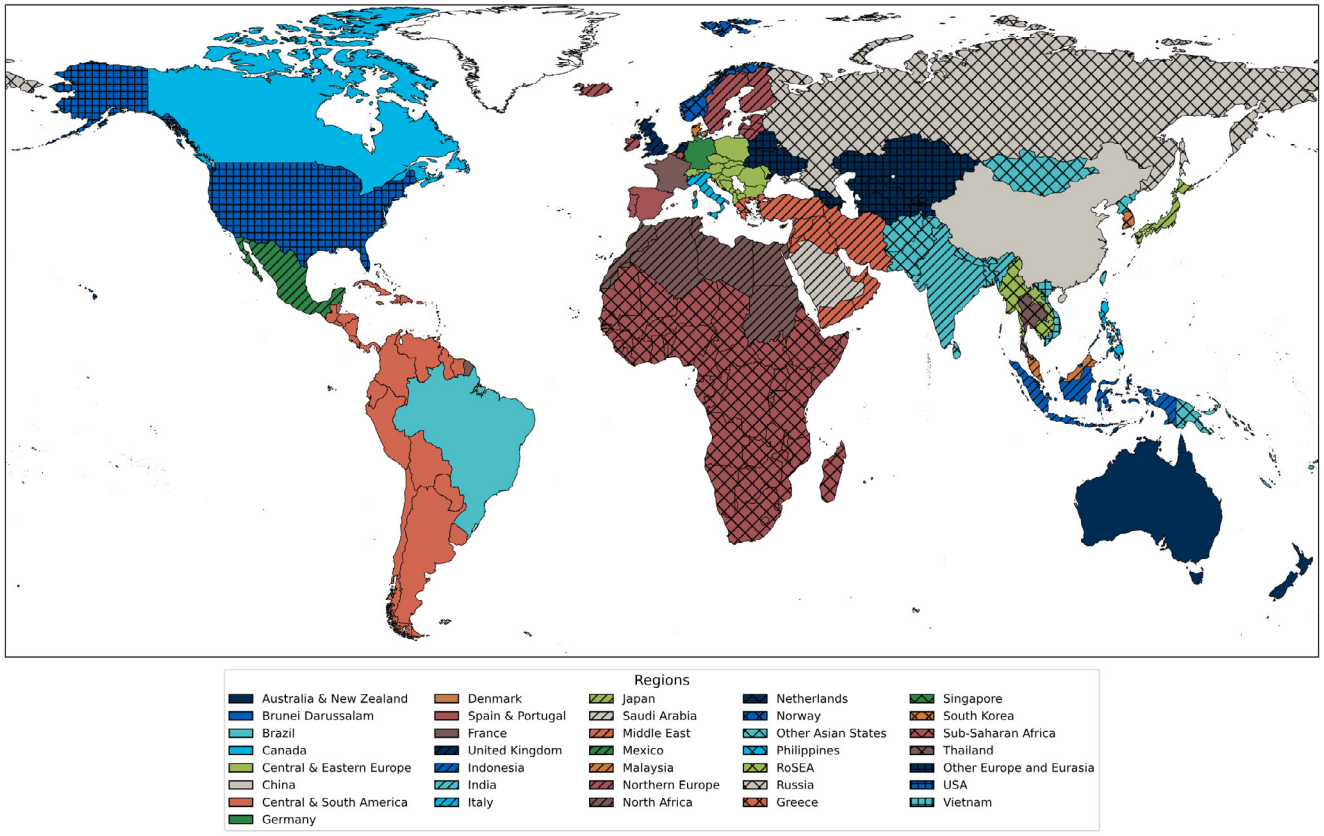


Figure 58. GENZO model regions.

This regional disaggregation allows for detailed analysis of India's energy system while accounting for international energy trade opportunities.

The modelling framework establishes emission budgets based on linear reduction pathways from 2031 baseline emissions to each region's pledged net zero year. Rather than imposing annual emission constraints, allowed emissions were aggregated into multi-year periods (2031-2040, 2041-2050, 2051-2060, and 2061-2065), enabling the model to optimise the timing of emissions reductions within each period while ensuring overall budget compliance (Figure 59).

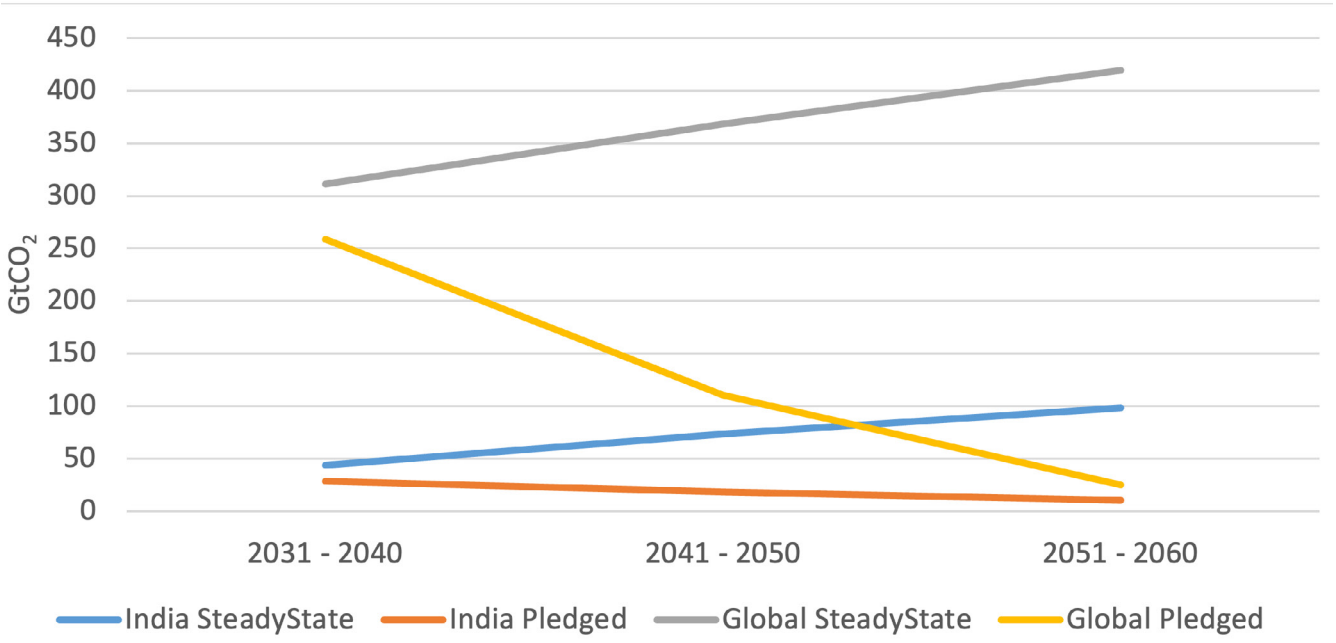


Figure 59. CO_2 budget

38. Scenario design and CO_2 storage assumptions

The analysis examines six distinct net zero scenarios that vary along two key dimensions: CO_2 storage development rates and geographic storage constraints. The storage development rate assumptions are based on historical precedents, particularly the global development of natural gas infrastructure, which grew at approximately 9.5% annually.

Growth rates were applied to CO_2 storage development that reflect the rate at which drilling and construction can be mobilised, without modelling pressure constraints or other in-reservoir limitations. Countries with far more storage capacity than their expected needs, such as the United States, can sustain these growth rates for the full modelling period through 2065. In contrast, countries with significantly smaller total storage capacities, such as the Netherlands, reach their maximum carrying capacity sooner, meaning storage growth stops once that limit is reached.

This approach uses maximum storage capacity values for 45 countries from the OGCI CO_2 Storage Resource Catalogue and an internal assessment for 75 more countries with known storage that comprise GENZO regions (Oil Gas Climate Initiative, 2024). Singapore, Timor-Leste, Kenya, and Iceland were excluded for lack of data. These capacity values are fixed for each country, though in reality, they could be higher or lower, which would directly affect results.

The default growth rate of 9.5% is based on historic gas field development rates derived from GlobalData, a proprietary oil and gas database (GlobalData, 2025b). The growth rates applied – 9.5%, 14%, and 19% – are based on the historic gas field development rate, plus 1.5× and 2× those rates. For some regions in the Expected scenario, we also assume a 4.75% rate, which is ½ the historic gas field development rate. The Global CCS Institute's CO_2RE data was used to determine cumulative CO_2 stored by 2031; this year serves as the starting point in applying these growth rates. For projects without a start year, 2031 was assumed. For projects without an injection rate, P50 values of known projects were used.

For countries in the dataset but not in CO_2RE, it was assumed that by 2035 they would store 0.02% of their net capacity, based on P10 values from countries with available data. Knowing each country's maximum carrying capacity and chosen growth rate, the year of peak storage was calculated to match the 2031 data point.

A SteadyState scenario without a net zero target is included as a reference comparison scenario. The net zero scenarios only differ by the assumed growth rate in CO_2 storage development in each region:

- **Default**: All regions develop CO_2 storage at a rate consistent with historic global development of natural gas infrastructure (~9.5% per annum).
- **Expected**: Each region develops CO_2 storage at an expected rate (India at 14%; others between 4.75% and 19%). In general for the Expected scenario, we relied on expert judgement to assign a rate based on a combination of economic resources, technical capacity, and political will to develop storage. 14% is assumed for India based on this assessment; 14% also provides a middle scenario between Default and Rapid for India.
- **Rapid**: All regions develop storage at 19% annually.
- **Default_domestic / Expected_domestic / Rapid_domestic**: Same assumptions as the above, but India is restricted to domestic storage only.

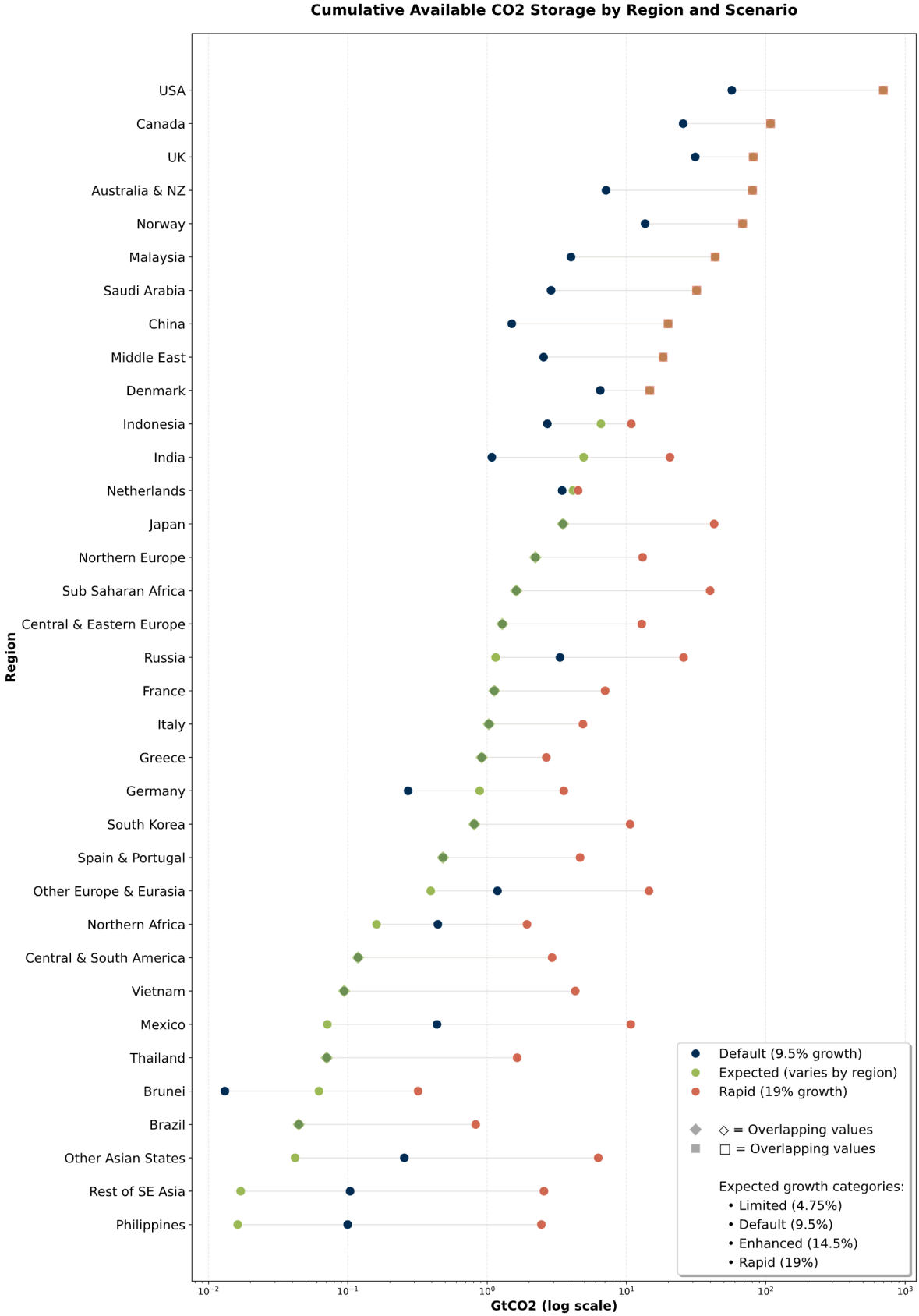


Figure 60. Maximum CO_2 storage available through 2065 by region for the Default, Expected and Rapid scenario assumptions, ordered by Expected from largest to smallest (log scale).

The total CO_2 storage potential varies dramatically across scenarios and regions. In the Expected scenario, some regions like the United States, can develop storage capacity that exceeds global requirements, creating opportunities for international CO_2 transport and storage. Note that GENZO is not required to develop all of this storage capacity; GENZO is *allowed* to develop storage up to this maximum limit. In practice, the United States, for example, develops significantly less than allowed in the Rapid scenario. For regions with limited domestic storage potential, the economic viability of CCS technologies depends critically on the costs of international CO_2 transport, either through pipeline networks to neighbouring regions or via shipping to more distant storage locations.

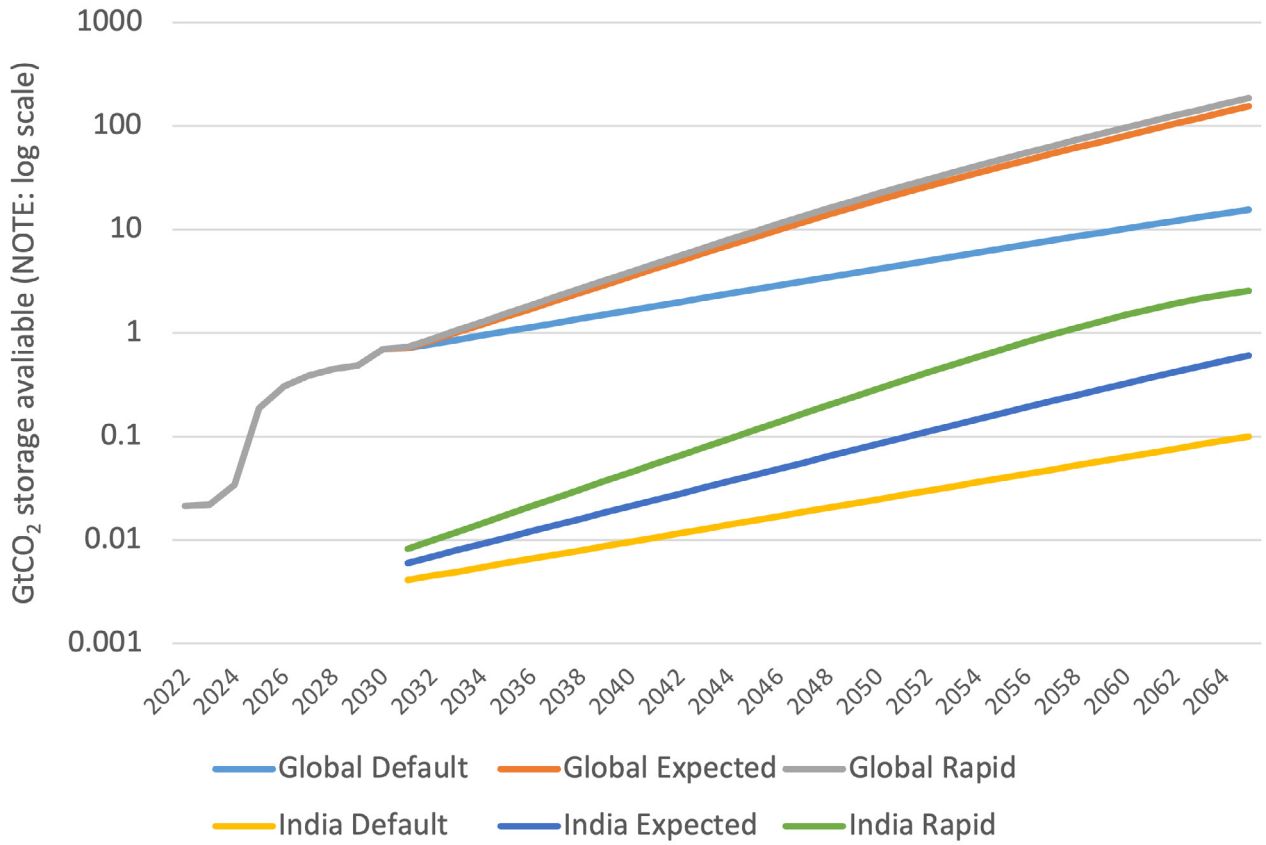


Figure 61. Global and Indian maximum annual CO_2 storage available for the net zero scenarios (log scale)

The annual storage capacity constraints reveal how quickly regions can scale up their CO_2 storage infrastructure. India's storage development profile shows substantial capacity expansion in scenarios with higher growth rates, but the domestic-only variants reveal the limitations imposed when international storage options are unavailable.

39. Pathways to net zero: Technology mix and timing

The modelling results suggest that, under the assumptions used, meeting the modelled net-zero constraints involves substantial changes across India's energy system, with the specific technology mix and deployment timing varying significantly across scenarios based on CO_2 storage availability and development rates (Figure 62).

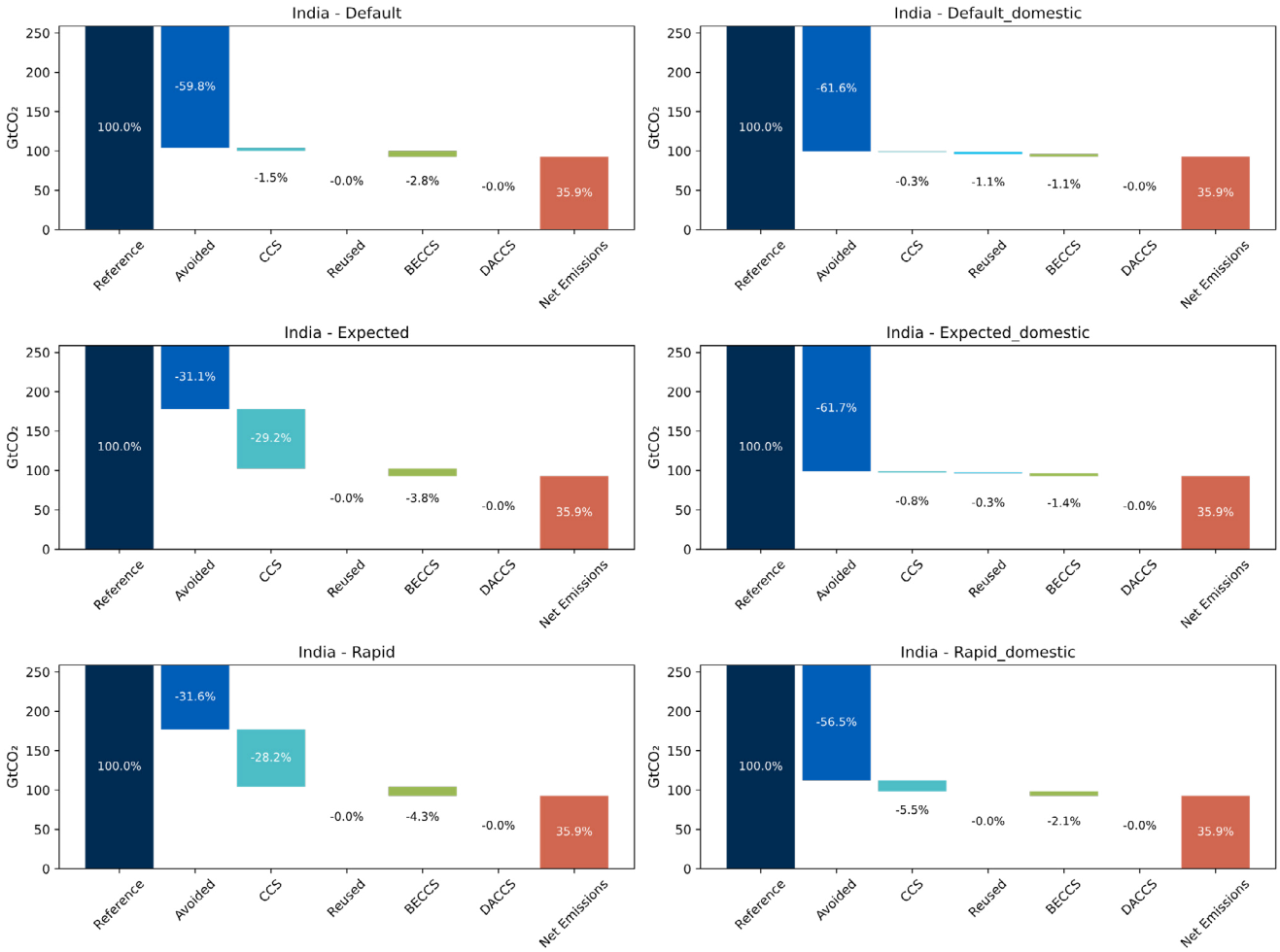


Figure 62. How net zero is achieved

In scenarios with limited CO_2 storage capacity, particularly the domestic-only variants, the energy system compensates through choices that avoid generating emissions in the first place, such as accelerated deployment of renewable energy technologies, increased electrification of end-use sectors, and greater reliance on hydrogen-based solutions. The Expected and Rapid scenarios with international storage access show more balanced technology portfolios, with CCS playing an increasingly prominent role in the later periods as storage capacity becomes abundant. Primary energy consumption patterns reflect these different decarbonisation strategies (Figure 63).

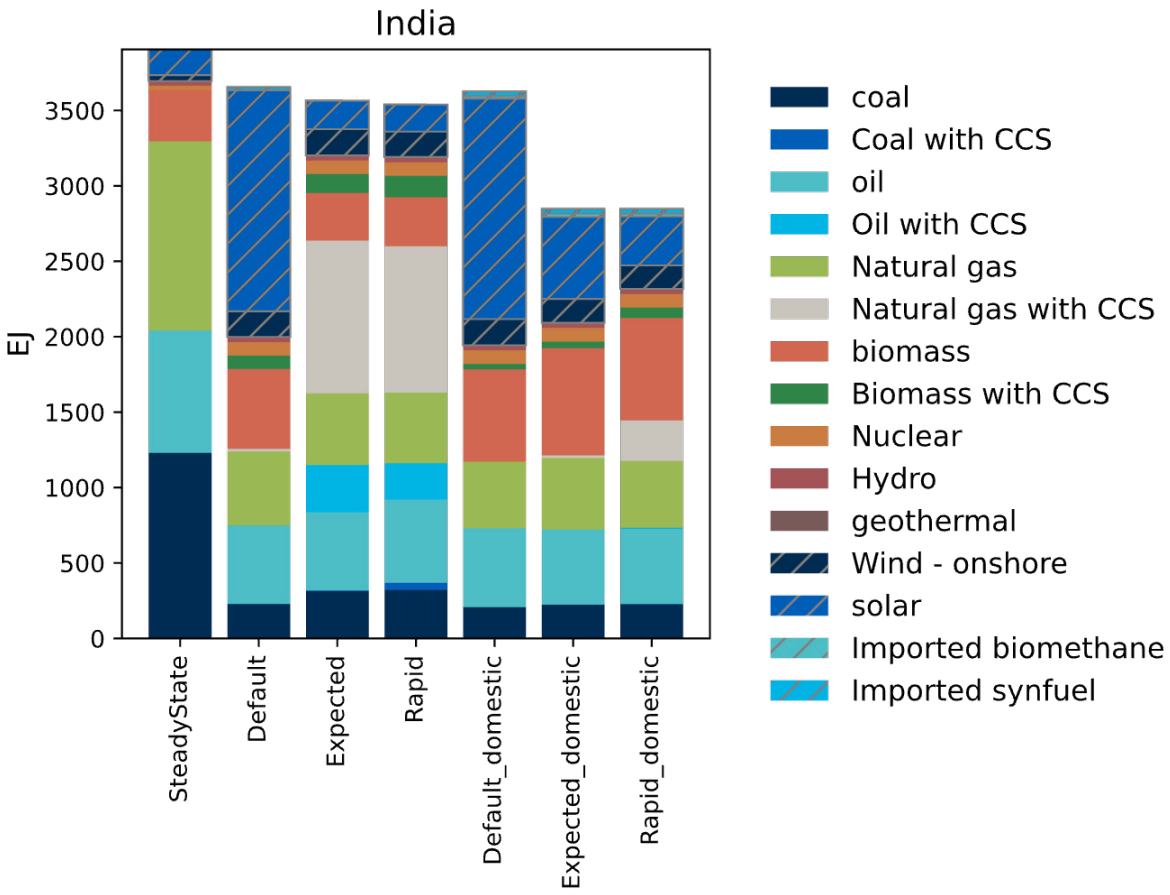


Figure 63. Primary energy use

All net zero scenarios have lower overall energy consumption than the SteadyState scenario because of the shift toward more efficient technologies throughout the energy system. Even though scenarios with limited storage result in more efficient demand-side technology choices, these scenarios rely heavily on pathways that involve tremendous amounts of electricity generation from solar energy to produce hydrogen, and much of that hydrogen is then used to produce baseload dispatchable electricity. That circuitous supply-side pathway is energy-intensive and therefore results in higher primary energy consumption than scenarios with greater CO_2 storage availability. Scenarios with more CO_2 storage availability result in a higher proportion of fossil fuel consumption.

4.3 Carbon capture and storage

The deployment of CCS technologies across different sectors and applications reveals distinct patterns based on storage availability and economic optimisation, with a particularly important dimension being the international transport of captured CO_2.

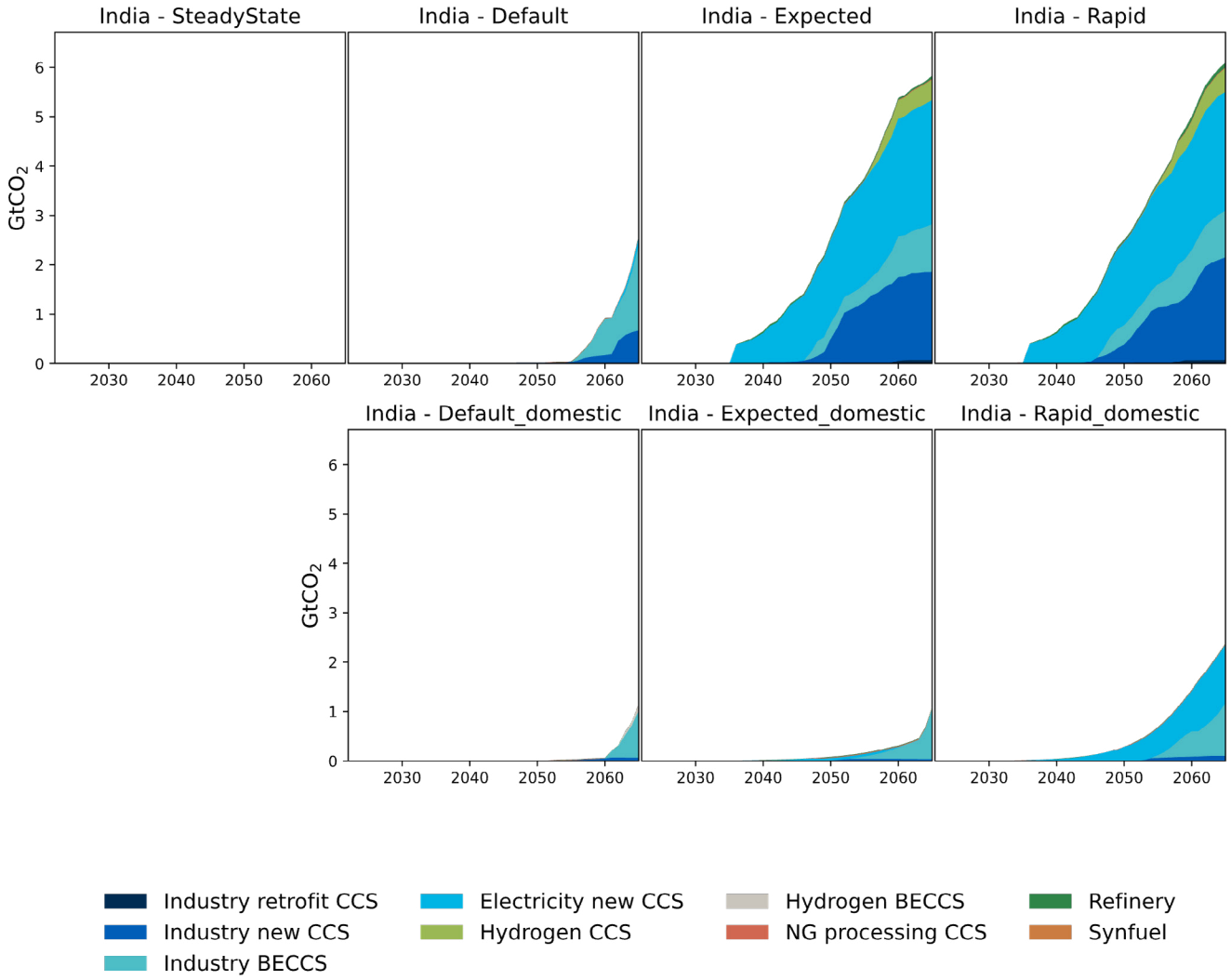


Figure 64. Carbon capture by application

CCS deployment follows markedly different trajectories depending on international CO_2 storage availability and development rates (Figure 64). In the scenarios with international storage access, the model shows CCS deployment accelerating significantly in the 2040s. The 2035-2045 period marks a critical transition where deployment scales up from negligible levels to substantial industrial application, followed by rapid expansion through 2050-2065. Domestic-only storage scenarios show more constrained and delayed deployment, with significant deployment beginning only in the 2050s and reaching much lower ultimate levels.

In scenarios with more domestic storage and international storage access (Expected, Rapid), electricity generation with CCS emerges as the dominant application, reaching 2.5 Gtpa of CO_2 captured by 2065. Power sector deployment begins modestly around 2035 with 0.01-0.017 Gtpa, then accelerates rapidly through the 2040s, reaching 1.2-1.7 Gt by 2045 and plateauing at 2.4-2.5 Gt by

2060-2065. The Rapid domestic scenario has enough available storage to support a more modest 0.82-1.18 Gt by 2060-2065. The Default scenario results in only 0.174 Gt from electricity CCS by 2065. The Expected domestic has negligible amounts of electricity CCS, and the Default domestic has zero.

The electricity CCS results highlight both the power sector's ability to switch to renewable alternatives when CCS is constrained and the economic preference for maintaining some fossil fuel generation with CCS when abundant international storage is available.

Industrial CCS applications follow more consistent but lower-magnitude deployment patterns across scenarios. Industry BECCS becomes the primary industrial CCS application, beginning deployment around 2050 in most scenarios and reaching 0.94-1.07 Gtpa by 2065 across scenarios regardless of storage constraints. This consistency reflects the sector's limited alternatives for deep decarbonisation and the critical role of BECCS in achieving negative emissions to offset residual positive emissions elsewhere in the economy. In contrast, DACCS is not deployed in India in any scenario. DACCS can be cost-effective, but only in regions with both high available storage capacity where DACCS can be located near storage and low-cost low-carbon energy to run DACCS. Even in regions where DACCS can be cost-effective, BECCS is prioritised because it offers not only carbon removal services but also useful carbon-neutral energy. DACCS, by contrast, only offers carbon removal services.

The GENZO model optimises across sectors, meaning that the goal is to find the lowest total system cost. For any given company, BECCS is unlikely to be the lowest cost option. A fossil CCS alternative to BECCS will almost always be less expensive. GENZO builds BECCS in industry not because that is the lowest cost option for industry, but because BECCS is needed for the system to offset residual emissions, and industry BECCS is the lowest cost option to implement BECCS for the benefit of the whole system. In practice, additional policy is needed to give the right price signal to the industrial sector to implement BECCS, such as a direct payment for the carbon removal services that BECCS provides.

New industrial fossil CCS facilities show more storage-dependent deployment patterns. The Rapid scenario achieves the highest deployment levels, reaching 2.08 Gt by 2065, while the Expected scenario follows at 1.78 Gt. Scenarios with domestic storage constraints show dramatically reduced deployment: Expected_domestic reaches only 0.034 Gt and Default_domestic achieves 0.066 Gt by 2065, representing over 95% reductions compared to their international counterparts.

Hydrogen production with CCS emerges only in scenarios with abundant international storage access. The Expected and Rapid scenarios develop significant hydrogen CCS capacity in the 2055-2065 period, reaching 0.41-0.49 Gtpa. This application appears only when both storage capacity is plentiful and international transport infrastructure is available. Fossil fuel-based hydrogen production with CCS is less expensive than hydrogen production from electrolysis and dedicated renewable energy, but when CO_2 storage is limited, other CCS applications become the priority and crowd out hydrogen production with CCS.

The hydrogen CCS that is deployed is from oil partial oxidation technology. Coal gasification with CCS is a hydrogen option within GENZO, but this technology is never deployed in India because the available domestic storage is too limited, even in the Rapid scenario; other, more cost-effective CCS options are used to fill that limited storage space. Shipping CO_2 captured from coal gasification to produce hydrogen makes the cost of that hydrogen uncompetitive compared to other options. As a sensitivity analysis, we attempted to force in some hydrogen production from coal, and the costs were not compeititive under the model assumptions.

Natural gas processing with CCS and CCS in refineries have modest deployment across most scenarios, typically reaching 0.01-0.09 Gtpa, owing to their low capture costs and proximity to storage, at least for natural gas processing.

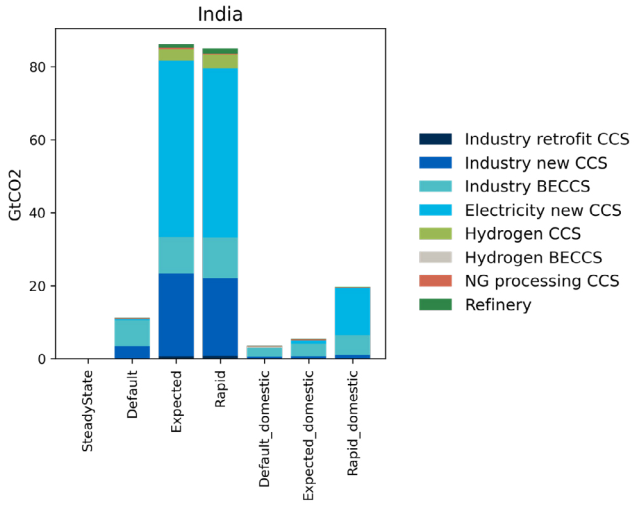


Figure 65. Cumulative capture by application

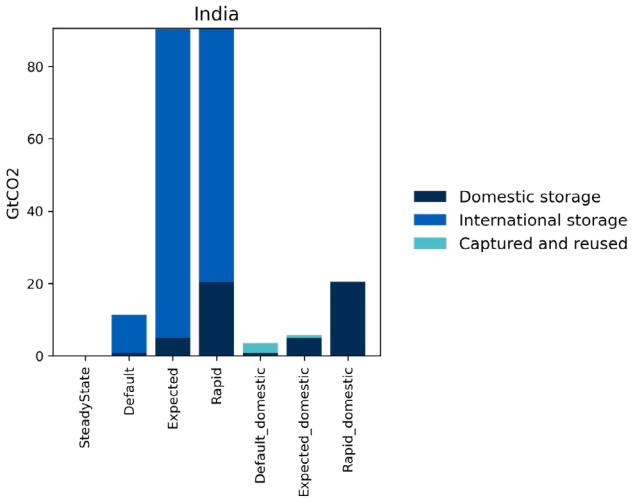


Figure 66. Cumulative capture by destination

The Default_domestic scenario demonstrates that substantial CO_2 capture can occur even under the most restrictive domestic storage constraints, as much of the captured CO_2 is utilised for synthetic fuel production rather than requiring permanent geological storage (Figure 66). This reuse pathway allows the Default_domestic scenario to capture nearly as much CO_2 as its international counterpart, but with fundamentally different end-use applications.

4.4 Discussion: Comparison with existing literature

This analysis contributes to a growing body of literature examining India's pathways to net zero emissions, with several key findings that both align with and extend previous research. The results provide important insights when compared to major studies from international organisations and academic institutions that have analysed India's decarbonisation prospects.

40. Alignment with IEA global analysis

The International Energy Agency's comprehensive analysis of CCUS in clean energy transitions emphasises that CCS is "virtually the only technology solution for deep emissions reductions from cement production" and "the most cost-effective approach in many regions to curb emissions in iron and steel and chemicals manufacturing" (International Energy Agency, 2020a). Our modelling results strongly support this assessment, with industrial CCS applications showing consistent deployment across scenarios, particularly in cement, steel, and chemicals production, where alternative decarbonisation options remain limited.

The IEA's analysis of India's clean energy transition estimates that achieving net zero by 2070 requires approximately $160 billion/year in energy sector investment between now and 2030 – three times current investment levels (International Energy Agency, 2021). Our system cost analysis provides a detailed sectoral breakdown that complements these aggregate investment estimates by revealing how CCS availability affects overall economic efficiency.

The IEA's global perspective on CCUS deployment timelines also aligns with our results, indicating that "the initial focus of CCUS is on retrofitting existing fossil fuel-based power and industrial plants as well as lower-cost CO_2 capture opportunities such as hydrogen production," with bioenergy with CCS (BECCS) and direct air capture (DAC) becoming more prominent over time (International Energy Agency, 2020b). Our scenarios show somewhat similar patterns, with electricity sector CCS dominating early CCS deployment, followed by industrial applications when carbon storage is readily available, while BECCS becomes important in all our net zero scenarios from 2050 onward, reaching around 1 Gtpa by 2065.

41. Relationship to IPCC assessment reports

The IPCC's Sixth Assessment Report provides critical context for interpreting our results. The IPCC WGIII report states that "Net zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels, and use of CCS in the remaining fossil system" (IPCC, 2023). Our scenarios demonstrate exactly this transition, with CCS enabling continued but limited fossil fuel use while renewable energy provides the majority of India's energy supply.

The IPCC's Sixth Assessment Synthesis Report indicates that, even in pathways with very high renewable deployment, achieving net zero CO_2 requires rapid scale-up of industrial carbon capture by 2030, together with substantial reductions in overall fossil fuel use, minimal residual unabated fossil fuel use, and the targeted application of CCS to the remaining fossil fuel system (IPCC, 2023). Our Expected scenario shows India alone could capture over 2 Gtpa by 2065 across all applications, suggesting substantial contributions to global CCS deployment requirements.

Net-zero pathways assessed by the IPCC, including the four illustrative 1.5°C pathways in SR1.5, all rely on CO_2 removal alongside rapid emissions reductions, with bioenergy with CCS (BECCS) and afforestation/reforestation providing the dominant CDR contributions (IPCC, 2018). Our scenarios align with this assessment, showing BECCS deployment primarily in industrial applications where it can provide useful energy, emissions reductions and negative emissions to offset residual emissions elsewhere in the economy.

42. Comparison with Indian academic studies

Recent academic studies specific to India provide important benchmarks for our results. Chaturvedi & Malyan (2022) use the GCAM model to analyse four combinations of peaking and net-zero years for India (2030-2050, 2030-2060, 2040-2070, and 2050-2080) under varying assumptions about the availability of CCS and hydrogen, and show that these technologies play a growing role in enabling deeper and more cost-effective decarbonisation across the scenarios. Our analysis extends this by providing a detailed quantification of how different CCS storage development rates affect technology deployment and costs.

Recent power sector modelling by Shukla et al. (2023) using the MESSAGE model concluded that "Solar PV, wind onshore and offshore, battery storage are the dominant technologies in achieving net zero emissions" with "Solar and wind together contribute 85% and 90% of the total generation capacity in 2050 and 2060, respectively" (Shukla et al., 2023).

Our electricity generation results show similar renewable energy dominance, but our inclusion of CCS scenarios demonstrates how carbon capture can provide additional flexibility in the power sector while maintaining grid reliability.

A comprehensive energy system analysis by S. Dhar et al. (2022) using the MARKAL model examines whether sufficient technological options and opportunities exist to fully decarbonise India's energy system by around mid-century and finds that, under current technology assumptions, a fully net zero energy system by 2050 is not achievable without additional breakthroughs or stronger deployment of emerging options. In that context, the scenarios here show that, if CCS is available at scale alongside other low-carbon technologies, deep decarbonisation of India's energy system becomes achievable, and that the presence or absence of CCS strongly influences both the cost and feasibility of reaching net zero.

43. Comparison with McKinsey analysis

McKinsey's 2022 analysis of India's decarbonisation pathways models two scenarios – a "current line-of-sight (LoS) scenario with current (and announced) policies" and an "accelerated scenario with far-reaching policies" – finding that "India could reduce annual emissions from a historical trajectory of 11.8 $GtCO_2e$ to 1.9 $GtCO_2e$ by 2070" in the LoS scenario (McKinsey & Company, 2022). Our analysis provides complementary insights by focusing specifically on how CO_2 storage development rates affect technology choices and costs, rather than policy scenarios.

McKinsey identifies CCUS as one of four "cross-cutting decarbonisation opportunities" for India, estimating that "CCUS could help capture 11.4 $GtCO_2e$ across these sectors cumulatively by 2070" (McKinsey & Company, 2022). McKinsey estimates of cumulative capture are consistent with our Default scenario, but our Expected and Rapid scenarios show dramatically more capture. The McKinsey analysis is not based on a global energy model that can find the cost-effective international carbon transport opportunities like GENZO can.

44. Unique contributions of this analysis

This study makes several unique contributions to the existing literature on India's net zero pathways. First, the focus on CO_2 storage development rates as a key uncertainty provides granular insights into how infrastructure constraints affect technology deployment – an aspect not thoroughly examined in previous studies. The comparison between domestic storage constraints and international storage access reveals economic implications that extend beyond technology choices to international cooperation and trade patterns.

Second, the detailed analysis of CO_2 transport costs provides novel insights into the economic geography of net zero transitions. Previous studies have generally treated CCS as a domestic technology choice, while our analysis demonstrates how international cooperation on CO_2 infrastructure can generate substantial economic benefits despite requiring significant cross-border payments.

Third, the comprehensive integration of energy system modelling that includes energy and commodity trade between regions reveals how different decarbonisation pathways reshape India's position in global commodity markets. This analysis extends beyond the energy system to examine broader economic implications, including shifts from oil imports to steel and aluminium exports and the emergence of international CO_2 transport as a significant economic sector.

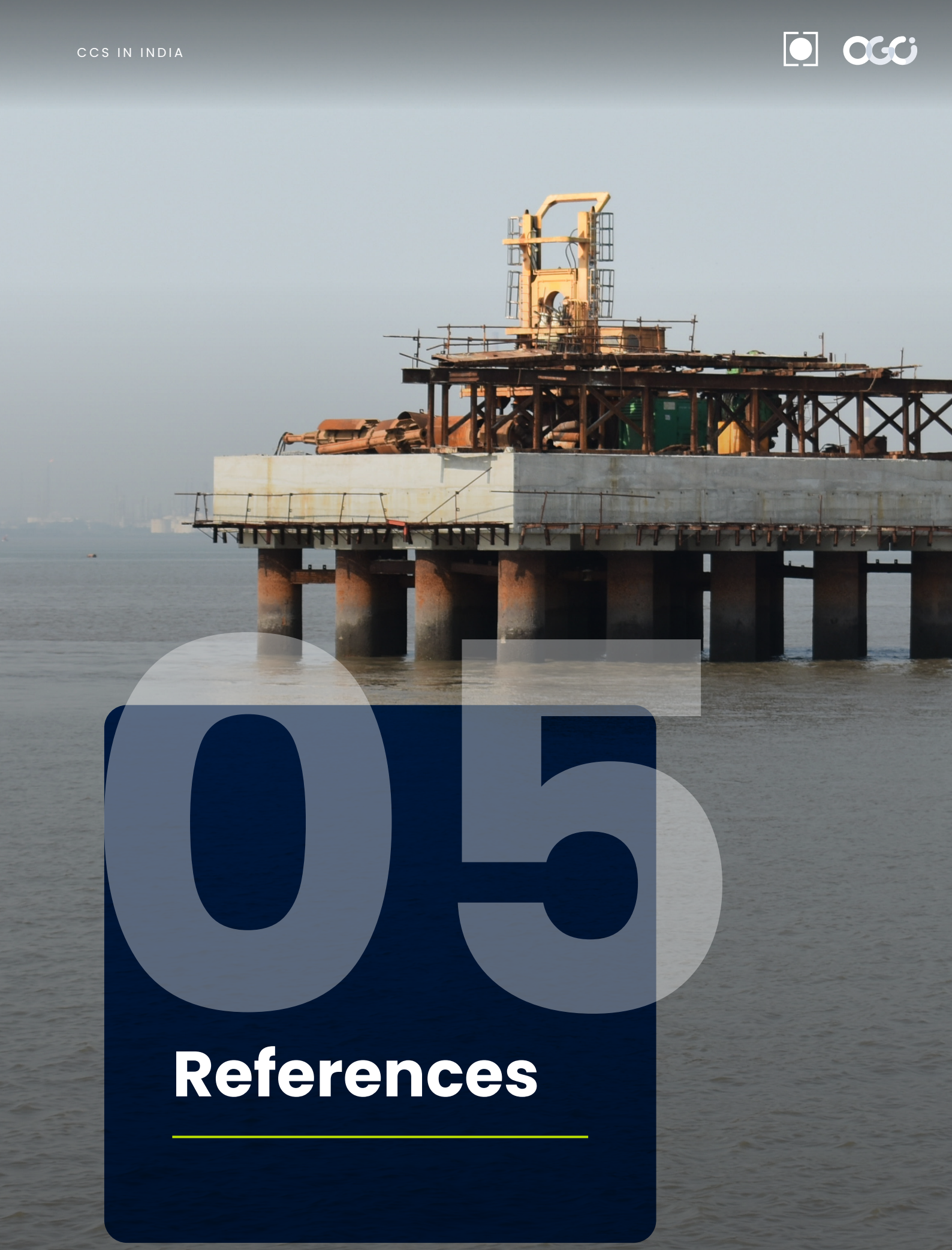
The modelling results reveal several critical policy implications for India's net zero strategy. The role of CCS technologies depends fundamentally on storage development policies, international cooperation frameworks, and the relative support provided to alternative decarbonisation technologies.

Storage development policies emerge as perhaps the most critical determinant of CCS deployment levels. The scenarios demonstrate that storage capacity growth rates significantly impact the economic attractiveness of CCS across all sectors. Policy frameworks that support geological assessment, regulatory development, and infrastructure investment can substantially alter the technology mix required to reach net zero.

International cooperation on CO_2 transport and storage creates substantial economic opportunities for India. The scenarios with international storage access achieve net zero at lower total cost and with less disruption to existing industrial processes. However, this approach requires substantial international coordination and infrastructure development that may face political and technical challenges.

The timing of technology deployment reveals important strategic considerations for policy development. CCS deployment accelerates substantially in the 2040s and 2050s across most scenarios, suggesting that policy support and infrastructure development would likely need to be established well in advance of large-scale deployment. Early-stage support for research, development, and demonstration projects becomes critical for ensuring technology readiness when rapid deployment becomes necessary.

Sector-specific policies must account for the varying roles of CCS across different industries. The results indicate that the electricity sector can decarbonise without relying on CCS, but CCS enables significant cost reductions in the electricity sector, while hard-to-abate industries are more reliant on CCS applications to decarbonise, suggesting that policy support should prioritise hard-to-abate industrial sectors while allowing appropriate policy-driven price signals to guide power sector transformation. However, if the electricity sector relies on a renewables plus hydrogen pathway, the demand for hydrogen puts significant upward pressure on hydrogen prices.



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