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CCUS IN THE INDIAN CEMENT INDUSTRY A REVIEW OF CO_2 HUBS AND STORAGE FACILITIES

Global Cement and Concrete Association

CARBON CAPTURE, UTILIZATION & STORAGE
ACCELERATING CCUS TOGETHER
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

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1.0 INTRODUCTION

India has committed to achieving net zero by 2070, and to achieve 50% electricity generation from renewable sources by 2030. India's economic growth over the past two decades has been among the highest globally, with oil and coal being the foundation for industrial growth and modernization. The rapid population growth has also seen a significant increase in fossil energy consumption - India is currently the world's third highest greenhouse gas emitter. This creates a significant opportunity for carbon capture utilisation and storage (CCUS) to be deployed as a mitigation pathway for India to reach its transformation and emissions reduction targets [1].

Without additional policies, India's Paris Agreement pledges could still see CO_2 emissions from hard-to-abate sectors increasing about 2.6 times between 2020 and 2050. Among others, policy incentives such as carbon pricing that would make CCUS economically competitive, will be critical to achieving sustainable emissions reductions in hard-to-abate sectors [2].

Cement production is responsible for 7-8% of current global CO_2 emissions, and approximately 5.8% of CO_2 emissions in India (2022), the world's second largest cement producer [3]. A recent study by MIT estimated Indian cement production to grow between 150-280% under various scenarios, which will significantly increase CO_2 emissions from this sector. Based on the magnitude of the emissions, the study concludes that "CCS is the only option that substantially reduces both energy emissions and process emissions in cement production" [4].

Concrete is the second most widely used substance on earth after water, reducing CO_2 emissions while producing enough cement to meet growing demand is a daunting challenge. Key strategies to reduce the cement industry's carbon emissions include improved process and material efficiency, switching to lower carbon fuels, and deploying CCUS. In 2021, Global Cement and Concrete (GCCA) published an ambitious Roadmap for carbon neutral concrete by 2050. It outlines multiple levers and milestones that need to be taken on the path to zero emissions. The GCCA roadmap below highlights the critical role CCUS will play i.e. 36% of planned emissions as a global average. Other essential levers include efficiency in design and construction (22%) and efficiency in concrete production (11%) and savings in clinker production (11%).

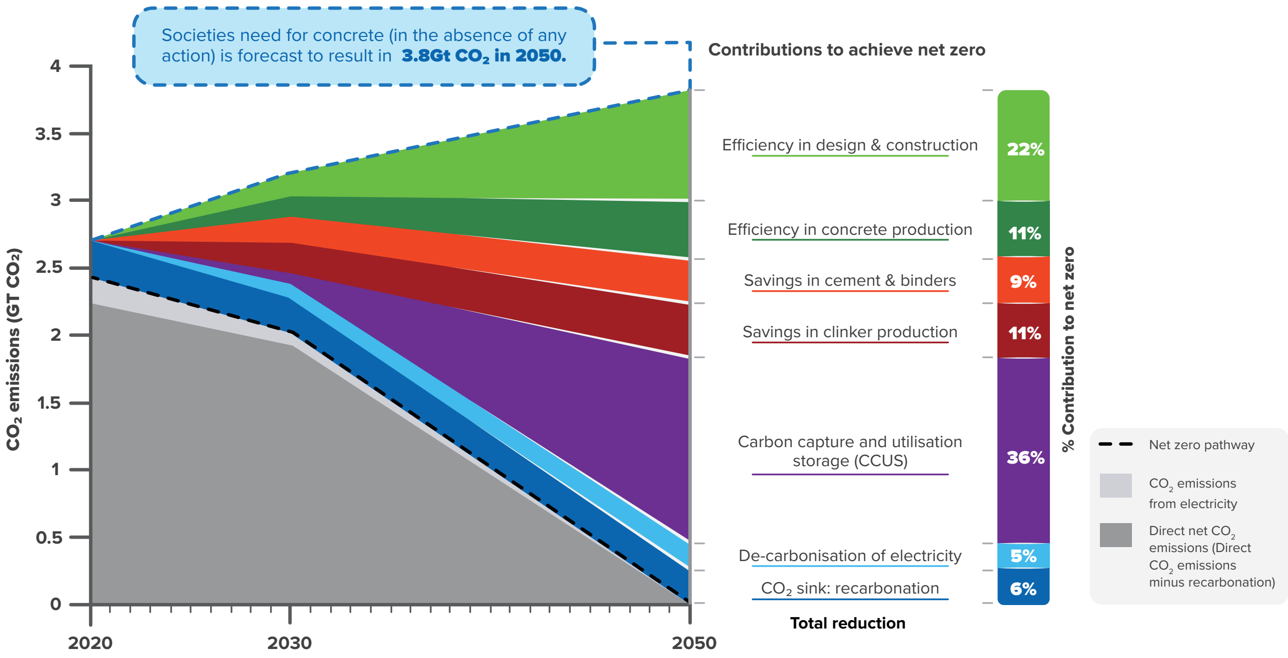


Figure 1: Emissions Reduction Roadmap (GCCA)

In-line with the global roadmap, GCCA India in collaboration with TERI is working on an India-specific roadmap for the Indian cement industry and will be released soon.

In 2023, The Global Cement and Concrete Association (GCCA), The Global CCS Institute (GCCSI) and the Clean Energy Ministerial (CEM) CCUS Initiative partnered to collaboratively deliver a study on how to kickstart the deployment of CCUS in the Indian cement industry. This paper is the first in a series of papers that will explore all relevant aspects of such deployment, including capture, transport and storage aspects, as well as the policy, legal, and regulatory environment, and commercial models for deployment of CCUS in the Indian cement sector.

This report includes a review of onshore and offshore geological storage resources in India, where captured CO_2 from cement facilities could potentially be transported and permanently stored. It further provides an analysis of the potential to develop CO_2 hubs (clustering of cement facilities based on locational information) in proximity to the most viable potential storage locations. A techno-economic analysis, based on emissions data of cement facilities in India, estimating the total cost of capture, compression and transport, assuming renewables provide the necessary energy for capture and compression, completes the source-sink analysis.

The study underscores a significant lack of publicly available data for a more reliable assessment of CO_2 storage resources in saline formations across all basins. Consequently, the reported values in this study, as well as those in the literature, are subject to uncertainty, emphasizing the urgent need to take action on gathering and publishing the required subsurface data.

Significant potential exists to capture, transport and store CO_2 emissions from the Indian cement industry, supporting India's committed GHG emissions reduction targets, and further analysis will be required to fully understand and capitalise on this potential.

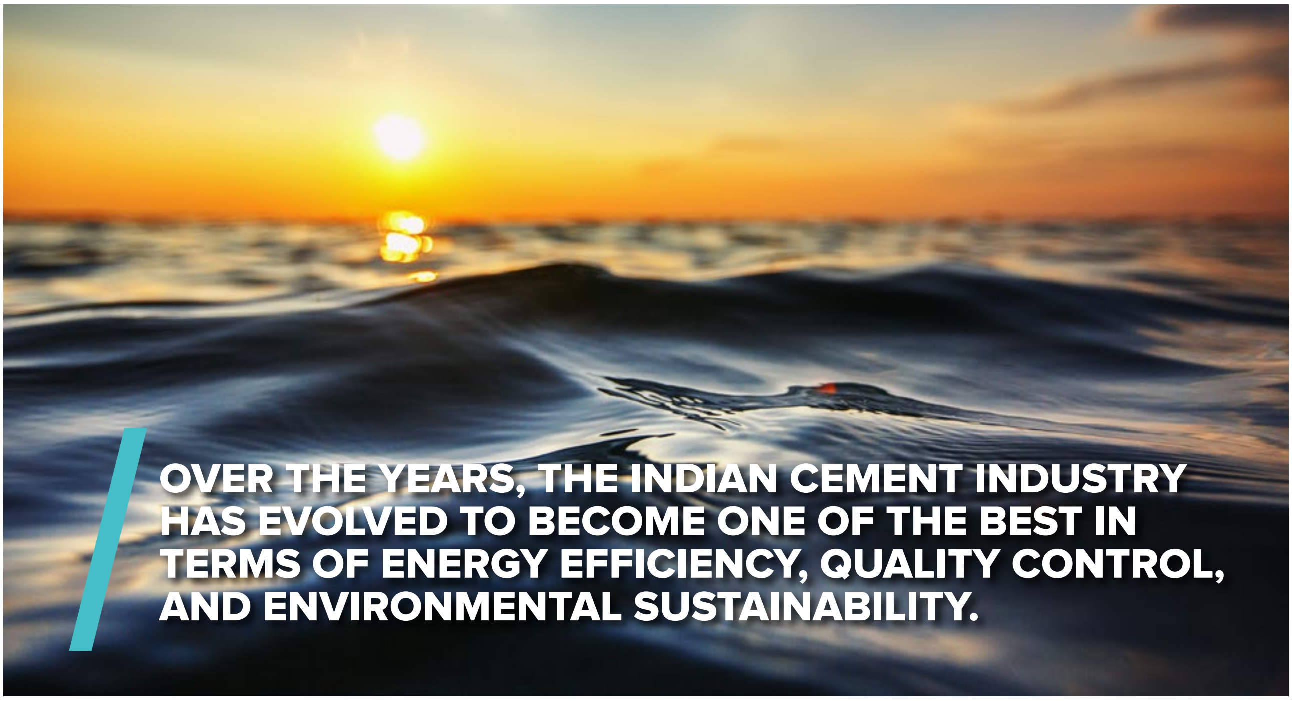
2.0 CURRENT STATUS OF THE INDIAN CEMENT INDUSTRY

Cement is the primary product used in infrastructure development and housing sectors. India's cement sector has achieved one of the lowest emission intensities in the world. The Indian cement industry is one of India's core industries and holds significant importance in the country's economy. It is the second-largest cement industry in the world, following China, accounting for 8% of total installed capacity.

The cement industry plays a vital role in the growth and economic development of India because of its strong linkage to other sectors such as infrastructure, construction, housing, transportation, coal, power, etc. The current installed capacity of the cement industry in India (2022-23) is 594.14 million tonnes, with cement production of around 361 million tonnes (2021-22). There are a total of 333 cement manufacturing units in India, comprising 150 large integrated cement plants, 116 grinding units, 62 mini cement plants, and 5 clinkerization units. Cement consumption in India is around 260 kg per capita against a global average of 540 kilograms per capita, which shows significant potential for the growth of the industry. Indian cement industry employs more than a million people directly or indirectly [5]. For every million tonnes of installed cement production capacity, 20,000 downstream jobs are created [6].

Over the years, the Indian cement industry has evolved to become one of the best in terms of energy efficiency, quality control, and environmental sustainability. Indian cement and concrete sector is forward-looking and would like to accelerate the decarbonisation initiatives further to achieve net zero CO_2 emissions at Concrete and in alignment with the government of India's net zero commitment.

Indian cement industry has been working on the issue of its GHG emissions and has brought down the CO_2 emission factor from 1.12 t CO_2/tonne of cement in 1996 to 0.719 t of CO_2/tonne of cement in 2010. Moreover, the CO_2 emission factor was further reduced to 0.617 t CO_2/tonne of cement by 2020-21 [7], [8], [9].



3.0 CO_2 STORAGE RESOURCES IN INDIA

The aim of this study is to estimate storage resources in saline formations, conventional oil and gas fields, and basalt lava flows in India. The reported values can serve as a reference for gaining a basic understanding of the storage resources in India.

3.1 Basin assessment

According to data from the Directorate General of Hydrocarbons (DGH) [10] and the National Data Repository (NDR) of India [11]. India has 25 sedimentary basins (Assam Shelf and Assam-Arakan Fold belt are both part of the Assam-Arakan Basin), covering an extensive 3.36 million km^2. Figure 2 illustrates the distribution of these basins across the country. Table 1 provides the names of these basins along with their respective areal extents. The areal extent includes both onshore and offshore components, where applicable.

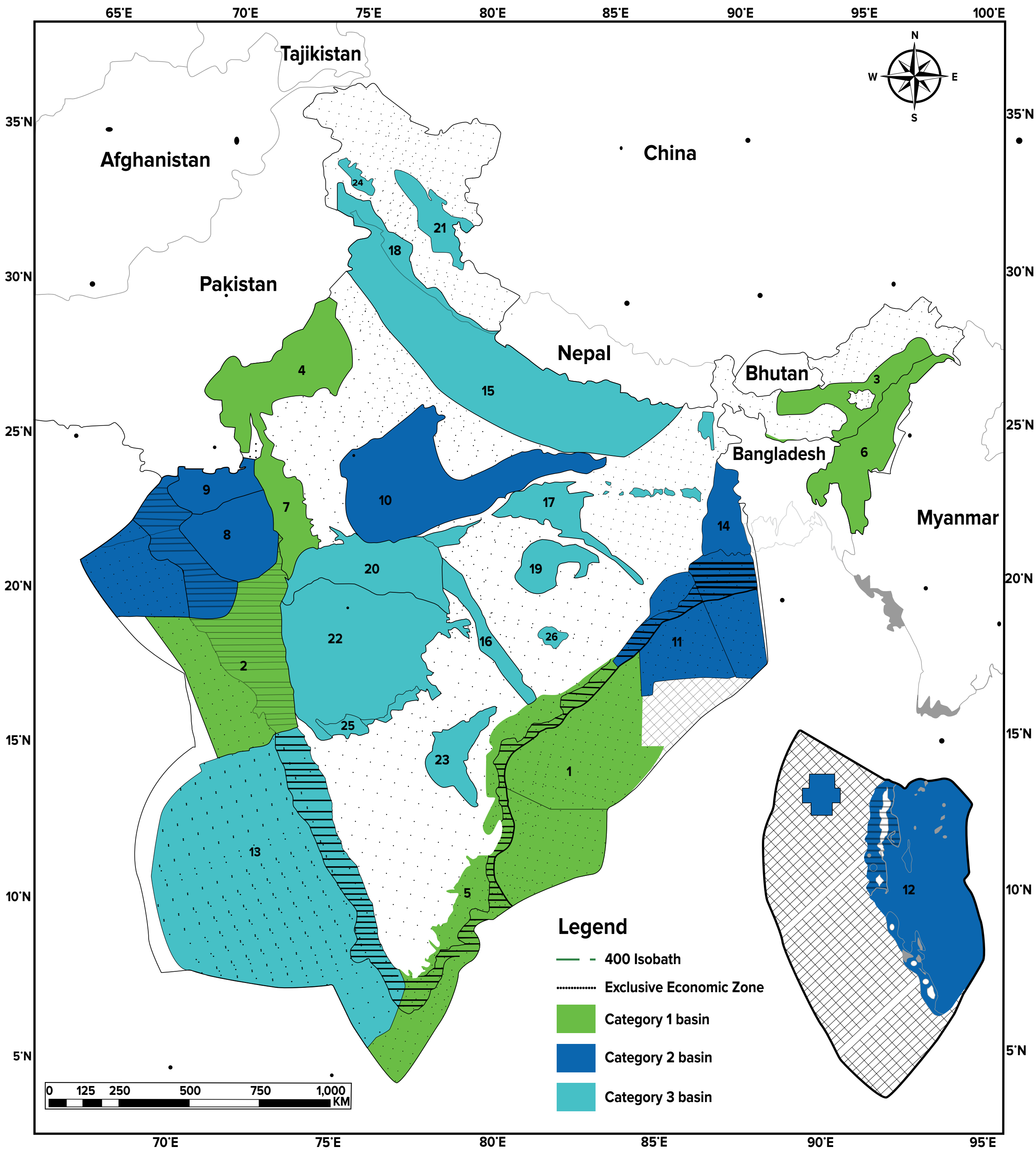
In this study, basins with a well-established hydrocarbon exploration and production history are categorised as Category 1 (Figure 1), basins with contingent resources pending commercial production (partially explored with no production history) are categorised as Category 2, and basins that are largely unexplored and offer prospective resources awaiting discovery are categorised as Category 3.

An analysis of the number of hydrocarbon fields, encompassing both conventional and unconventional oil and gas fields, as well as heavy oil fields within each basin, reveals that the Krishna-Godavari, Mumbai Offshore, Rajasthan, Cauvery, Assam-Arakan, and Cambay basins have been well explored (Category 1). In contrast, the Saurashtra, Kutch, Vindhyan, Mahanadi, Andaman-Nicobar, and Bengal basins are only partially explored (Category 2), while the remaining basins are largely unexplored (Category 3). Table 1 provides insights into the quantity of conventional and unconventional oil and gas fields, along with heavy oil fields in each basin. Basins grouped under categories 1 and 2 cover 29.66% and 26.83% of the basinal area.

As depicted in Figure 3, producing conventional oil fields are exclusively found in basins belonging to Category 1. The Cambay Basin stands out with 21 out of 40, highlighting its extensive hydrocarbon exploration history. Figure 4 displays the number of discovered conventional oil fields per basin in India, all of which are situated in Category 1 basins. Figure 5 showcase the number of operational conventional gas fields per basin in India, all of which are located in Category 1 basins. Figure 6 presents the number of discovered conventional gas fields per basin across India, spanning both Category 1 and 2 basins. The status of conventional oil and gas fields is presented in Table 2 and Table 3. The field's data are sourced from the GlobalData platform.

Considering the exploration and production track record of hydrocarbon fields in Category 1 basins, saline formations, as well as the oil and gas fields within these basins, offer early opportunities for CO_2 storage.

There have been no comprehensive formation-scale studies (in English) on the geological CO_2 storage potential of saline formations in India for which supporting data is available. This is mainly due to the limited availability of subsurface data in the public domain in India. This data, primarily sourced from petroleum wells, includes information on saline formation extent, thickness, and net-to-gross ratio (NTG), and reservoir properties such as porosity, permeability, pressure, and temperature. Such data is crucial for conducting detailed formation or site-scale assessments. Therefore, without access to this data, such analysis is beyond the scope of this study.



01. Krishna-Godavari (KG)
02.Mumbai Offshore
03. Assam-Shelf
04. Rajasthan
05. Cauvery
06. Assam-Arakan Fold Belt
07. Cambay
08. Saurashtra
09. Kutch
10. Vindhyan
11. Mahanadi
12. Andaman
13. Kerala-Konkan (KK)
14. Bengal-Purnea
15. Ganga-Punjab
16. Pranhita-Godavari (PG)
17. Satpura- South Rewa-Damodar
18. Himalayan Foreland
19. Chhattishgarh
20. Narmada
21. Spiti-Zanskar
22. Deccan Syneclise
23. Cuddapah
24. Karewa
25. Bhima-Kaladgi
26. Bastar

Figure 2 Sedimentary basins of India [10]

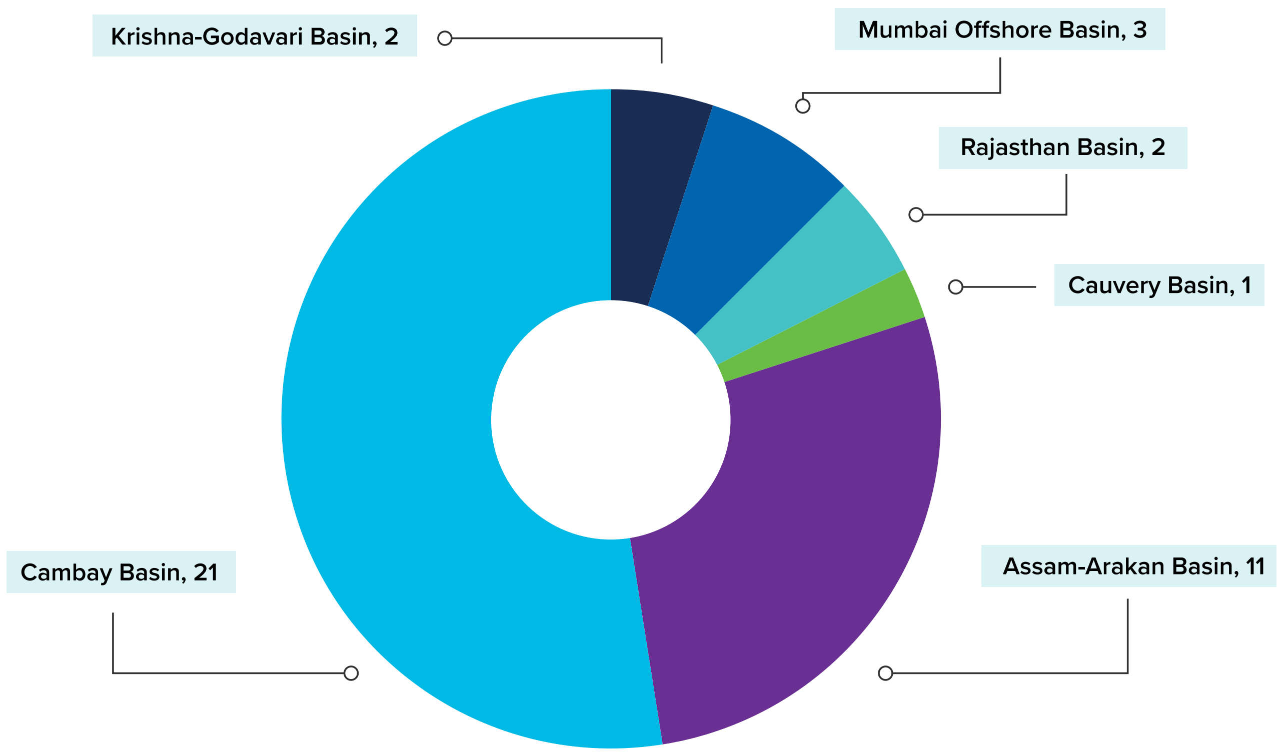


Figure 3 Producing conventional oil fields in India with the basin and number of fields labelled.

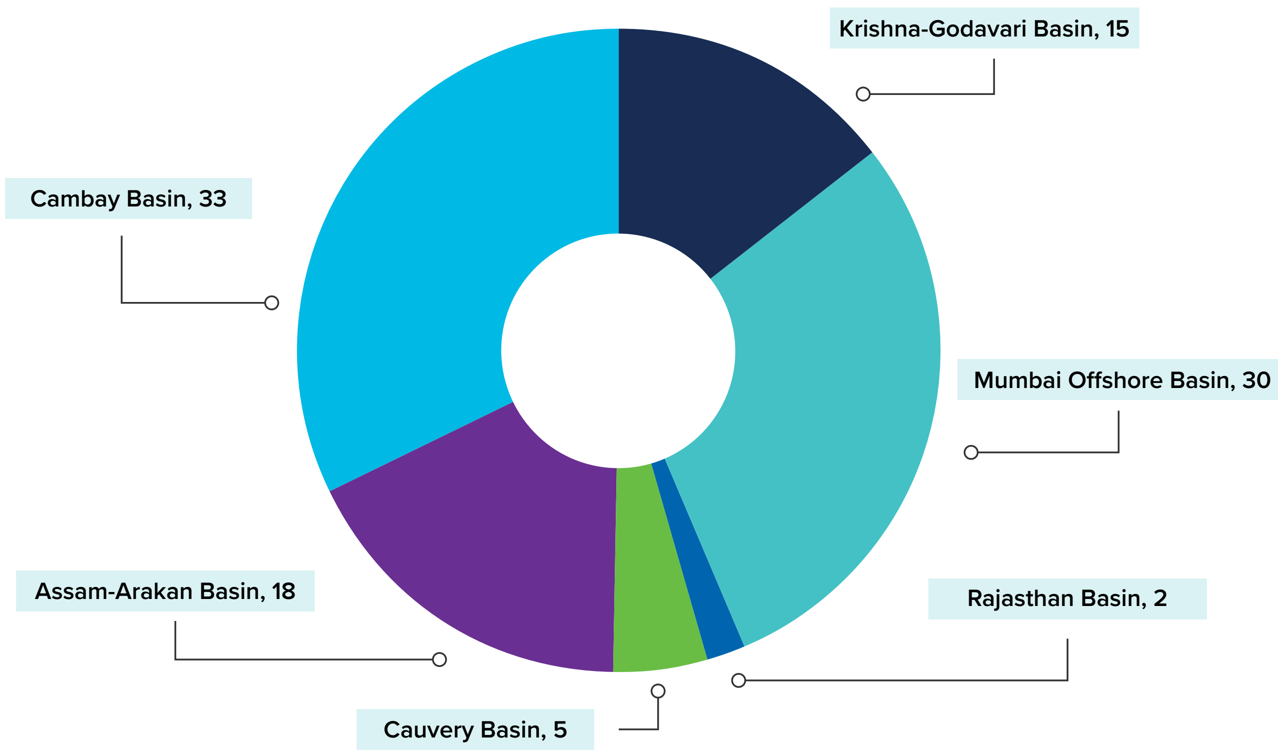


Figure 4 Discovered conventional oil fields in India with the basin and number of fields labelled.

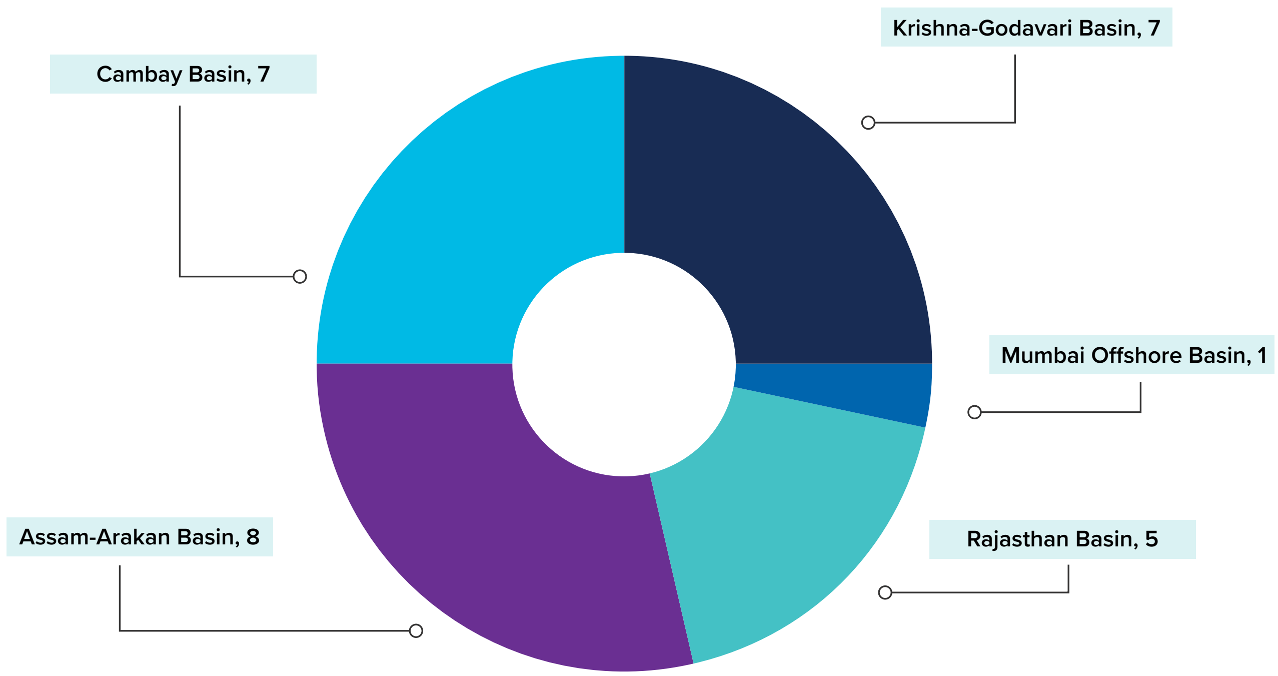


Figure 5 Producing conventional gas fields in India with the basin and number of fields labelled.

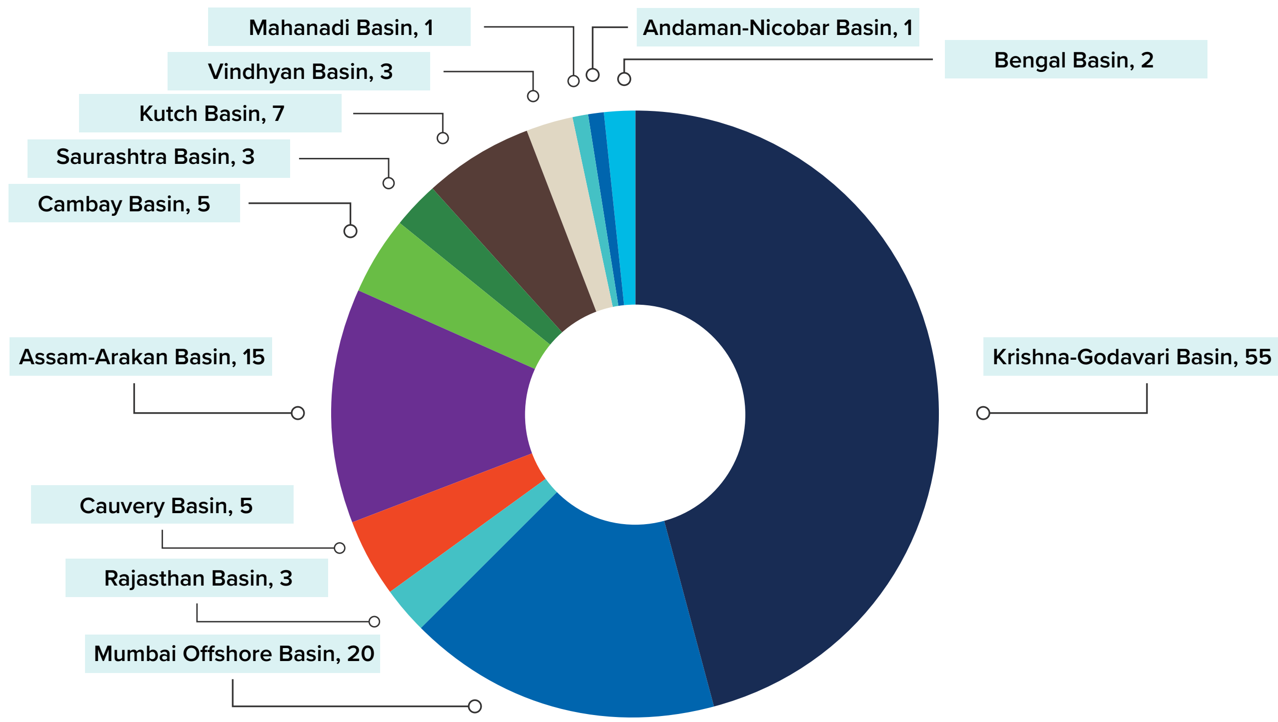


Figure 6 Discovered conventional gas fields in India with the basin and number of fields labelled.

BASIN	AREA (KM²)	OFFSHORE/ ONSHORE	CATEGORY	NUMBER OF CONVENTIONAL OIL FIELDS	NUMBER OF CONVENTIONAL GAS FIELDS	NUMBER OF HEAVY OIL FIELDS	NUMBER OF UNCONVENTIONAL GAS FIELDS
Krishna-Godavari	230,000	Onshore and Offshore	1	20	73		
Mumbai Offshore	212,000	Offshore	1	38	30		
Rajasthan	126,000	Onshore	1	4	13	3	
Cauvery	240,000	Onshore and Offshore	1	10	7		
Assam-Arakan	136,825	Onshore	1	38	29	2	
Cambay	53,500	Onshore and Offshore	1	68	16	5	1
Saurashtra	194,114	Onshore and Offshore	2		3		
Kutch	58,554	Onshore and Offshore	2	1	8		
Vindhyan	202,888	Onshore	2		4		
Mahanadi	99,500	Onshore and Offshore	2		7		
Andaman-Nicobar	225,918	Offshore	2		1		
Bengal	121,914	Onshore and Offshore	2		2		
Kerala-Konkan	580,000	Offshore	3				
Ganga	304,000	Onshore	3				
Pranhita-Godavari	30,000	Onshore	3				
Satpura	57,180	Onshore	3				
Himalayan Foreland	30,110	Onshore	3				
Chhattisgarh	32,000	Onshore	3				
Narmada	95,215	Onshore	3				
Spiti Zanskar	32,000	Onshore	3				
Deccan Syneclise	237,500	Onshore	3				
Cuddapah	40,100	Onshore	3				
Karewa	6,671	Onshore	3				
Bhima Kaladgi	14,100	Onshore	3				
Bastar	5,360	Onshore	3				

Table 1 Indian sedimentary basins and their exploration status. The table presents the cumulative count of fields, categorised by status, including producing, abandoned, announced, discovered, and planned.

BASIN	CATEGORY	OIL FIELDS - ABANDONED	OIL FIELDS - ANNOUNCED	OIL FIELDS - DISCOVERED	OIL FIELDS - PLANNED	OIL FIELD - PRODUCING	OIL FIELDS - STALLED	OIL FIELDS - SUSPENDED
Krishna-Godavari	1		1	15	2	2		
Mumbai Offshore	1		4	30		3	1	
Rajasthan	1			2		2		
Cauvery	1			5		1	3	1
Assam-Arakan	1		5	18	2	11	2	
Cambay	1	3	7	33	1	21	2	1
Saurashtra	2							
Kutch	2		1					
Vindhyan	2							
Mahanadi	2							
Andaman-Nicobar	2							
Bengal	2							

Table 2 Status of conventional oil fields in India

BASIN	CATEGORY	OIL FIELDS - ABANDONED	OIL FIELDS - ANNOUNCED	OIL FIELDS - DISCOVERED	OIL FIELDS - PLANNED	OIL FIELD - PRODUCING	OIL FIELDS - STALLED	OIL FIELDS - SUSPENDED
Krishna-Godavari	1	1	9	55		7	1	
Mumbai Offshore	1	1	7	20		1	1	
Rajasthan	1	3		3		5	2	
Cauvery	1	2		5				
Assam-Arakan	1	1	3	15		8	2	
Cambay	1	1	2	5		7		1
Saurashtra	2			3				
Kutch	2		1	7				
Vindhyan	2		1	3				
Mahanadi	2		6	1				
Andaman-Nicobar	2			1				
Bengal	2			2				

Table 3 Status of conventional gas fields in India

4.0 CO_2 STORAGE RESOURCES OF SALINE FORMATIONS

4.1 Overview of existing studies

There have been only few studies that assessed the storage resources of saline formations in India. These studies primarily calculate storage resources at the basin scale, and the reported numbers come with a high degree of uncertainty. This degree of uncertainty is standard during the early screening and ranking phase at the basin scale. Table 4 presents the reported values from these studies.

- The IEA and Holloway studies [12], [13] utilised a theoretical specific storage capacity of 0.2 $MtCO_2/km^2$, applying it to the areal extent of the basins while assuming the presence of suitable saline formations in 50% of the Indian basins. This methodology is based on Wildenborg et al. [14], who derived a specific storage density of 0.2 Mt of CO_2/km^2 for Europe.

- Bakshi et al. [15] on the other hand, employed the same theoretical specific storage capacity of 0.2 $MtCO_2/km^2$ and applied it to the areal extent of the basins while assuming the presence of suitable aquifers in all the Indian basins.

- Singh et al. [16] based their assessment on borehole information from two samples, drilling as deep as 1,500 meters, around Delhi from ONGC, and groundwater well bores (ranging from 200 to 300 meters deep). The authors assumed the existence of several large and potentially suitable sedimentary basins onshore, and the results were extrapolated to estimate the total capacity for the entire country.

Upon comparing these studies, it is evident that there are variations in the areal extent values used for some basins. In this study, the most recent values reported by the Directorate General of Hydrocarbons (DGH) and the National Data Repository (NDR) of India were relied upon for assessment.

REFERENCE	STORAGE RESOURCES (GIGATONNE CO_2)
IEA [12]	63
Holloway et al. [13]	63
Singh et al. [16]	360
Bakshi et al. [15]	325
Vishal et al. [17]	291

Table 4 Estimated net CO_2 storage resources in saline formations in India.

4.2 Results and Discussion: Saline Formations

The results of the saline formation calculations are presented in Table 5 (Refer to Appendix for the methodology of saline formation resource calculation).

The total net storage resources, obtained by summing the P50 values across all 25 basins, amount to 618 Gigatonnes (Gt) CO_2. It's important to note that within this total, around 300 Gt corresponds to onshore resources, 76 Gt to offshore shallow resources, and 243 Gt to offshore deep resources. For reference, the conservative P10 value is still estimated at 113 $GtCO_2$, which includes onshore and offshore.

As discussed in the Basin assessment section, basins grouped under Category 1 offer early opportunities for CCUS deployment followed by basins grouped under Category 2. Basins grouped under Category 1 account for 29.7% of storage resources, while those under Category 2 account for 26.8% of total storage resources. This ratio is similar to the surface area ratio mentioned earlier because, due to a lack of data, all parameters except surface area are kept similar between all the basins in our calculations.

BASIN	CATEGORY	NET AREA (KM²)	AREA - ONSHORE (KM²)	AREA - OFFSHORE - SHALLOW (WATER DEPTH <400 M) (KM²)	AREA OFFSHORE-DEEP (KM²)	NET RESOURCES ($GTCO_2$)			ONSHORE RESOURCES ($GTCO_2$)	OFFSHORE-SHALLOW (WATER DEPTH <400 M) RESOURCES ($GTCO_2$)	OFFSHORE-DEEP RESOURCES ($GTCO_2$)	STORAGE RESOURCES (%)
						P10	P50	P90	P50	P50	P50	
Krishna-Godavari Basin	1	230,000	31,456	256,49	172,895	7.71	42.24	206.63	5.78	4.71	31.75	29.70
Mumbai Offshore Basin	1	212,000	0	118,389	93,611	7.10	38.94	190.46	0.00	21.74	17.19	
Rajasthan Basin	1	126,000	126,000	0	0	4.22	23.14	113.20	23.14	0.00	0.00	
Cauvery Basin	1	240,000	37,825	43,723	158,452	8.04	44.08	215.61	6.95	8.03	29.10	
Assam-Arakan Basin	1	136,825	136,825	0	0	4.58	25.13	122.92	25.13	0.00	0.00	
Cambay Basin	1	53,500	48,882	4,618	0	1.79	9.83	48.06	8.98	0.85	0.00	
Saurashtra Basin	2	194,114	75,076	42,617	76,421	6.50	35.65	174.39	13.79	7.83	14.04	26.80
Kutch Basin	2	58,554	30,754	20,500	7,300	1.96	10.75	52.60	5.65	3.77	1.34	
Vindhyan Basin	2	202,888	202,888	0	0	6.80	37.26	182.27	37.26	0.00	0.00	
Mahanadi Basin	2	99,500	15,500	14,211	69,789	3.33	18.27	89.39	2.85	2.61	12.82	
Andaman-Nicobar Basin	2	225,918	0	18,074	207,844	7.57	41.49	202.96	0.00	3.32	38.17	
Bengal Basin	2	121,914	42,414	33,465	46,035	4.08	22.39	109.52	7.79	6.15	8.45	
Kerala-Konkan Basin	3	580,000	0	90,380	489,620	19.43	106.52	521.06	0.00	16.60	89.92	43.50
Ganga Basin	3	304,000	304,000	0	0	10.18	55.83	273.11	55.83	0.00	0.00	
Pranhita-Godavari Basin	3	30,000	30,000	0	0	1.01	5.51	26.95	5.51	0.00	0.00	
Satpura Basin	3	57,180	57,180	0	0	1.92	10.50	51.37	10.50	0.00	0.00	
Himalayan Foreland Basin	3	30,110	30,110	0	0	1.01	5.53	27.05	5.53	0.00	0.00	
Chhattisgarh Basin	3	32,000	32,000	0	0	1.07	5.88	28.75	5.88	0.00	0.00	
Narmada Basin	3	95,215	95,215	0	0	3.19	17.49	85.54	17.49	0.00	0.00	
Spiti Zanskar Basin	3	32,000	32,000	0	0	1.07	5.88	28.75	5.88	0.00	0.00	
Deccan Syneclise Basin	3	237,500	237,500	0	0	7.96	43.62	213.36	43.62	0.00	0.00	
Cuddapah Basin	3	40,100	40,100	0	0	1.34	7.36	36.02	7.36	0.00	0.00	
Karewa Basin	3	6,671	6,671	0	0	0.22	1.23	5.99	1.23	0.00	0.00	
Bhima Kaladgi Basin	3	14100	14,100	0	0	0.47	2.59	12.67	2.59	0.00	0.00	
Bastar Basin	3	5360	5,360	0	0	0.18	0.98	4.82	0.98	0.00	0.00	
Total storage resources ($GTCO_2$):						113	618	3,023	300	76	243	

Table 5 Net storage resource of saline formations in each basin.

4.3 Applicability and Limitations

As discussed earlier, due to the lack of studies on saline formations in Indian basins and, the absence of data, several major assumptions have been made in the assessment, leading to a high degree of uncertainty. Therefore, the results presented above should only be considered as a high-level theoretical values for understanding of the net storage resources in the saline formations of each basin.

The methodology and results presented in this study are not a substitute for detailed assessments required at the site-scale for CO_2 storage project development.

Regarding the limitations of the used approach in this study, it should be noted that using equation 1 (refer to appendix) ($MCO_2 = A.\ H.Ø.\ E.\rho$), only physical trapping can be estimated. Equation 1 does not consider solubility trapping. Additionally, the used approach assumes the existence of open boundaries, which may not apply to all saline formations. Closed boundary conditions will negatively impact the storage resources due to pressure constraints.

5.0 POTENTIAL SALINE FORMATIONS

Due to the lack of publicly available subsurface data on saline formations, analytical assessments at the formation scale could not be conducted to identify, screen, and rank formations for CO_2 storage.

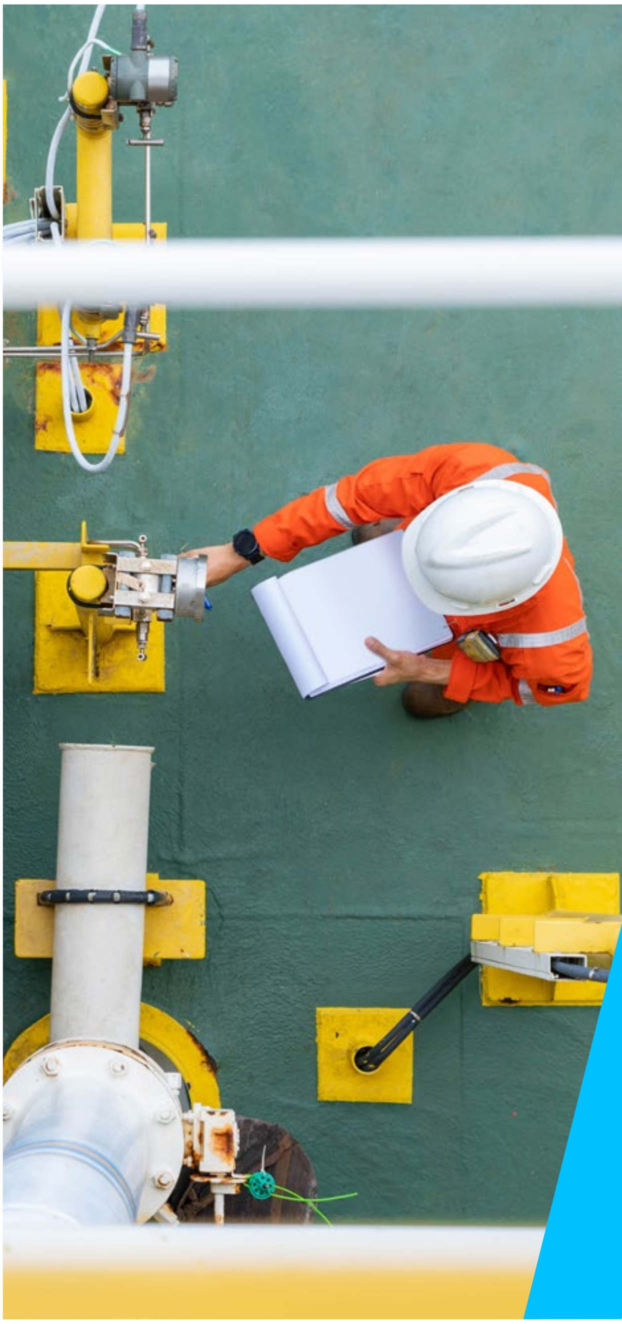
In the absence of data, the petroleum systems of the Category 1 basins are used to identify potential CO_2 storage formations. These formations host hydrocarbon resources and may also host viable saline formations with sealing units. The production of hydrocarbons means there are viable reservoirs (that host gas and oil) and seals (that trap the oil and gas). The intention here is to highlight these formations for future studies to assess their CO_2 storage potential. The petroleum system information is gathered from the Directorate General of Hydrocarbons (DGH) website [10]. Note that due to the lack of publicly available data, critical reservoir and seal properties (such as porosity, permeability, surface area, depth, and thickness) are also largely unknown for most formations below. Therefore, some of these formations may not be suitable for CO_2 storage (Refer to studies listed in 'Overview of Existing Studies').

5.1 Krishna-Godavari Basin

The Krishna-Godavari Basin is the second-largest basin among those grouped under Category 1, covering both onshore (14% of the total basin area) and offshore areas. Only 11% of the basin's area is in shallow (<400 m) offshore regions, while 75% is in deep waters. Figure 7 shows a generalised geological section of the Krishna-Godavari Basin. Formations that are potentially suitable for storage are outlined in Table 6 . As noted above, the reservoir properties of the formations are largely unknown. Hence, there is a chance that some of these formations may not fall within the suitable depth range or possess good permeability and/or thickness, and therefore may not be suitable for CO_2 storage.

For example, the sandstones in the Mandapeta Formation are tight and require reservoir stimulation for hydrocarbon production [10]. However, porous and permeable patches are also present, although there is a significant challenge in locating them [10].

Furthermore, based on the petroleum systems of the basin, it appears that the Krishna Formation does not host any hydrocarbon resources. The formation lies underneath the Raghavapuram Shale layer, which can act as a seal for it. With further analysis, this sandstone formation may be found suitable for storage.



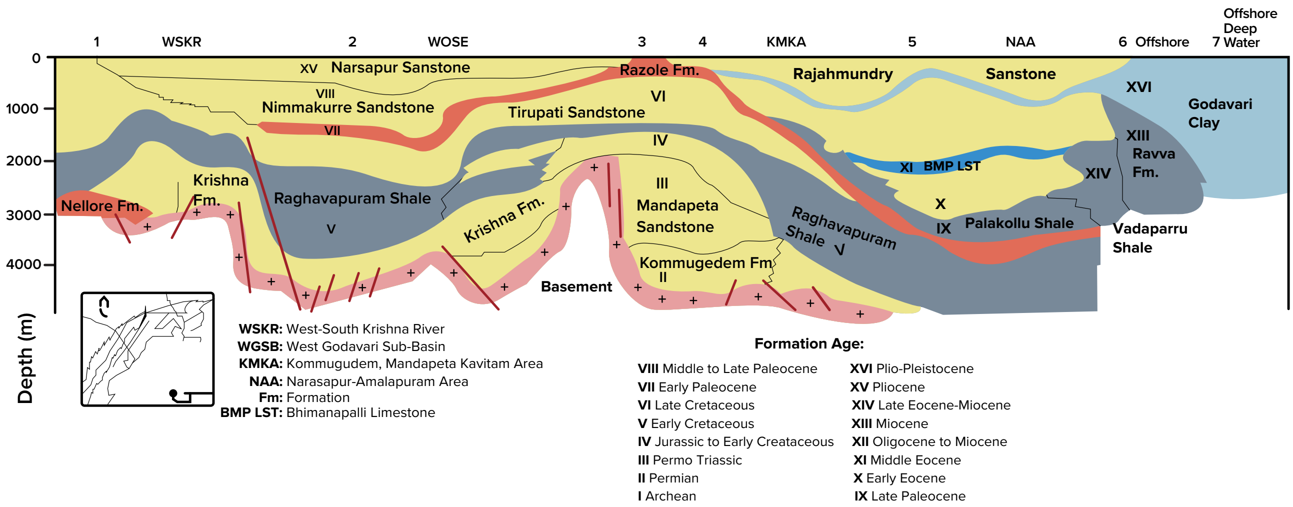


Figure 7 Generalised geological section of Krishna-Godavari Basin [11]

FORMATIONS	SEAL(s)	HYDROCARBON ENTRAPMENT STYLE
Lenticular sands within Raghavapuram Shale	Raghavapuram Shale	Strati-structural
Golapalli Sandstone	Raghavapuram Shale	Structural
Tirupati Sandstone	Razole Formation (Deccan Basalt)	Structural
Mandapeta Sandstone	Tight layers within Mandapeta Sandstone	Structural
Pasarlapudi Formation	Laterally persistent shales within Pasarlapudi Formation have been found to act as effective seals for the accumulations within Pasarlapudi Formation. Palakollu Shale encompassing the occasional sands within the Formation also acts as seal for them.	Though structural entrapment is the dominant element for Pasarlapudi Formation, strati-structural element also appears to be occasionally present
Matsyapuri Sandstone Sands within Rava formation Sands within Vadaparru Shale	Shales within Matsyapuri and Ravva Formations, Vadaparru Shale and Godavari Clay act as effective seals.	Though structural element plays dominant role for hydrocarbon accumulations in this system, role of strati-structural element is noticed

Table 6 Formations that are potentially suitable for CO_2 storage.

5.2 Mumbai Offshore Basin

The basin is exclusively offshore and is characterised primarily by carbonate-to-siliciclastic shelf margin facies. Figure 8 shows a generalised lithostratigraphy map of the Mumbai Offshore Basin. Formations that are potentially suitable for storage are outlined in Table 7.

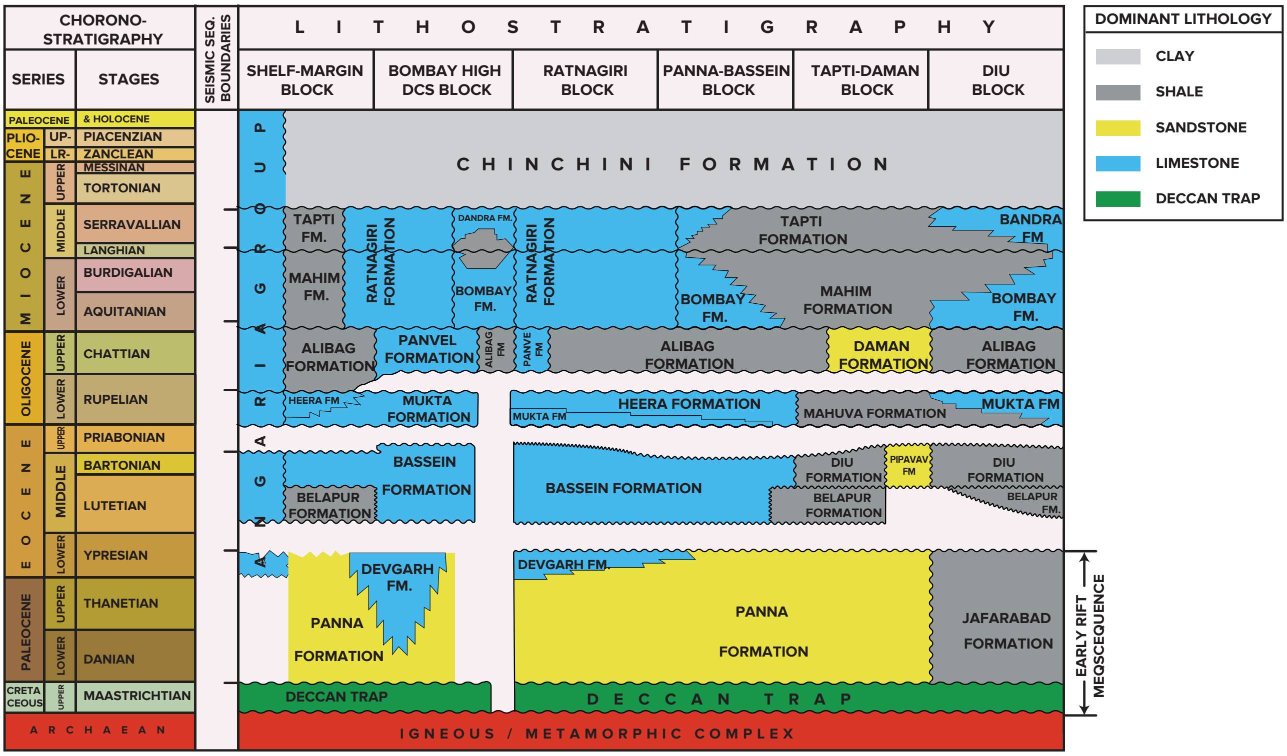


Figure 8 Generalised lithostratigraphy of the Mumbai Offshore Basin [11].

FORMATIONS	SEAL(s)	HYDROCARBON ENTRAPMENT STYLE
Ratnagiri and Bandra and Bombay limestone formations	Different shale formations have acted as effective seals over hydrocarbon accumulations. These shale layers can help containing CO_2.	A diverse range of trapping scenarios, including structural closures of various sizes, fault closures with effective fault sealing, and strati-structural features contribute to entrapment situations in the area.
Daman Sandstone Formation		
Panvel Limestone Formation		
Bassein, Mukta and Heera limestone formations		
Panna Sandstone Formation		

Table 7 Formations that are potentially suitable for CO_2 storage.

5.3 Rajasthan Basin

The basin is exclusively onshore and is divided into three sub-basins separated by major faults: Jaisalmer, Bikaner-Nagaur, and Barmer-Sanchor. Figure 9 shows the generalised lithostratigraphy of the Barmer-Sanchor Sub-basin. Publicly available, detailed maps of the other two sub-basins could not be found. Formations that are potentially suitable for storage are outlined in Table 8.

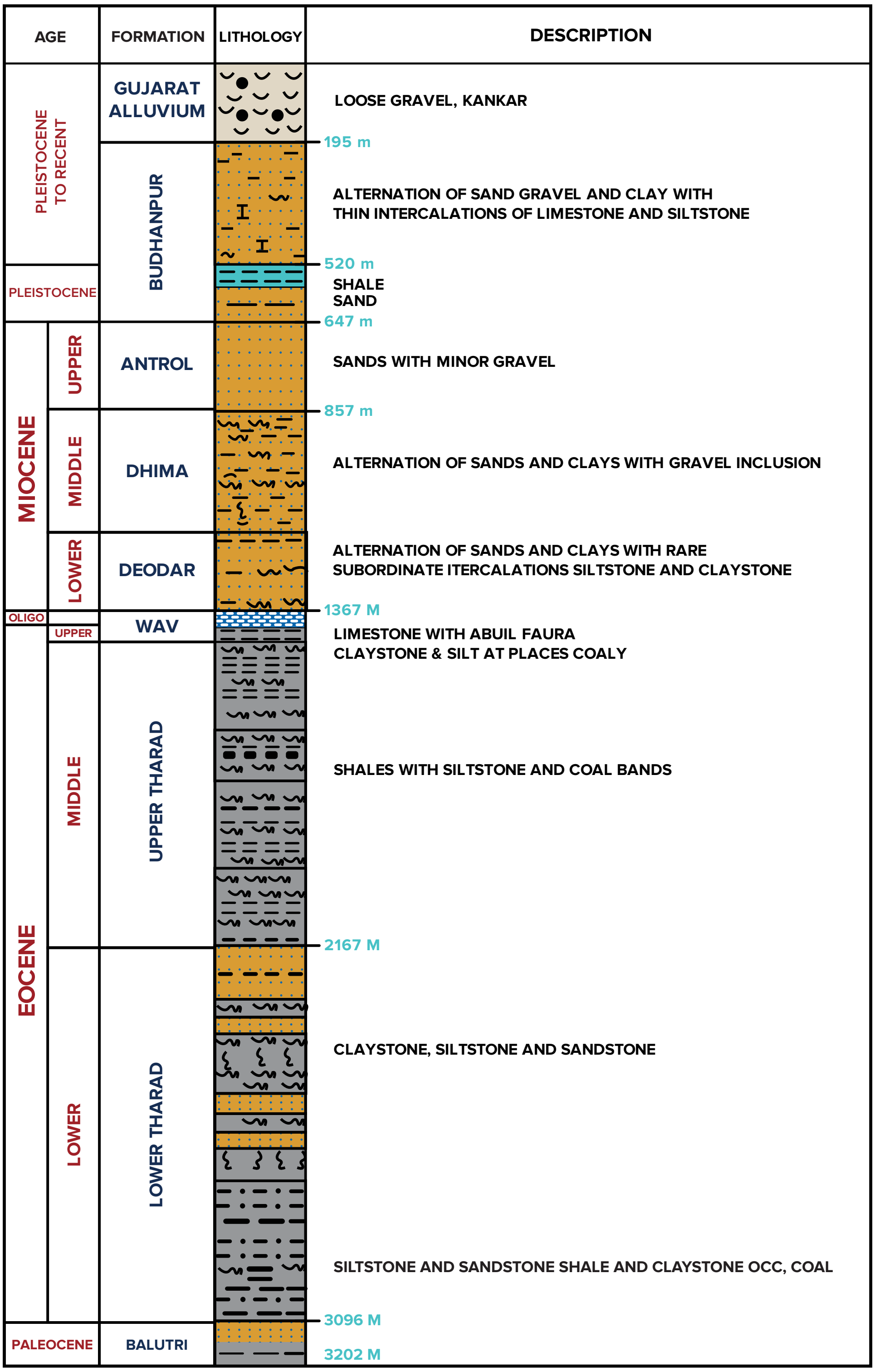


Figure 9 Generalised lithostratigraphy map of the Barmer-Sanchor Sub-basin [10]

SUB-BASINS	RESERVOIR	SEAL	HYDROCARBON ENTRAPMENT STYLE
Jaisalmer	Baisakhi-Bedesir sandstone formation	Different shale formations have acted as effective seals over hydrocarbon accumulations. These shale layers can help containing CO_2.	Anticlinal Closures, Fault-related Closures, Unconformity-related traps and Lithostratigraphic traps
	Pariwar sandstone formation		
	Goru sandstone formation		
	Sanu sandstone formation		
	Khuiala sandstone formation		
	Lower Bandah Limestones / Khuiala Limestones		
Bikaner-Nagaur	Nagaur Sandstones		Moderate to high basement-controlled anticlinal structures and fault closures
	Jodhpur Sandstone		
	Bilara Dolomites		
Barmer-Sanchor	Barmer sandstone formation		Roll over anticlines developed on the previously planer boundary faults and fault closures against the transverse faults
	Tharad sandstone formation		
	Lathi silty sandstone formation		
	Sarnu Hill feldspathic sandstone formation		

Table 8 Formations that are potentially suitable for CO_2 storage.

5.4 Cauvery Basin

It is the largest basin among those grouped under Category 1, covering both onshore (16% of the total basin area) and offshore areas. Only 18% of the basin's area is in shallow (<400 m) offshore regions, while 66% is in deep waters. Figure 10 shows the generalised stratigraphy of the Cauvery Basin. Formations potentially suitable for storage are outlined in Table 9. The Bhuvanagiri Formation is primarily developed in the northern and central parts of the basin, consisting predominantly of sandstone with minor occurrences of claystone and shale. The Andimadam Formation comprises pale grey, fine to coarse-grained, micaceous sandstone, and micaceous silty shale and was deposited onto Archaean Basement rocks.

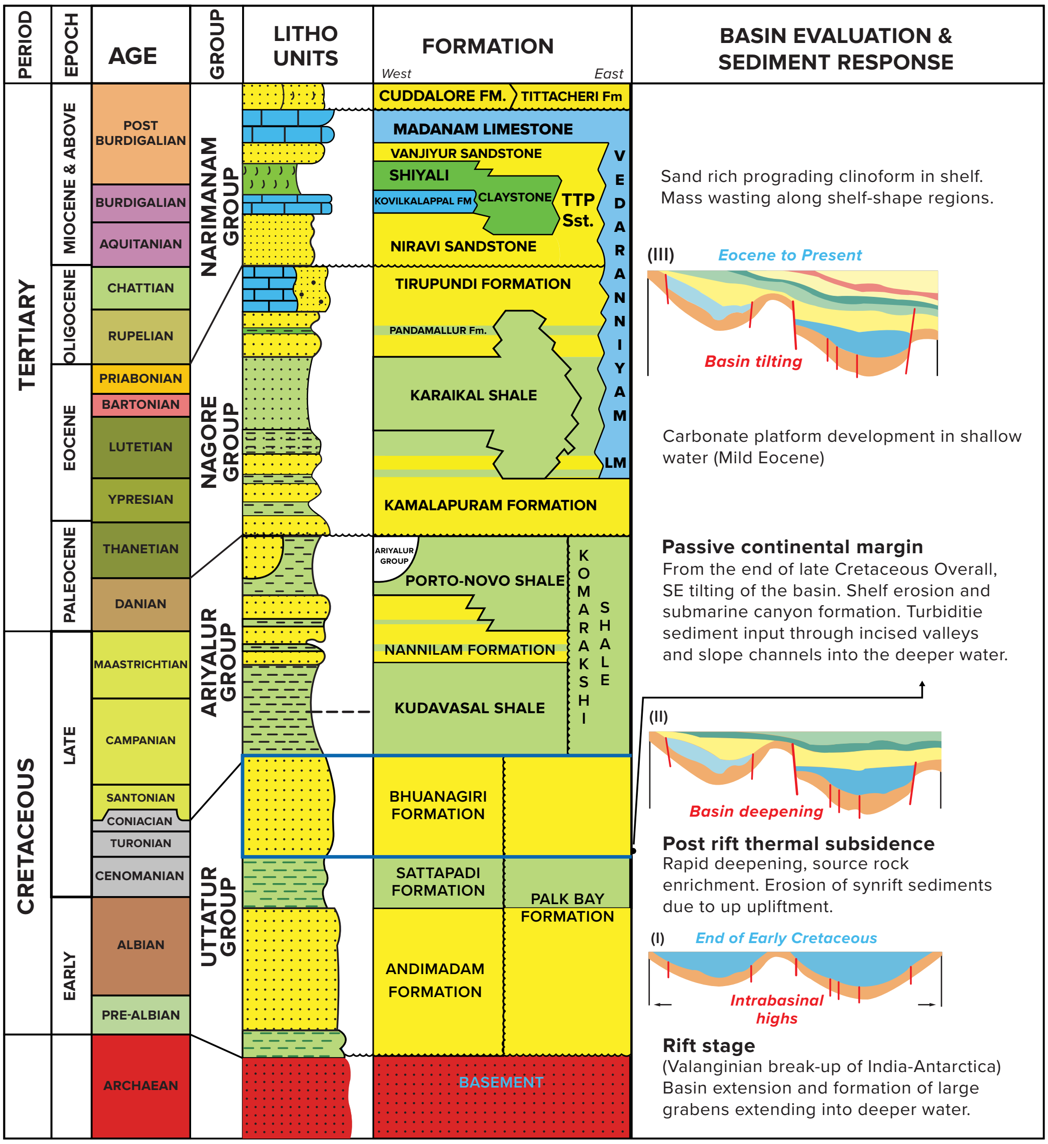


Figure 10 Stratigraphy and basin history of the Cauvery Basin [18]

FORMATIONS	SEAL(s)	HYDROCARBON ENTRAPMENT STYLE
Bhuvanagiri	Sattapadi shale within Cretaceous Post unconformity shales like Kudavasal and Kamlapuram.	Structural/ Stratigraphic, Combination traps.
Andimadam		

Table 9 Formations that are potentially suitable for CO_2 storage.

5.5 Assam-Arakan Basin

The basin is exclusively onshore, and its major tectonic elements include the Assam Shelf, Assam-Arakan Fold Belt, and Naga Schuppen belt. Formations potentially suitable for storage are listed in Table 12. Figure 11 and Figure 12 show the lithostratigraphy maps of Upper Assam Basin and Assam Shelf [18], [19].

FORMATIONS	SEAL(s)	HYDROCARBON ENTRAPMENT STYLE
Tura sandstones	Three main seals exist in the tertiary sedimentary layers. The lower one, found in the Upper Eocene, is the Kopili Formation, which is clay-rich. The middle cap rock is the Barail Coal-Shale Unit, and the uppermost one, situated above the Tipam Sandstone, is the Girujan Clay.	Structural combination (fold + fault) traps
Barail Formation		
Tipam Sandstone		
Kopili sandstones		
Girujan Formation		
Bokabil Formation		
Renji		
Bhuban		

Table 10 Formations that are potentially suitable for CO_2 storage.

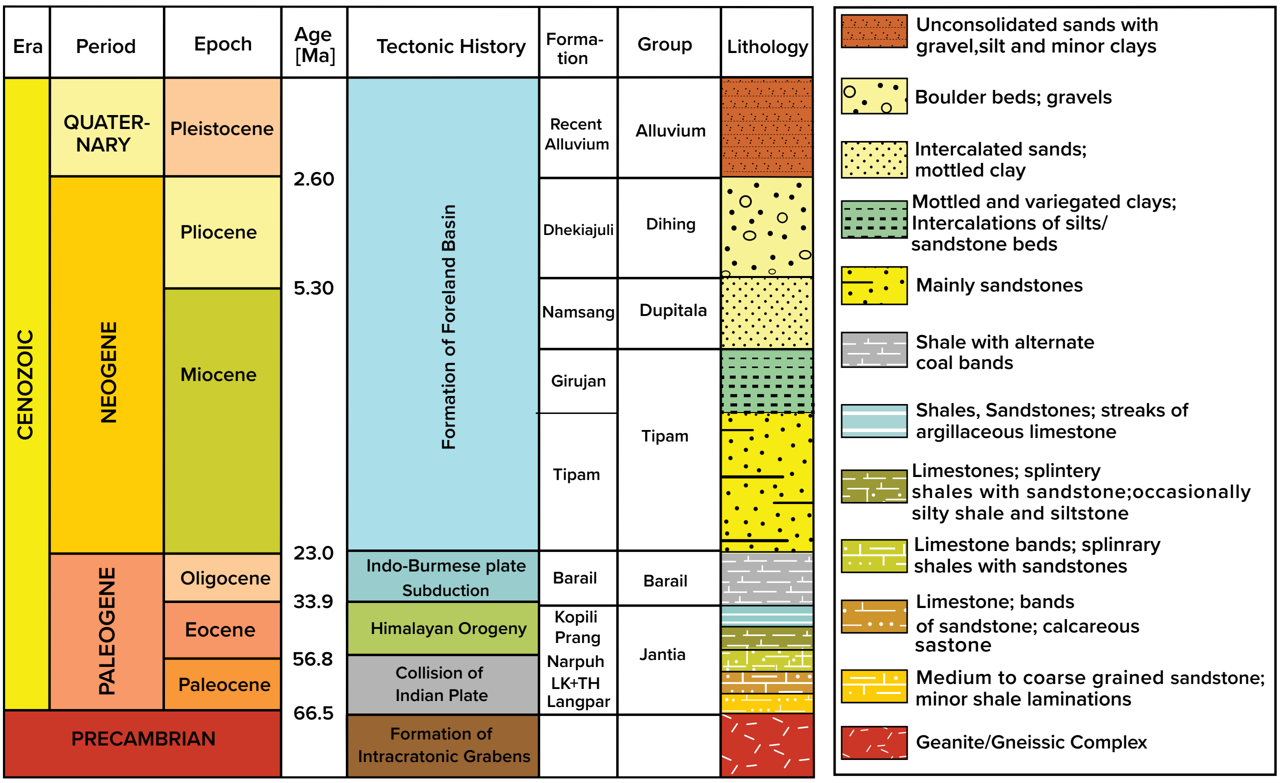


Figure 11 Lithostratigraphy of the Upper Assam Basin [20].

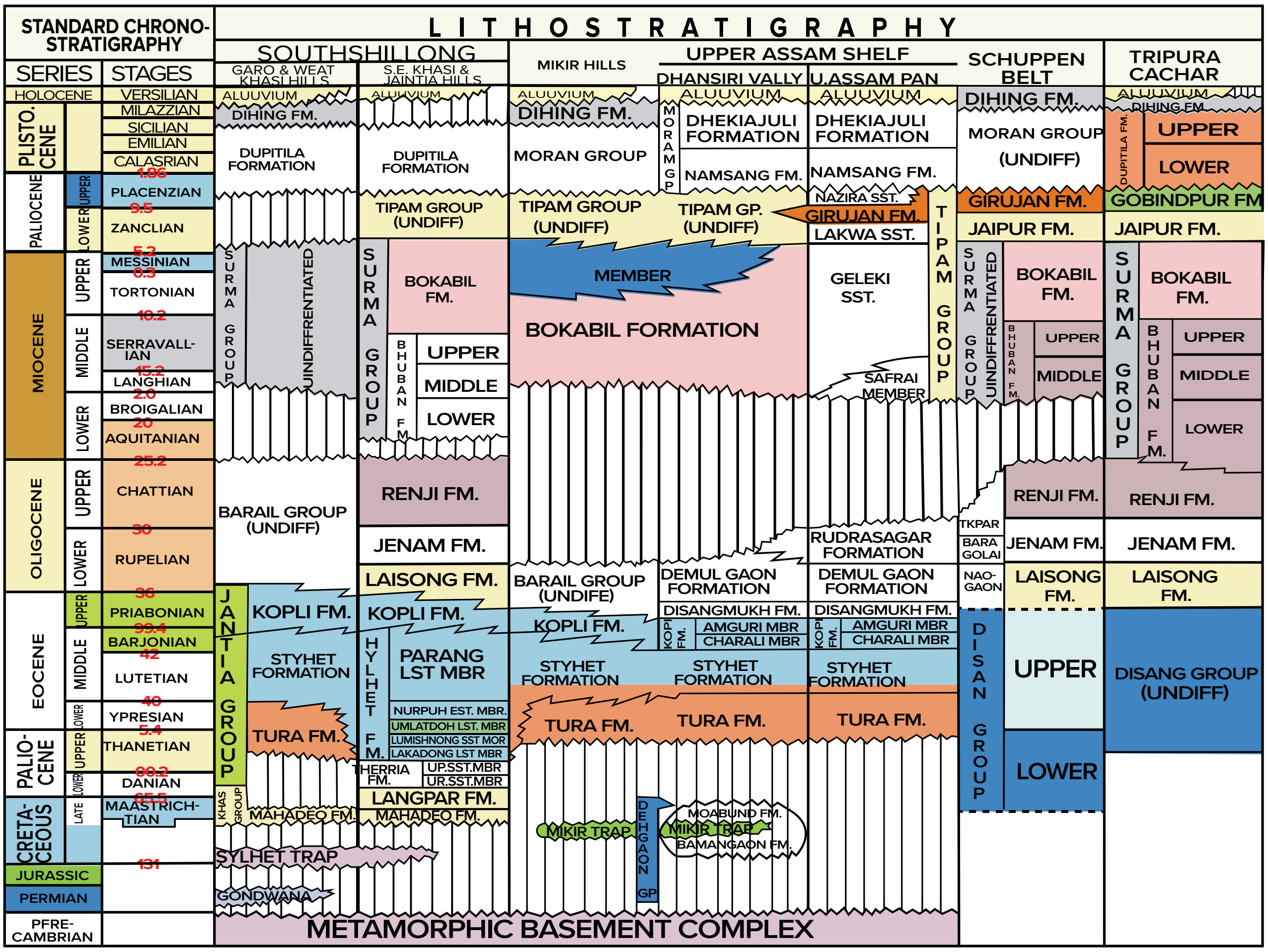


Figure 12 Lithostratigraphy of the Assam Shelf [21]

5.6 Cambay Basin

The basin covers onshore (91% of the total basin area) and offshore areas (shallow waters). Figure 13 shows a generalised stratigraphy map of the Cambay Basin, with formations potentially suitable for storage outlined in Table 11. Several reservoirs are found within the trapwacke sequence of the Olpad Formation [10]. Currently, Synergia Energy is assessing the formation for CO_2 storage [22]. According to the company, the Olpad Formation's true vertical depth (TVD) ranges between 2000 and 3000 m, with its thickness varying from 50 to 500 m, increasing from west to east. Figure 14 displays the well-to-well correlation for four wells intersecting the formation [23]. The company estimates the formation's porosity to be between 10% and 25%; however, permeability and injectivity are yet to be determined. Synergia Energy estimates storage resources of over 0.5 Gt in the formation. This value is approximately one-third of the estimated P10 value calculated by this study for the entire Cambay basin. Considering the average TVD of the Olpad Formation and the generalised stratigraphy map of the basin (Figure 13), our estimated storage resources for this basin may be optimistic. As mentioned on multiple occasions in this study, analyses at the formation scale are required to better evaluate storage resources in India, and for this, multiple types of data are required, which are not publicly available.

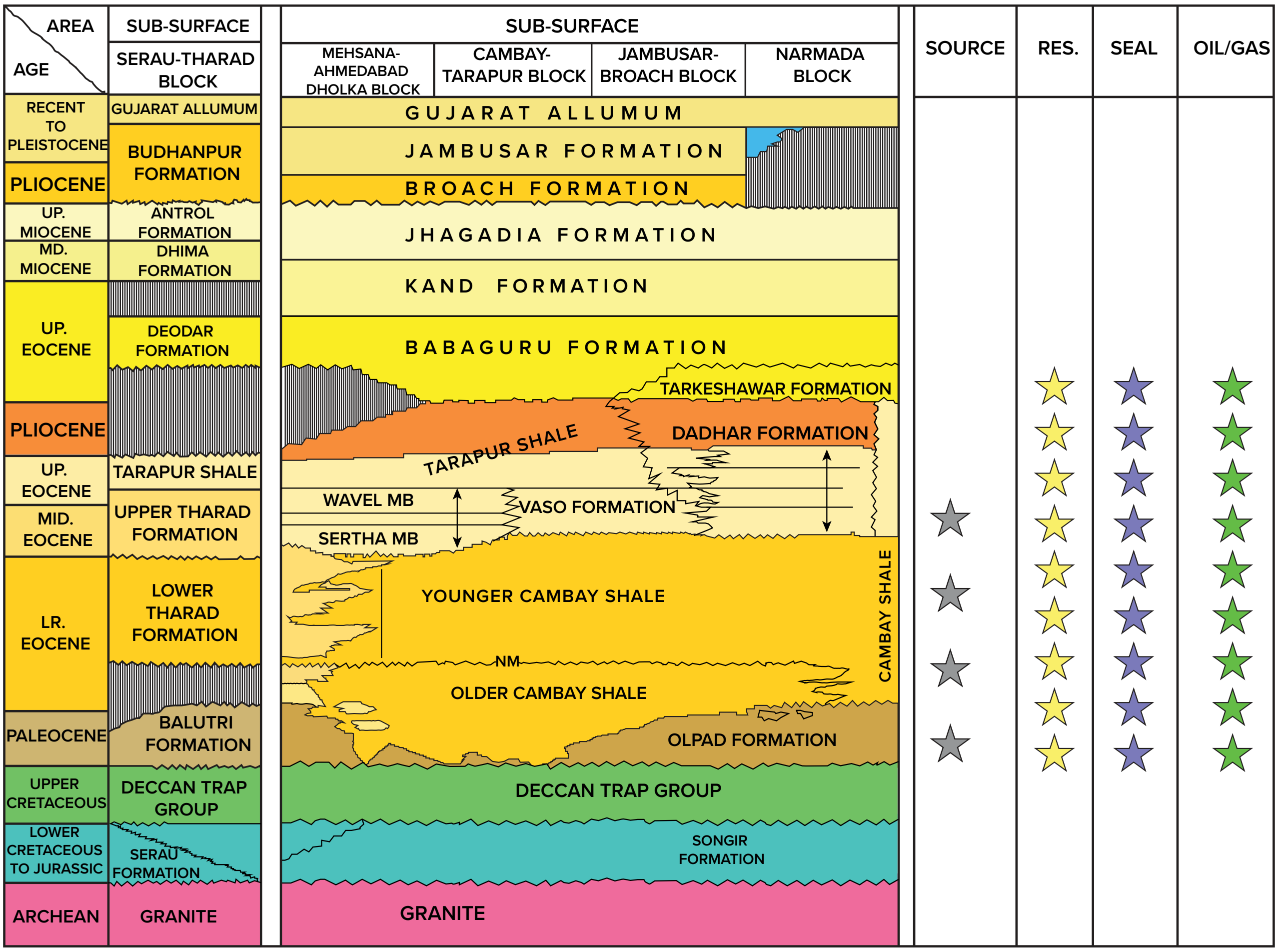


Figure 13 Generalised Stratigraphy of the Cambay Basin [19]

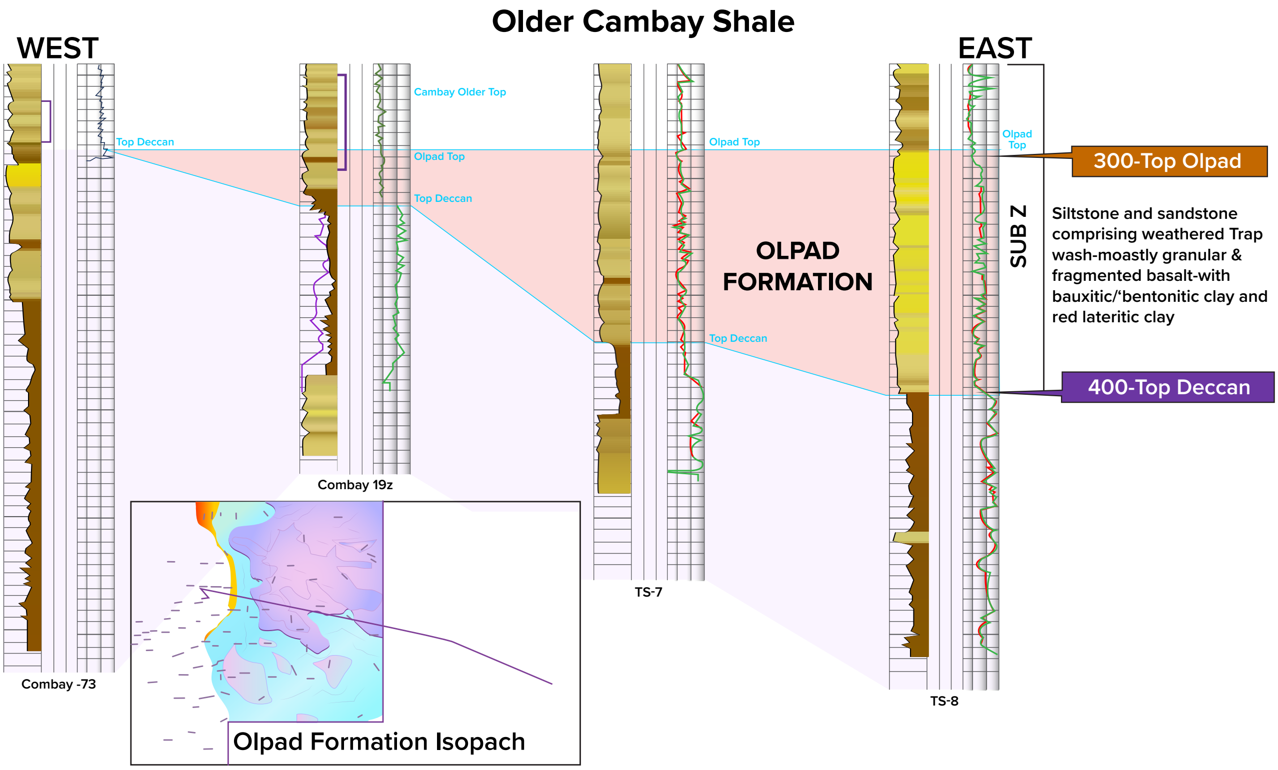


Figure 14 Well-to-well correlation of the Olpad Formation[1]

FORMATIONS	SEAL	HYDROCARBON ENTRAPMENT STYLE
Olpad Formation	Thick Cambay Shale	N/A
Localised sandstone reservoirs within the Cambay Shale		N/A

Table 11 Formations that are potentially suitable for CO_2 storage.

[1] Cambay Carbon Capture & Storage Scheme, Rolan Wessel, January 2023;
https://www.synergiaenergy.com/sites/synergia-energy-ltd/files/2022-12/cambay-carbon-capture-and-storage-scheme.pdf

6.0 CO_2 STORAGE RESOURCES OF CONVENTIONAL OIL AND GAS FIELDS

The CO_2 storage resources of conventional producing oil and gas fields and those planned and announced for production are evaluated. It is worth noting that planned or announced fields would not be available for CO_2 storage until they are depleted, which could be decades.

6.1 Results and discussion - Conventional oil fields

Figure 15 illustrates the net storage resources (P50 values) for all the studied oil fields. The bars shown in navy represent 'Announced' fields, those in green represent Planned fields, and those in light blue represent Producing fields. Refer to Appendix for the methodology of conventional oil and gas field resource calculation.

Most of these fields have limited hydrocarbon resources with 80% exhibiting a recoverable amount of oil in place smaller than 67 million barrels of oil (MMbbl). Therefore, their CO_2 storage resources will also be limited, with 80% of fields possessing CO_2 storage resources (P50 values) less than 5.7 $MtCO_2$. This small CO_2 storage resource means the field is not viable for a commercial-scale carbon capture and storage facility unless the field is part of a larger saline formation. This study finds only five fields have CO_2 storage resources higher than 20 Mt, making them suitable for medium to large-scale carbon capture and storage. These fields include Mumbai High (the largest oil field in India with P50 CO_2 storage resources of 300 $MtCO_2$), Gujarat (52 $MtCO_2$), Greater Jorajan (21.5 $MtCO_2$), Greater Naharkatiya field (26.3 $MtCO_2$), and Panna-Mukta (33.5 $MtCO_2$). For more information regarding these fields, refer to Table 12. The locations of these fields are shown in Figure 16. Based on the estimated oil and gas extraction efficiencies (i.e., percentage of recoverable hydrocarbon that is produced) from these fields, it becomes evident that the Greater Jorajan, Greater Nahorkatiya, and Panna-Mukta fields are near depleted and near the end of their life. As such, they offer early opportunities for CO_2 storage.

Table 13 displays the cumulative CO_2 storage resources of currently producing, announced, and planned conventional oil fields in each basin. The Mumbai Offshore Basin stands out with the highest CO_2 storage resources, mainly due to hosting the largest conventional oil field in India—the Mumbai Field.

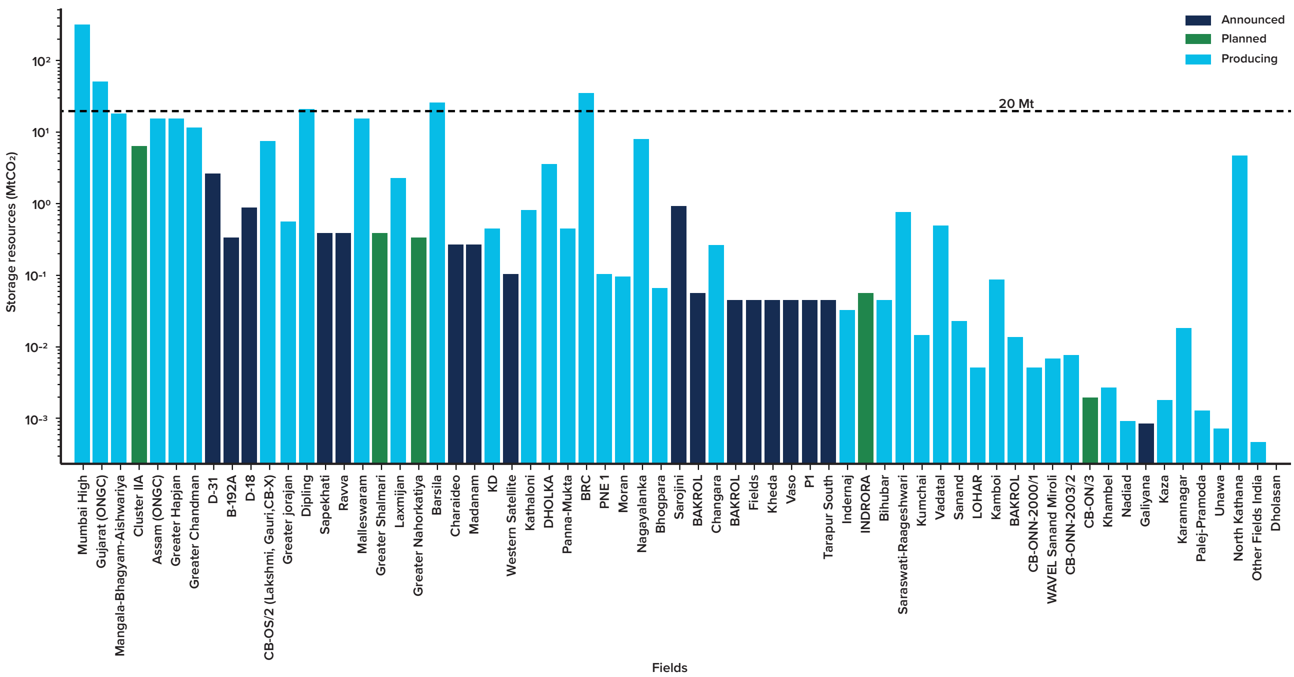


Figure 15 Storage resources of studied conventional oil fields in India. The bars shown in navy represent announced fields, those in green represent planned fields, and those in light blue represent producing fields.

FIELD NAME	BASIN	ONSHORE/ OFFSHORE	P10 ($MTCO_2$)	P50 ($MTCO_2$)	P90 ($MTCO_2$)	EXTRACTION EFFICIENCY OIL (%)	EXTRACTION EFFICIENCY GAS (%)
Mumbai High	Mumbai Offshore	Shallow Water	221.73	299.97	406.87	73	56
Gujarat	Cambay	Onshore	38.50	52.13	70.76	60.5	81.5
Greater Jorajan	Assam-Arakan	Onshore	16.40	21.51	28.29	98	95
Greater Nahorkatiya	Assam-Arakan	Onshore	19.48	26.27	35.48	99	98
Panna-Mukta	Mumbai Offshore	Shallow Water	26.57	33.54	42.22	99	99

Table 12 Conventional oil fields with the highest storage resources

BASIN	P10 ($MTCO_2$)	P50 ($MTCO_2$)	P90 ($MTCO_2$)
Assam-Arakan Basin	84.49	111.97	148.91
Cambay Basin	45.99	61.89	83.44
Cauvery Basin	0.36	0.48	0.63
Krishna-Godavari Basin	17.56	23.63	31.93
Kutch Basin	0.08	0.12	0.18
Mumbai Offshore Basin	251.89	338.47	455.94
Rajasthan Basin	11.16	18.38	29.26
Net storage resources	411.53	554.93	750.30

Table 13 Storage resources in currently Producing, Announced, and Planned conventional oil fields in each basin.

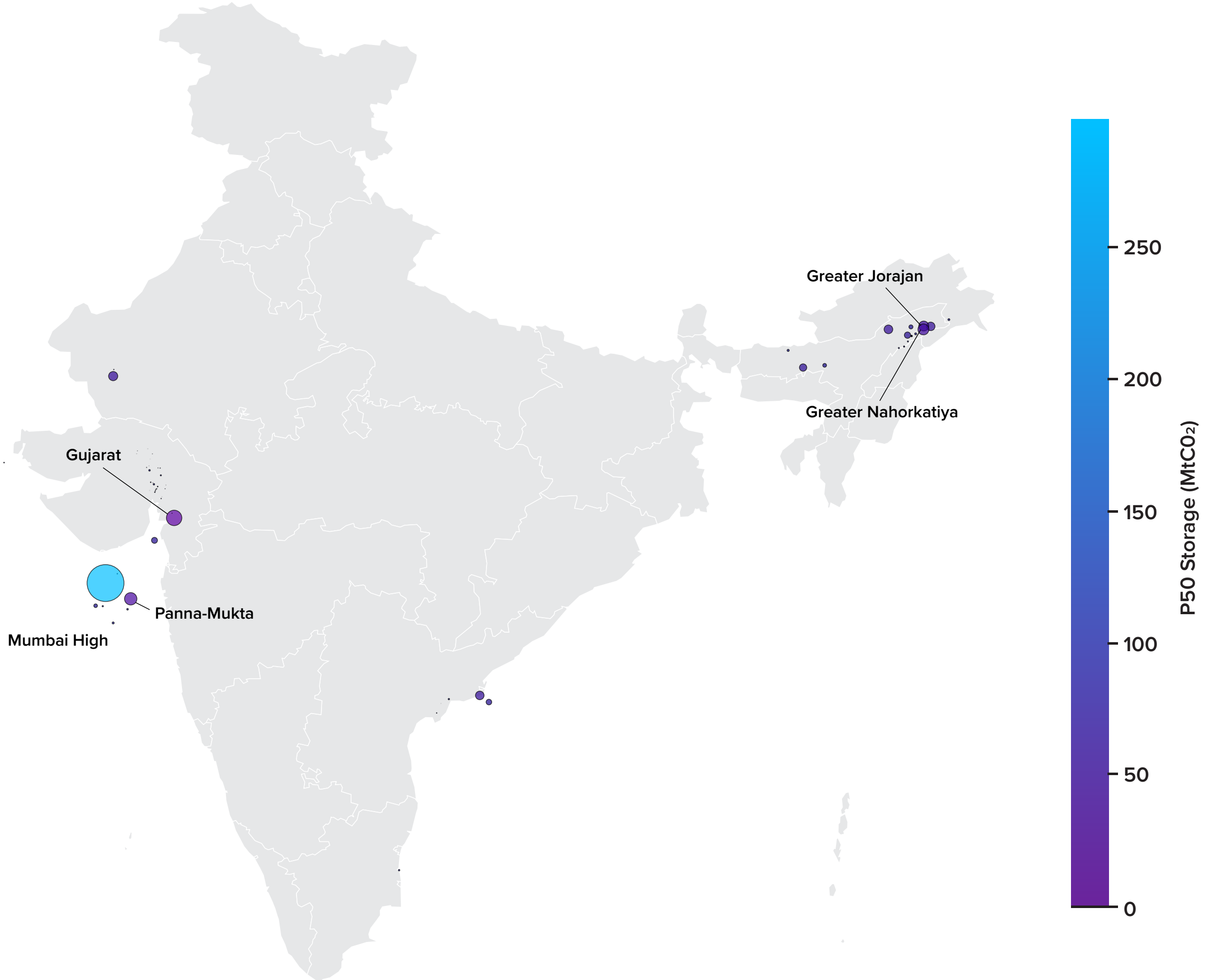


Figure 16 CO_2 storage resources in studied conventional oil fields in India. Only five fields offer storage resources (P50 values) exceeding 20 Mt, making them suitable for medium to large-scale carbon capture and storage projects.

6.2 Results and discussion - Conventional gas fields

Figure 17 illustrates the net storage resources (P50 values) for all the studied gas fields. As most of these fields have limited hydrocarbon resources, their CO_2 storage resources are also limited. Specifically, 60% of the fields possess CO_2 storage resources (P50 values) of less than 5 $MtCO_2$, making them unsuitable for commercial-scale carbon capture and storage unless the fields are connected by a large regional aquifer.

According to our analysis, out of the 59 studied fields, only 12 fields have CO_2 storage resources higher than 20 Mt. Note that none of these 12 fields has yet been depleted to be suitable for CO_2 storage. Using production history-matched numerical simulation of each field, one can predict their end-of-life time. The details of these fields, their storage resources, and their current extraction efficiency (i.e., percentage of recoverable hydrocarbon that is produced) are presented in Table 14. Among these fields, the Bassein Gas Field stands out. The field is located in Block Mumbai High NW, with a water depth of around 75 m.

Table 15 displays the cumulative CO_2 storage resources in currently producing, announced, and planned conventional gas fields in each basin. The Mumbai offshore basin stands out with the highest CO_2 storage resources, mainly due to hosting the Bassein Gas Field.

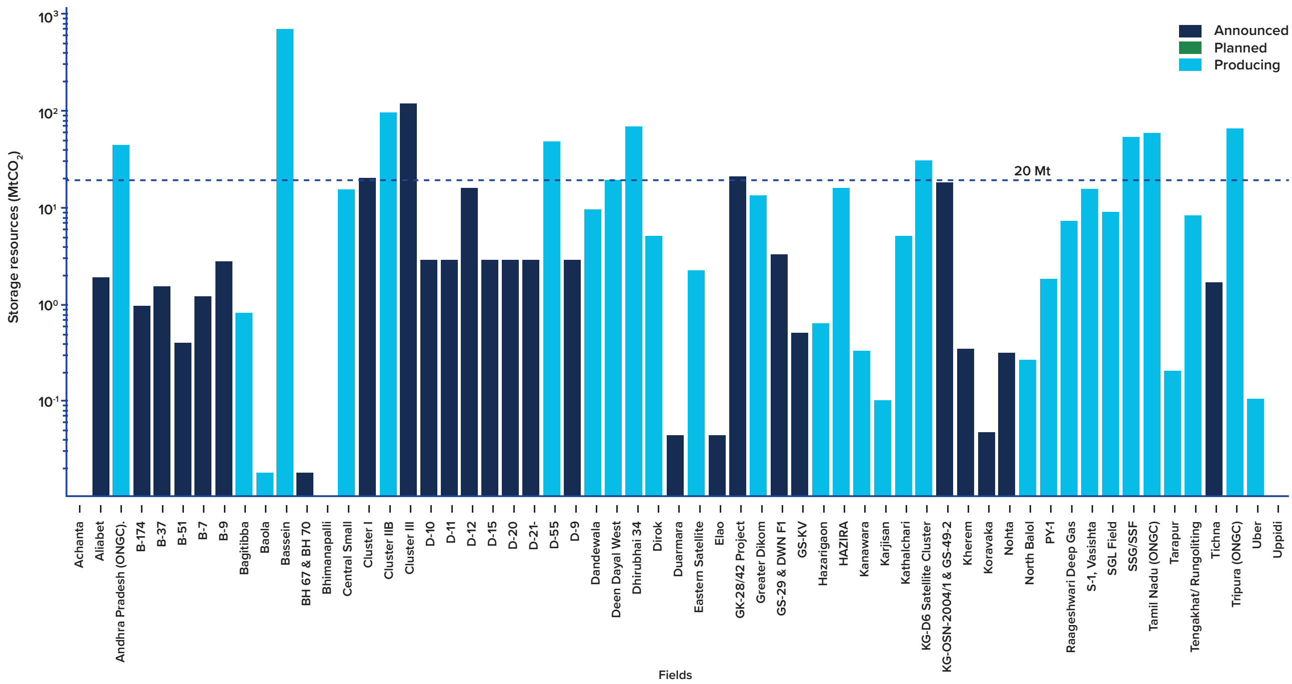


Figure 17 Storage resources of studied conventional gas fields in India. The bars shown in navy represent Announced fields, those in green represent Planned fields, and those in light blue represent producing fields.

FIELD NAME	BASIN	ONSHORE/ OFFSHORE	P10 ($MTCO_2$)	P50 ($MTCO_2$)	P90 ($MTCO_2$)	EXTRACTION EFFICIENCY OIL (%)	EXTRACTION EFFICIENCY GAS (%)
Andhra Pradesh	Krishna-Godavari	Onshore	35.5	44.5	55.2	67.50	82.12
Bassein	Mumbai Offshore	Shallow Water	557.7	696.0	855.9	55.52	76.09
Cluster IIB	Krishna-Godavari	Deepwater	78.8	98.4	121.0	NA	3.98
Cluster III	Krishna-Godavari	Ultra-Deepwater	95.6	118.4	145.4	NA	0.00
D-55	Krishna-Godavari	Deepwater	40.5	50.5	61.7	NA	
Dhirubhai 34	Krishna-Godavari	Ultra-Deepwater	54.1	66.6	81.7	NA	20.51
SSG/SSF	Rajasthan	Onshore	44.1	55.2	67.7	NA	8.25
Tamil Nadu	Cauvery	Onshore	46.4	58.0	71.4	81.47	58.35
Tripura	Assam-Arakan	Onshore	53.8	66.6	81.6	5.53	44.08
Cluster I	Krishna-Godavari Basin	Deepwater	16.3	20.2	24.6	NA	0.00
GK-28/42 Project	Kutch Basin	Shallow Water	17.1	21.2	26.0	0.00	0.00
KG-D6 Satellite Cluster	Krishna-Godavari Basin	Deepwater	25.3	31.5	38.7	NA	16.3

Table 14 Conventional gas fields with highest storage resources

BASIN	P10 ($MTCO_2$)	P50 ($MTCO_2$)	P90 ($MTCO_2$)
Assam-Arakan Basin	94.89	119.09	148.39
Cambay Basin	14.87	18.41	22.74
Cauvery Basin	47.89	59.80	73.65
Krishna-Godavari Basin	391.18	486.20	597.46
Kutch Basin	17.07	21.15	25.98
Mahanadi Basin	13.73	17.03	20.94
Mumbai Offshore Basin	579.05	722.43	888.49
Rajasthan Basin	65.62	81.70	100.22
Vindhyan Basin	0.25	0.31	0.38
Net storage resources	1,224.55	1,526.13	1,878.25

Table 15 Storage resources in currently Producing, Announced, and Planned conventional gas fields in each basin.

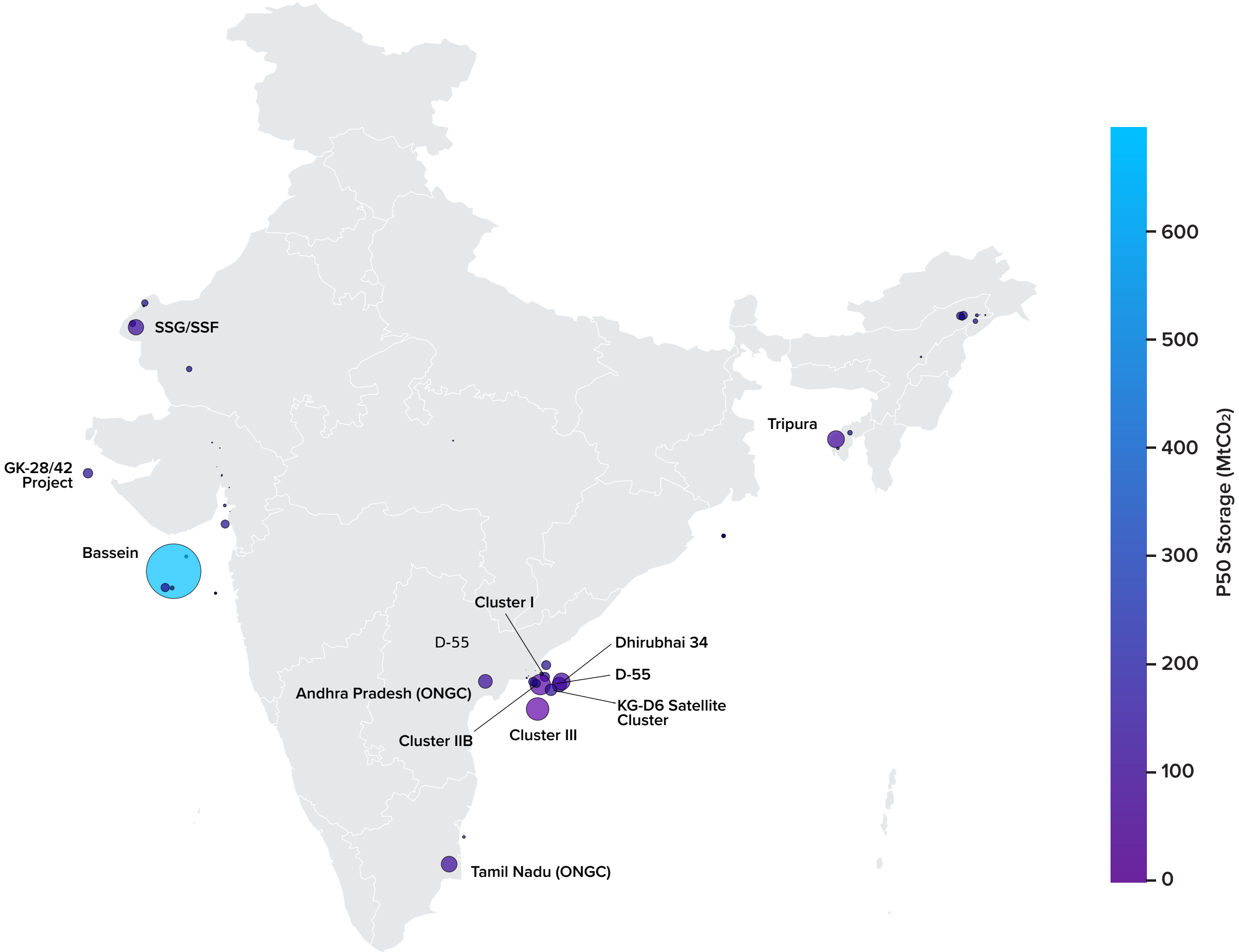


Figure 18 CO_2 storage resources in studied conventional gas fields in India. Twelve fields offer storage resources (P50 values) exceeding 20 Mt, making them suitable for medium to large-scale carbon capture and storage projects.

6.3 Applicability & limitations

The equation used (Refer to appendix, equation 5) accounts only for the physical trapping of CO_2 and does not consider solubility trapping. CO_2 solubility in oil is higher than in water, and depending on the amount of remaining oil in place and oil properties, solubility trapping in oil fields may play a role in net storage capacity compared to saline formations and gas fields. Furthermore, the equation used does not account for the pore space made available due to water production during the primary production phase, which is due to a lack of data.

This study identifies fields with CO_2 storage resources exceeding 20 Mt, which can potentially facilitate commercial-scale carbon capture and storage deployment. However, the suitability of these fields for carbon capture and storage project development requires further detailed studies, such as assessing injectivity, sealing capacity of the top seal, and the impact of faults.

Furthermore, according to the NDR website [11], there are approximately 1000 wells spread across India. These wells range from actively producing wells to abandoned ones, and their concentration is notably higher in well-explored basins (refer to Figure 19) where potentially suitable oil and gas fields and/or saline formations for CO_2 storage are available. However, the heightened density of wells in these regions poses a risk of CO_2 leakage, especially in the case of legacy wells and older ones that may not adhere to current drilling standards, thereby increasing the potential for leakage. A comprehensive study of these wells is imperative, focusing on assessing their CO_2 leakage potential. This process is expected to be time-consuming and expensive. Initiating this assessment as early as possible is crucial to unlock the storage resources.

It is important to note that unconventional oil and gas fields are not considered in this study, as CO_2 storage in these fields is deemed economically unviable. The injectivity in these fields is notably poor due to their ultra-low permeability, rendering them unsuitable for any CO_2 storage projects.

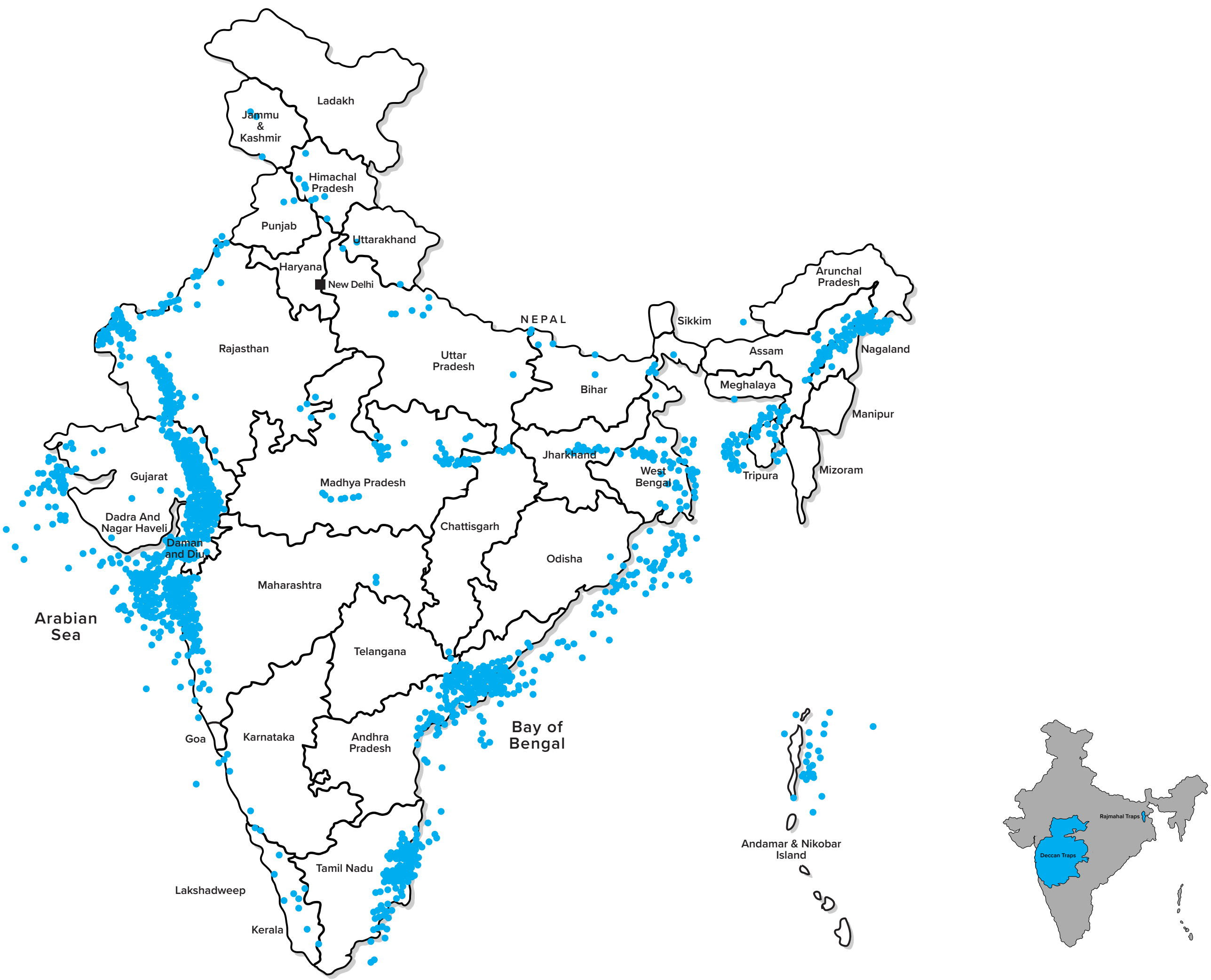


Figure 19 Density map of wells across India [11]

7.0 CO_2 STORAGE RESOURCES OF BASALTS

The Deccan Traps constitute one of the world's largest continental flood-basalt province (Figure 20). Encompassing an area of approximately 500,000 km^2 in west-central India, its thickness varies from a few meters in the east to over 2.5 km in the west. The estimated volume of the Deccan volcanic province is approximately 512,000 km^3 [24].

In addition to the Deccan Traps, there is a smaller basalt formation in northeast India known as the Rajmahal Trap (Figure 20). Covering an area of around 18,000 km^2, it consists of basalt with a thickness ranging from 450 to 600 m. The central part of the Rajmahal basalt contains over 28 lava flows, each with a thickness ranging from 20 to 70 m [24].

These extensive flood basalts may hold significant potential for in-situ carbon mineralisation. However, the absence of essential data, including quantitative X-ray diffraction (QXRD), pressure, temperature, porosity, permeability, interflow thickness, and fracture network information for these basalt formations, prevents the estimation of their mineral carbonation potential in this study.

Published assessments rely on broad storage factors, such as estimating 41 and 70 kg CO_2/m^3 of rock. These storage factors are not based on the mineralogy, geology, and subsurface conditions of the Deccan basalts. Their results indicate a net storage resource ranging between 97 to 316 $GtCO_2$ [15], [17]. Given the critical impact of various parameters mentioned earlier on mineral carbonation potential in basalts, as well as on the economic viability and technical feasibility of the technology, it is advisable to avoid relying on such an oversimplified approach for estimating the storage resources of basalts.

This study recommends conducting Quantitative X-ray Diffraction (QXRD) analysis on several samples collected from various locations across the area to gain an initial understanding of the mineralogical composition and heterogeneities in the area. Subsequently, conducting batch geochemical studies at in-situ pressure and temperature conditions where samples are collected is recommended. This approach is the best and most reliable way to determine the range of CO_2 storage factor of the targeted area and, consequently, the theoretical CO_2 storage resources in the Deccan Traps and Rajmahal Trap. Note that even then, the obtained values are potentially optimistic, as multiple factors affect injection and mineralisation rates. A detailed assessment of the site, coupled with batch and reactive transport modelling studies, is essential to find the most accurate value.

Figure 20: Continental Flood Basalts of India.

8.0 MATCHING CO_2 EMISSION SOURCES WITH STORAGE OPPORTUNITIES IN INDIA

8.1 Carbon Capture in India

India is the world's third-largest emitter of CO_2 [25]. However, carbon capture is predominantly concentrated in specific industries where it is a fundamental part of the process. For instance, in urea manufacturing, which produces about 24 million metric tons annually, carbon capture is employed during the ammonia-to-urea conversion process. Major industrial facilities like Reliance Industries in Jamnagar, Gujarat, and Jindal Steel & Power Ltd in Angul, Odisha, are also employing carbon capture [26]. Reliance Industries has a petcoke gasification capacity of 10 million tonnes per year, while JSPL has a coal gasification capacity of 2 million tonnes per year. In these facilities, CO_2 capture is integral to the gas conditioning process. However, most of the captured CO_2 from these processes is released into the atmosphere, and these facilities do not transport CO_2 for storage.

On a smaller scale, pilot projects are being undertaken to assess the viability of carbon capture technologies in various settings. The Indian Oil Corporation Ltd (IOCL) Research and Development Centre has implemented an amine and biological enzyme-based carbon capture plant. Similarly, Tata Steel in Jamshedpur has established a pilot-scale plant capable of capturing 5 metric tonnes/day of CO_2 from blast furnace gases [26]. Recently, India's largest coal-fired power plant, NTPC's 4.8-GW Vindhyachal Super Thermal Power Station, has announced capturing 20 TPD CO_2 from thermal plant flue gas through energy efficient absorption process provided by Carbon Clean Solutions and conversion of CO_2 to methanol through catalytic hydrogenation process [27].

In 2022, the Department of Science and Technology, Government of India, announced setting up two National Centers of Excellence in Carbon Capture and Utilization (NCOE-CCU) at the Indian Institute of Technology, Bombay, and the Jawaharlal Nehru Center for Advanced Scientific Research, Bengaluru. The NCOE-CCU at IIT Bombay will define milestones and spearhead science and technology initiatives for industry-oriented CCU innovation in India, alongside developing novel methodologies for improving the technology readiness levels in CCU. It will accelerate the R&D efforts in methods of carbon capture and utilisation. The centre will also work on the conversion of captured carbon dioxide to chemicals, CO_2 transport, compression and utilisation, as well as on enhanced hydrocarbon recovery as co-benefit pathways. The NCoE-CCU will also develop and demonstrate efficient CO_2 capture from representative flue gas from the effluents of power plant and biogas plant.

The NCCCU at JNCASR, Bengaluru, will aim to develop and demonstrate carbon capture and conversion by developing relevant materials and methodologies. These processes will be scaled up to pilot scale mode to produce hydrocarbons, olefines and other value-added chemicals and fuels. It will also work on reaching technology readiness level on par with the commercial requirement at the industry level. The centre will promote the CCU research, provide training and consultancy and translate its research excellence into solutions with global economic and social impact [28].

8.2 Review of Source-to-Storage Matching in India

Focused attempts to pursue commercial development of carbon capture and storage hubs and modelling of potential source-sink matching in India have been limited. The primary interest has been in separate studies of carbon capture, storage, or individual projects rather than hubs. However, there are some initial studies and one commercial project that provide a foundation to build upon. These are summarised in Table 16 followed by brief reviews of each.

SOURCE	EMITTER REGION	STORAGE BASIN	ESTIMATED MID CAPACITY ($MTCO_2$)[2]
[29]	Coastal Gujarat and Mumbai	Mumbai Offshore	Not Listed
	Coastal Andhra Pradesh	Krishna-Godavari Offshore	Not Listed
	Kolkata	Onshore Bengal	Not Listed
	Chennai and surrounding	Cauvery-Palar	Not Listed
[25]	Mumbai	Mumbai Offshore	34,800
	Nagpur	Narmada Basin	5,100
	Chandrapur	Pranhita-Godavari	4,500
	Hazira	Mumbai Offshore and Narmada	39,900
[30]	Various Power Stations	Krishna-Godavari	150
[43]	Proximal to Basin	Cambay	500 [2]

Table 16: Inventory of Source-Sink Matching or Potential Hubs in India

[2] The basin capacities were copied from their respective sources and may differ between sources.
Cambay Carbon Capture & Storage Scheme, Rolan Wessel, January 2023;
https://www.synergiaenergy.com/sites/synergia-energy-ltd/files/2022-12/cambay-carbon-capture-and-storage-scheme.pdf

Global CCS Institute Study – In 2021, GCCSI identified five potential CO_2 source-sink networks across the Indian Subcontinent based on existing data [29]. Four of these are in India and include the Coastal Gujarat and Mumbai regions, Coastal Andhra Pradesh, the Kolkata region, and Chennai and its surrounds. Major oil and gas basins like the offshore Mumbai, Cambay, Tripura-Cachar Fold Belt, and Krishna Godavari have inherently lower storage risks because their reservoirs and seals are tacitly proven and supported by data from oil and gas operations. Note that fundamental storage assessments of each basin are required to identify and characterise prospective formations within the basins.

National University of Singapore Study – The National University of Singapore examined the potential for carbon capture and storage in India's Maharashtra and Gujarat states, particularly for emissions from the power and industry sectors [25]. The university identified CO_2 emissions amounting to 221 Mtpa CO_2 from power and 115 Mtpa CO_2 from industry in these states. The study found a substantial mid-range CO_2 storage capacity in nearby sedimentary basins, mainly in saline aquifers, which could store emissions for 420 years. Their analysis resulted in four carbon capture and storage hubs (Mumbai, Nagpur, Chandrapur, and Hazira). The Mumbai Basin is especially attractive due to the potential of using an existing pipeline that connects Mumbai to offshore fields.

Indian Institute of Technology, Kharagpur Study – This study employed a GIS platform and an optimisation algorithm to match CO_2 sources from thermal power stations to sinks in Eastern India [30]. They concluded that nearby storage options (Talcher Coalfield, IB Valley Coal Field, and Eastern Coalfields) did not have enough capacity for CO_2 injection beyond a few years. Their model predicted that most of the CO_2 would be routed to the Krishna-Godavari Basin after a short amount of time. This basin is ideal in terms of capacity, but for the selected facilities, it required CO_2 transport over very long distances. However, it may work well for cement facilities located closer to the basin.

Synergia Energy Hub – In January 2023, Synergia Energy Ltd announced its Cambay CCS hub project[2]. The aim is to sequester 43 $MtCO_2$ per year from combined cycle gas power plants and coal power plants in proximity to the Cambay field. However, nearby industrial emitters may also be considered. According to Synergia Energy Ltd, the overall capacity of the field exceeds 500 $MtCO_2$.

9.0 INDIA CEMENT HUBS

As India is the world's second largest cement producer, there is a strong potential for cement-focused carbon capture and storage hubs to develop. The map below provides the locations of most of the cement plants in India as of November 2022.

LEGEND
- Cement Plant (IU)
- Grinding Unit
- Clinkerisation Unit
- White Cement Unit

MAP NOT TO SCALE

S. No	State	No. of Plants	Capadty (int)
1	Rajasthan	26	79.51
2	Arunachal Pradesh	31	70.54
3	Karnataka	17	45.32
4	Madhya Pradesh	16	44.55
5	Gujarat	18	43.52
6	Tamil Nadu	20	42.92
7	Maharashtra	16	36.40
8	Uttar Pradesh	17	31.85
9	Telangana	16	30.71
10	Chhattisgarh	11	20.27
11	West Bengal	17	26.27
12	Odisha	10	23.45
13	Jharkhand	7	16.35
14	Himachal Pradesh	4	13.30
15		3	11.10
16	Haryana	6	8.96
17	Meghalaya	10	8.50
18		7	7.22
19		4	6.57
20		3	4.00
21	Kerala	1	0.50
22		1	0.76
23	Mini Cement Plants Across India	62	6.42
	Total	328	994.14

Figure 21: Cement map of India. As of November 2022.

For consideration of hub development, there are various methods used to group facilities into clusters, each with its distinct approach and application suitability. Clustering is a fundamental concept in data analysis and geographic information systems (GIS) that involves grouping a set of objects in such a way that objects in the same group, or cluster, are more like each other than to those in other groups. The justification for clustering, especially in optimising pipeline infrastructure between facilities, is rooted in efficiency and resource management. By identifying clusters of facilities that are geographically close, the overall requirements for pipeline infrastructure are reduced.

The choice of a clustering method depends on the specific objectives, the nature of the data, and the desired outcomes. Common methods include K-means clustering, hierarchical clustering, and density-based clustering like Density-Based Spatial Clustering of Applications with Noise (DBSCAN). K-means is known for its simplicity and efficiency in partitioning a dataset into K distinct, non-overlapping subgroups. Hierarchical clustering creates a tree of clusters and is adept at revealing hierarchical relationships within data. However, these methods have limitations, particularly in handling irregularly shaped clusters, which leads to the consideration of more advanced techniques like DBSCAN. This analysis uses DBSCAN.

DBSCAN is a clustering algorithm well-suited for spatial data analysis. Unlike methods that require the pre-specification of the number of clusters, DBSCAN does not need this prior knowledge, making it advantageous for analysing complex spatial datasets. The 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. It requires two parameters: the radius around a data point to search for neighbouring points, and the minimum number of points required to form a dense region.

A point is considered a core point if it has at least the minimum points within the defined radius. The algorithm begins by randomly selecting a point in the dataset. If this point is a core point, DBSCAN retrieves all points density-reachable from it and assigns them to a new cluster. Then, it iteratively processes each new point that was added to the cluster, checking whether they are core points too, and expanding the cluster accordingly. This process continues until all points are either assigned to a cluster or marked as noise.

Spatial data analysis was performed using Quantum GIS (QGIS) version 3.34.2, an open-source geographic information system software. The initial step involved mapping the cement facilities in QGIS. Coordinates were available for 259 cement facilities in India. This includes grinding, integrated, clinker, and uncategorised facilities.

CO_2 emissions estimates were able to be generated for 103 of the 259 cement facilities identified with spatial coordinates. Data for seven facilities identified as potential lighthouse projects were provided by GCCA member cement plants including M/s JK Cement Limited, Adani Cement facilities (including Jamul Cement Works, M/s Ambuja Cements Ltd. (Maratha Cement Works), and Ambuja Cement Ltd.), Ultratech Aditya Cement Works, Dalmia Ariyalur Cement Plant and JSW Cement Limited. For these seven facilities, flue gas flow and composition data provided was used to estimate the actual CO_2 that could be captured with carbon capture and storage from these facilities.

The CO_2 flows for the remaining facilities was estimated using overall cement production data provided by GCCA and a carbon emissions intensity derived from the GNR database for process and thermal emission related to clinker production of 0.821 tCO_2/tonne clinker.

Although cement grinding facilities indirectly emit CO_2, these facilities were excluded from this analysis. This is because emissions at grinding facilities are only emissions related to electricity use by equipment used to mill, convey, or store cement. Such that the emissions are considered Scope 2 emissions [32]. For scenarios where grinding facilities produce their own electricity, the CO_2 concentration in the associated flue gas is representative of power generation and is lower compared to the other plant types. With grinding facilities excluded, the analysis includes 101 facilities. These facilities were mapped in QGIS along with the clusters identified by DBSCAN (Figure 22). All GCCA member cement plants, where spatial data was provided, are identified to highlight their location with respect to identified clusters.

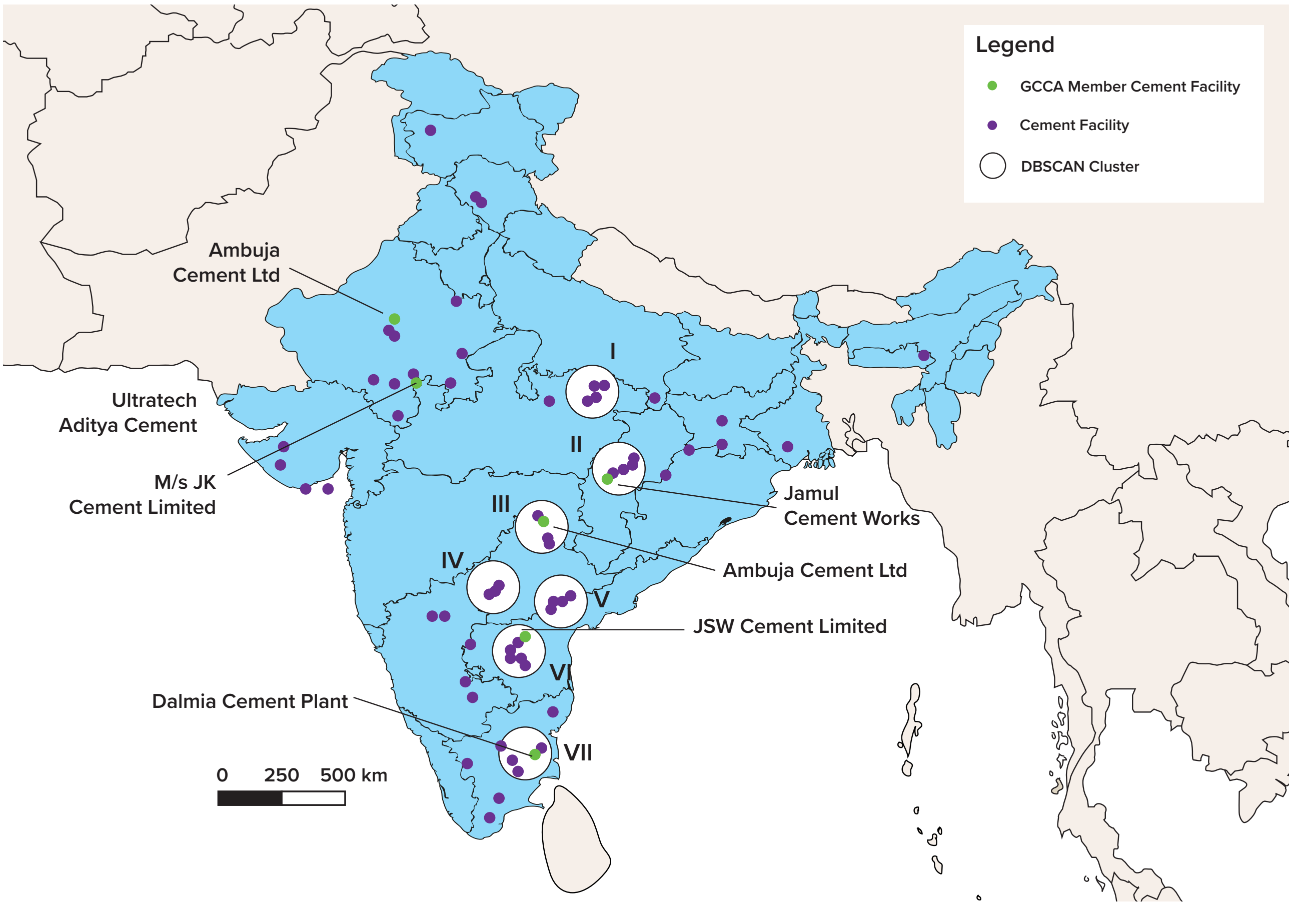


Figure 22: Cement facilities in India with cluster analysis results.

For the DBSCAN analysis, the minimum cluster size was set to five facilities with a maximum distance between points of 1 degree. This results in clusters that are up to 200 km in diameter. The approximation arises because DBSCAN uses degrees in its algorithm in place of linear distance between points. The distance in degrees relates to an angular distance between two points and is a combination of latitude and longitude. 1 degree of latitude is approximately equal to 111 km anywhere at the Earth's surface. This is constant because degrees of latitude are roughly the same distance apart at any longitude. However, the distance of one degree of longitude varies based on latitude – it is at a maximum at the Equator and decreases to zero at the poles. This causes each cluster to vary slightly in diameter. The clusters at the top of the map are approximately 202 km in diameter, whereas the clusters at the bottom of the map are approximately 217 km in diameter. The results of the clustering analysis are shown in Table 17.

CLUSTER ID	NUMBER OF FACILITIES	TOTAL EMISSIONS (MTPA CO_2)
I	6	10.6
II	6	9.1
III	6	11.2
IV	7	10.7
V	18	19.9
VI	12	17.6
VII	8	11.9

Table 17: Results of clustering analysis by DBSCAN

The clustering analysis resulted in seven clusters. Each cluster was labelled from the top to the bottom of the map to show the Cluster ID. Excluding consideration of storage locations, clusters V and VI are most appealing from the number of facilities and large volume of CO_2. In addition, from the map in Figure 22, cluster IV contains facilities that are very tightly grouped. The next step is to compare these clusters with the nearest high-potential storage location. This is shown in Figure 23. As discussed in the Storage section, early opportunities for storage lie in basins under Category 1. However, due to the lack of data regarding saline formations in India, for Category 1 basins, the average latitude and longitude data of the potential saline formations discussed in the section 'Saline Formations Potentially Suitable for Storage' are used as the ''potential storage location'' of the basin (green areas in Figure 23).

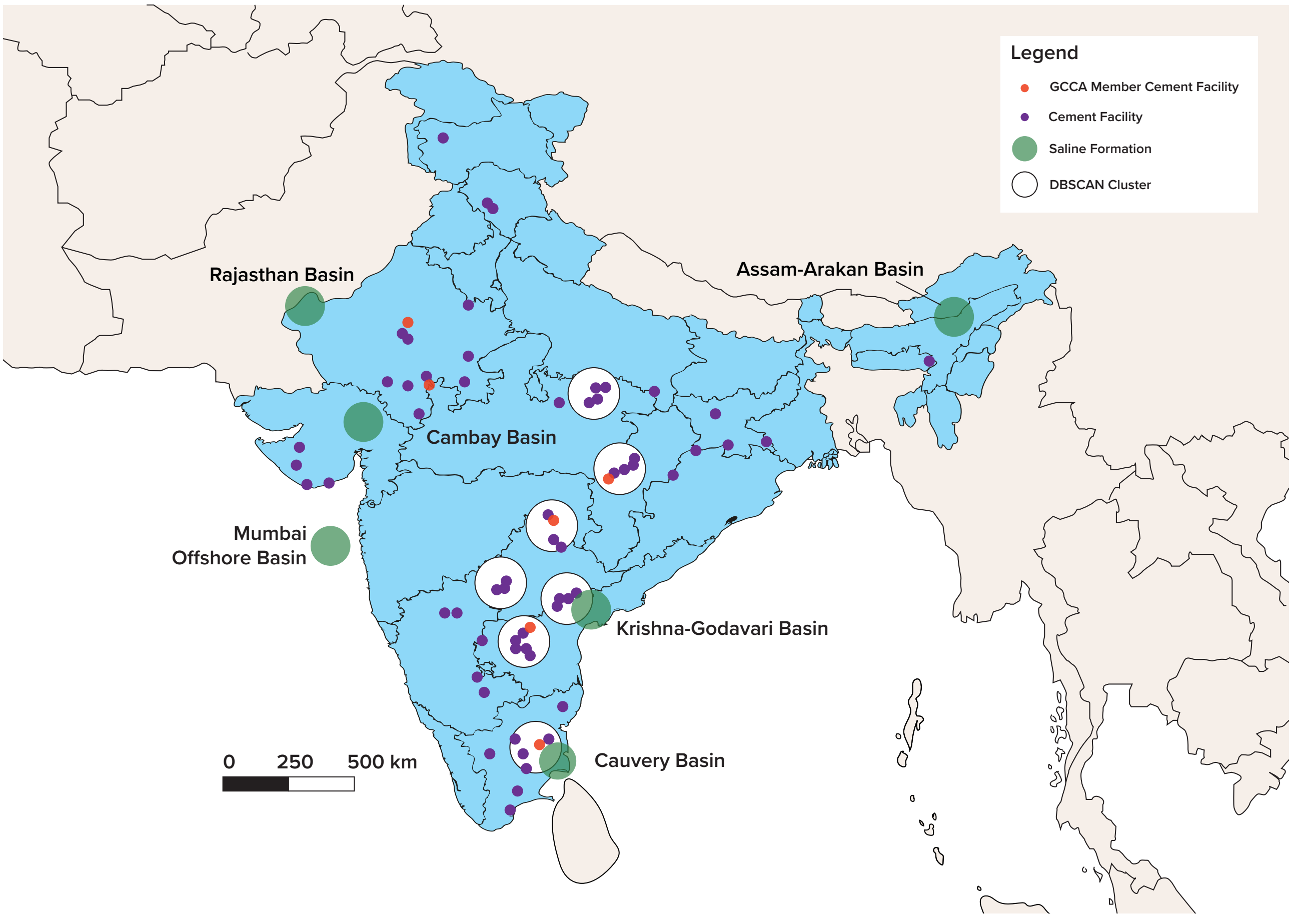


Figure 23: Cluster analysis results with Category 1 basins shown

Of the seven clusters, there are two in very close proximity to potential storage locations. These are clusters V and VII. Cluster V is near the potential storage location in the Krishna-Godavari Basin, and cluster VII is near the potential storage location in the Cauvery Basin. As noted earlier in this report, these basins are both in Category 1, which includes the most promising basins. The clusters near the Cauvery Basin and the Krishna-Godavari Basin provide the least distance to storage of all clusters. However, cluster V has 18 cement plants producing a total of 19.9 Mtpa CO_2 compared to cluster VII with 8 cement plants producing 11.9 Mtpa CO_2. Therefore, cluster V, near the potential storage location in the Krishna-Godavari Basin, was selected as the hub location for the technoeconomic assessment.

It should be noted that of the seven GCCA member cement plants included in the analysis, four were found to fall in identified clusters. While these clusters did not proceed to techno-economic analysis in this study they still demonstrate potential for carbon capture and storage. Through more detailed engineering design beyond this study, the application of carbon capture and storage to these clusters may be technically viable and cost-effective.

10.0 TECHNO-ECONOMIC ANALYSIS

This analysis compares the high-level economics of the potential Krishna-Godavari Basin hub with the case of a single cement plant with carbon capture use and storage. The cement facilities that reside in the Krishna-Godavari Basin hub are shown in Table 18.

The capture plant and compression system design assume the necessary energy for the capture plant and compression systems comes from the use of renewables; therefore, only process and thermal emissions related to clinker production are captured and stored. The costs associated with the infrastructure required to provide renewable energy are not included in this study. While the energy for the capture plant and compression system for transport is assumed to come from renewables in this analysis, it could also come from other sources such as waste heat recovery, fossil fuels or a combination of all sources. If fossil fuels are used at the cement plant to provide the energy for either the capture plant, compression system, or both; the resulting CO_2 produced would also be required to be captured and stored.

PLANT NAME	CITY	STATE	EMISSIONS (MTPA CO_2)
Gamalapadu1.97-Gamalapadu	Gamalapadu	Andhra Pradesh	1.2
Goli1.46-Goli	Goli	Andhra Pradesh	0.9
Guntur1.35-Guntur	Guntur	Andhra Pradesh	0.8
HeidelbergCement AG-Donda Padu	Donda Padu	Telangana	1.5
India Cements Ltd-Wadapally	Wadapally	Telangana	1.5
KCP Ltd-Macherla	Macherla	Andhra Pradesh	0.4
KCP Ltd-Mukteswarapuram	Mukteswarapuram	Andhra Pradesh	2.1
Nalgonda0.89-Nalgonda	Nalgonda	Telangana	0.5
Nalgonda1.49-Nalgonda	Nalgonda	Telangana	0.9
Nalgonda1.66-Nalgonda	Nalgonda	Telangana	1.0
Ncl Industries Ltd-Nalgonda	Nalgonda	Telangana	1.3
Penna Cement Industries Ltd-Wadapally	Wadapally	Telangana	0.7
Rain Industries Ltd-Ramapuram	Ramapuram	Telangana	0.8
Ramapuram0.58-Ramapuram	Ramapuram	Telangana	0.4
Ramco Cements Ltd-Krishna	Krishna	Andhra Pradesh	2.2
Sagar Cements Ltd-Nalgonda	Nalgonda	Telangana	1.1
UltraTech Cement Ltd-Budawada	Budawada	Andhra Pradesh	1.4
Wadapally1.84-Wadapally	Wadapally	Telangana	1.1
		Total Emissions:	**19.9**

Table 18: Facilities in the Krishna-Godavari Basin hub

10.1 Limitations of cost estimates

It is important for the reader to understand the high-level nature of costs in a study of this kind. Reports at this early stage tend to focus on obtaining cost data from similar projects in other parts of the world and then adjusting those costs for location, scale, complexity, and so on.

Accurate cost estimates require substantive engineering studies (pre-FEED, FEED or Detailed Design) to obtain ever more accurate estimates of project cost. These studies tend to be for specific individual projects and are significantly larger than the scope of this report.

At the early-stage assessment that this report has focused on, absolute individual cost estimates should not be relied upon. However, relative costs between different projects or project segments tend to be more reliable at this stage. This level of cost estimates in this report can help the reader understand less expensive or more expensive project elements relative to other elements.

10.2 Cost of Capture

For this analysis, the capital and operating and maintenance (O&M) costs for installing and operating CO_2 capture equipment were calculated for each case. These were then combined into the cost for CO_2 capture on a \$/tonne basis as the metric used for comparison. Capital costs were estimated using the six-tenths rule applied to a base case as described below and shown in the equation below.

$$C_2 \quad C_1 * \left(\frac{S_2}{S_1}\right)^n$$

Where:

- C_1 and C_2 are the capital costs for the original size and the scaled size of the plant, respectively.
- S_1 and S_2 represent the original and scaled capacities of the plant.
- n is the scaling exponent, which, in the case of the six-tenths rule, is typically 0.6.

In examining the cost dynamics of carbon capture, the greatest impact is due to economies of scale, especially since the focus is limited to a single application with cement and not subject to varying CO_2 partial pressures. Generally, in industrial processes, an increase in production capacity often leads to lower unit costs, and carbon capture processes are no exception to this rule. Capital costs for process plants, including CO_2 capture facilities, tend to increase non-linearly with scale. Scaling exponents may vary depending on the unique factors of a specific project, but 0.6 was considered sufficient for screening in this study. For instance, in a single train capture plant, doubling the capture capacity does not double the cost. Instead, the capital increase is likely to be slightly above 50%. Consequently, the capital cost per unit of production (cost divided by capacity) is expected to decrease by about 25%. This scale effect becomes more pronounced with larger scale increases. For example, a tenfold increase in scale could yield cost savings of approximately 60% per unit of production in a single train plant. This scaling can lead to significant cost savings per tonne of CO_2 captured on a large scale.

The basis for the capture plant upon which the cost scaling is based (C_1 and S_1) is the Edmonton Cement Plant in Edmonton, Canada. In 2021, Emissions Reduction Alberta funded a Feasibility Study of the Edmonton Cement Plant using Mitsubishi Heavy Industries Ltd's (MHI) KM CDR Process™I [33]. The results of that study are summarised in Table 19.

Facility	Lehigh Edmonton Cement Plant
Location	Edmonton, AB, Canada
Capacity	0.78 Mtpa CO_2
Capital Cost	511.36 million USD (2021)[3]
Fixed Operating Cost	7.75 million USD/y (2021)[3]
Variable Operating Cost	21.44 million USD/y (2021)[3]

Table 19: Basis information for the carbon capture capital and operating cost estimates.

MHI's technology uses a proprietary amine-based solvent coupled with a process that has been in development since the early 1990s. Other carbon capture technologies include alternative solvents, solid sorbents, membranes, cryogenic carbon capture methods, and process integrated measures such as oxyfuel. For cement production, amine-based solvents carry the least performance risk as they have been deployed in comparable applications such as coal-fired power generation. However, despite the experience, capital and operating costs may vary significantly depending on the selected technology provider and constructor. Furthermore, the Edmonton study is based on a kiln exhaust CO_2 concentration of 12.36% (v/v), and facilities with a higher concentration may see a lower cost of capture. Conversely, facilities with a lower concentration may see a higher cost of capture.

[3] Costs were converted from CAD to USD assuming 1 CAD = 0.8 USD.

For single train facilities, the information in Table 20 is enough to support capital cost scaling using the six-tenths rule. For facilities requiring multiple trains, the exponent can be increased. However, the available literature is not clear on the specific exponent that should be used. Therefore, this analysis considers 0.6 for all cases.

To ensure the cost of construction in India is reflected, the Richardson construction cost factors[3] were used. The Richardson construction cost factor for Alberta Canada at 0.98 was assumed for the current location. For India, the Richardson construction cost factor for Bombay India of 1.01 was assumed. This results in a location adjustment factor of 1.03 applied.

Variable and fixed operating costs are also available from the Edmonton study, and these are used as the basis for scaling variable and fixed operating costs of the hub facilities and the individual case. For the variable operating cost of the capture plant (which includes compression of captured CO_2 up to supercritical conditions), the assumption used is that the amount in USD/tonne is the same regardless of scale. Electricity and fuel pricing were provided for the seven facilities shown in Figure 22. However, since these were not located in the selected hub, all variable operating expenses are based on the Edmonton study. The maintenance portion of the fixed operating cost is indexed to the procurement cost of the overall plant. Fixed operating costs are shown in Figure 24, which has been adapted from the Edmonton study.

Equipment Maintenance – This has been studied extensively and ranges from 1.8 – 2% of the total equipment replacement value (total procurement cost) to over 5% for facilities that are managed poorly [34]. For the hub facilities, 2% is applied to 30% of the carbon capture capital cost. Therefore, the assumption is that 30% of the capital cost relates to equipment procurement. This is based on discussions with carbon capture project developers, and it increases the fixed operating expenses considerably in comparison to the Edmonton study.

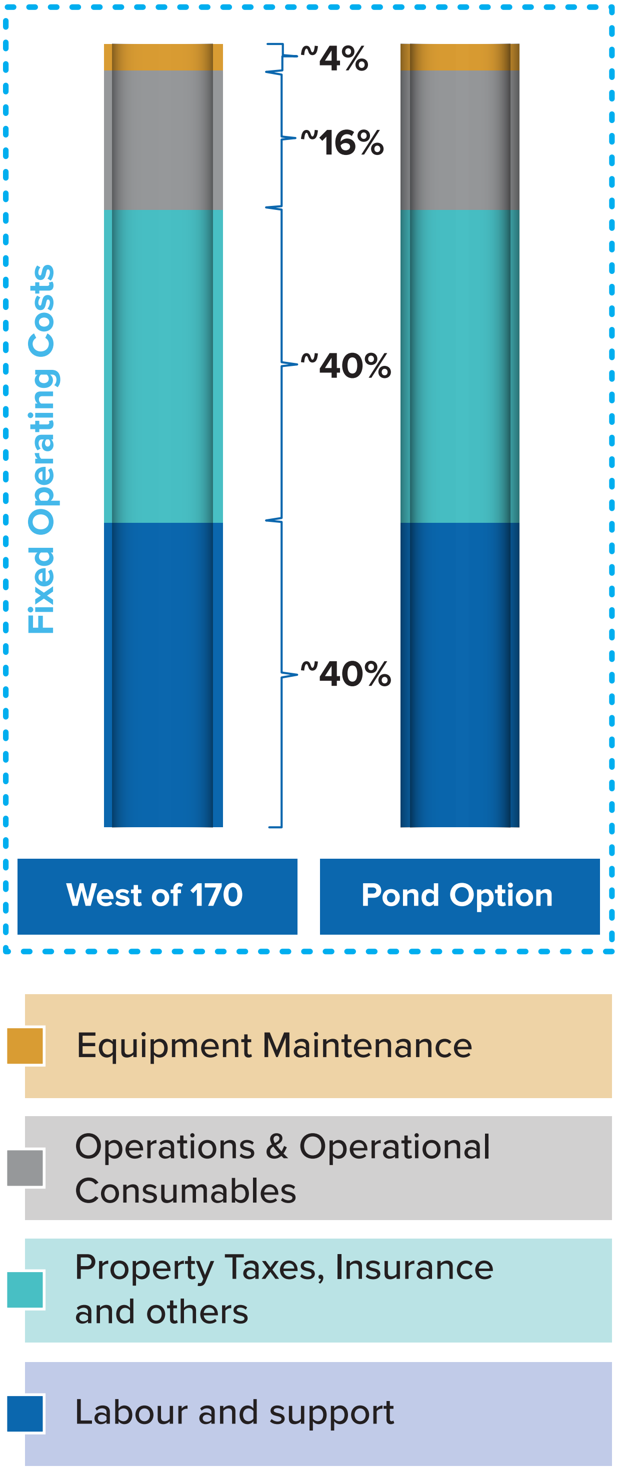


Figure 24: Breakdown of fixed operating costs from the Edmonton Study [34]

[3] The Richardson International Construction Factors are assembled by Cost Data Online (CDOL) (cdol.com). They provide a levelised cost factor for capital projects, including construction labour, materials and other factors relevant to construction costs. They are assembled as an index relative to capital cost of construction in a baseline location (historically, Richardson in the United States). The base location is assigned a Richardson factor of 1.0. Their usefulness is that reliable construction cost data from one part of the world can be transposed to another. It is suitable for pre-feasibility, screening level of cost assessments.

Operations and Operational Consumables – High-cost consumables are included in the variable operating expenses such as electricity or fuel consumption. This value relates to items such as laboratory chemicals needed for periodic analysis of the plant. This study assumes that the same types of and number of tests are required for successful operation at every scale. Therefore, this study assumes that this value is fixed on a per tonne basis for every plant. From the assumption of 16% in Figure 24, this amounts to $1.60 USD/tonne (2021).

Property Taxes, Insurance and others – This item relates to the size and value of the overall plant, and it is assumed to be consistent from the Edmonton cement plant to the cement facilities in India. This assumption is also prudent due to the limited available information related to property tax and insurance in India. From the assumption of 40% in Table 19, this amounts to $4 USD/tonne (2021).

Labour and support – According to industry experience, a similar number of operators and support staff are present regardless of the scale. Therefore, this portion is unchanged for larger facilities. From the assumption of 40% in Table 19, this amounts to $4 USD/tonne (2021). Note that this considers labour rates for operators based in Edmonton, Canada due to the limited data available for operators at each cement plant in the hub.

With these costs, the facilities are updated to show the carbon capture cost as shown inTable 20. A cost of capital of 10.5% based on the cost of capital for a gas turbine installed in India in 2021 reported by the IEA [35] (a comparable installed plant for this analysis) was used to derive the cost of capture for each of the plants.

PLANT NAME	EMISSIONS ($MTCO_2$/Y)	TOTAL CAPITAL COST (MUSD)	ANNUALISED CAPITAL COST (MUSD/Y)	TOTAL OPERATING COSTS (MUSD/Y)	COST OF CAPTURE (USD/TCO_2)
Gamalapadu1.97-Gamalapadu	1.2	681	69	49	98.8
Goli1.46-Goli	0.9	569	58	37	106.5
Guntur1.35-Guntur	0.8	544	55	34	108.7
HeidelbergCement AG-Donda Padu	1.5	767	78	59	94.1
India Cements Ltd-Wadapally	1.5	786	80	61	93.2
KCP Ltd-Macherla	0.4	365	37	18	130.3
KCP Ltd-Mukteswarapuram	2.1	965	98	86	86.1
Nalgonda0.89-Nalgonda	0.5	422	43	23	121.8
Nalgonda1.49-Nalgonda	0.9	576	59	37	106.0
Nalgonda1.66-Nalgonda	1.0	614	63	41	103.1
Ncl Industries Ltd-Nalgonda	1.3	708	72	52	97.2
Penna Cement Industries Ltd-Wadapally	0.7	506	52	30	112.2
Rain Industries Ltd-Ramapuram	0.8	531	54	33	109.8
Ramapuram0.58-Ramapuram	0.4	328	33	15	137.3
Ramco Cements Ltd-Krishna	2.2	986	100	89	85.3
Sagar Cements Ltd-Nalgonda	1.1	649	66	45	100.8
UltraTech Cement Ltd-Budawada	1.4	760	77	58	94.5
Wadapally1.84-Wadapally	1.1	654	67	46	100.5

Note that the capture plant location is based on Edmonton, Canada. Labour and material costs for India may be lower, resulting in a lower cost of capture. The costs for CO_2 transport and storage are estimated in the next section.

Table 20: Facilities in the Mandapeta Formation Hub including the cost of capture

10.3 Cost of Transport

The objective of this examination is to provide a clear economic perspective on the viability of carbon capture and storage in India's cement industry, considering the critical aspect of transport and storage costs. By comparing the hub and individual carbon capture and storage models, this section aims to offer valuable insights for decision-makers and stakeholders. Pipeline transport is the only transport method assumed in this analysis.

Figure 25 shows an enlarged view of the facilities in the Krishna-Godavari Basin in addition to the targeted storage site. There are 18 cement facilities included in the proposed hub, and these range from 0.4 to 2.2 Mtpa CO_2 of emissions. These are shown in Table 20. In total, they produce 19.9 Mtpa CO_2 at full capacity. Due to the possibility that these facilities may all be running at full capacity on any given day, the pipeline should be sized for the full amount of flow. Krishna-Godavari (Onshore) is expected to have a mid-range capacity of 5.78 gigatonnes of CO_2. Therefore, this hub could potentially operate for over 29 years before requiring a new sink.

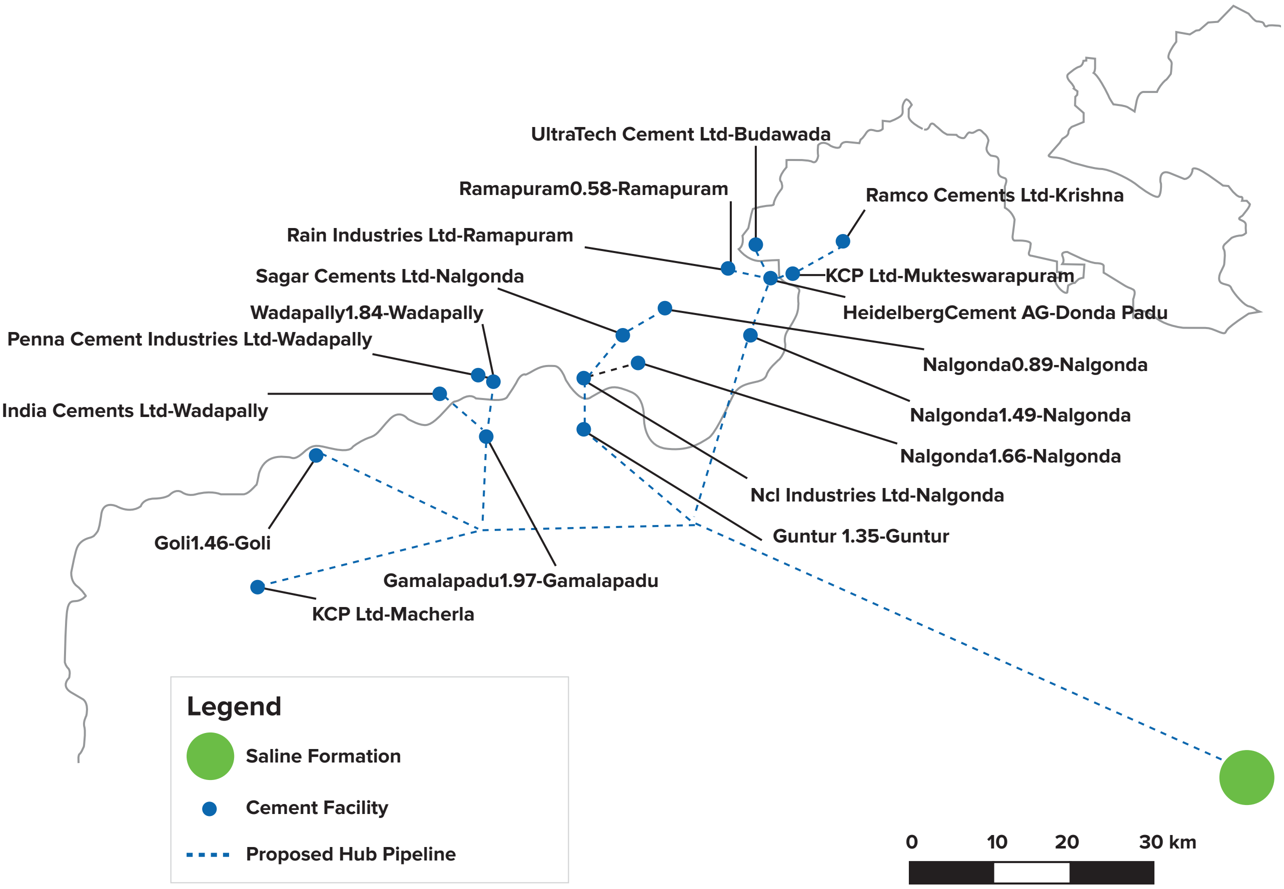


Figure 25: Proposed hub layout in the Krishna-Godavari Basin.

The first step in the analysis is segmentation of the pipeline. This was completed by mapping the pipeline and distances. This is shown in Figure 26. Every cement plant includes a pipeline that leaves the plant, and in some cases the outlet pipeline is very short because it ties into the outlet pipeline from a nearby cement plant. Note that compression from each cement plant is already included in the cost of capture.

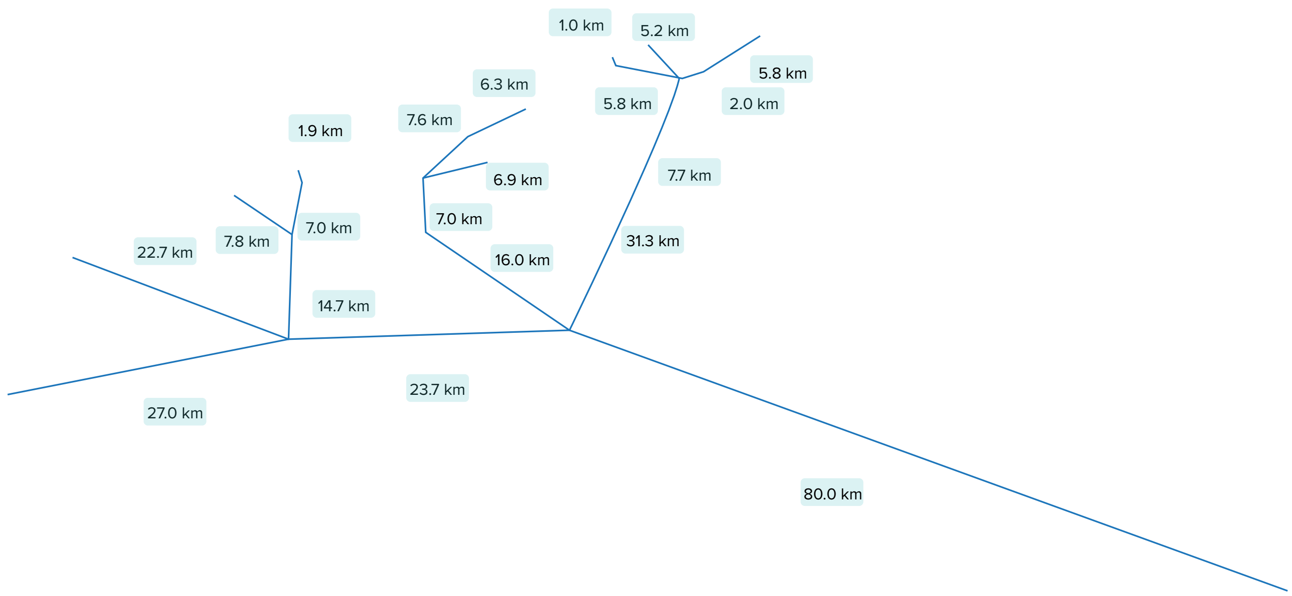


Figure 26: Proposed hub pipeline layout with pipeline segments identified

The proposed layout has not been optimised. Therefore, any benefit that this analysis shows may be amplified in a future stage through optimisation of the pipeline network and layout. Furthermore, no pipeline obstructions are considered, the pipeline is assumed to be at a constant elevation (matching the emitters), and atypical construction circumstances are not included.

Capital and operating costs for pipelines were estimated for each segment of the proposed hub. As the compression from each cement plant is up to supercritical conditions all pipelines are designed to suit supercritical operating pressures.

Pipeline sizing was based on the overall CO_2 flow expected for that given pipeline up to the maximum standard nominal pipe size of 600mm for supercritical/dense phase transport. Dense phase transport occurs at pressures in excess of the CO_2 critical pressure of ~73 bar. It requires piping with thicker walls to resist these high pressures. Standard piping with these thicker walls is not available above 600 mm nominal diameter. It is usually not economic to go to larger sizes as specialised pipeline orders are very expensive for long pipelines. Instead, multiple pipelines would be used.

Once length, pipe diameter, and schedule were determined, cost estimates were made for each pipeline in this study. An AEMO-published report on gas production and transmission costs [36] was used as the source of pipeline costs (in 2015 AUD):

Cost of steel line pipe:	2,500 AUD/tonne
Coating cost:	45.00 AUD/square meter
Construction cost:	30,000 AUD/inch-kilometer
Other (insurance, engineering, legal etc.)	15%
Contingencies	10%

The AEMO study is a particularly useful public resource for pipeline costing. Because it breaks down each element of pipeline costs, it enables a more reliable estimate of pipeline costs to be made. The original costs are for projects in Australia in 2015 Australian Dollars. We describe below the approach taken to adjust this cost basis to Indian locations.

All costs were calculated per meter of pipe length. Pipe weights were obtained online for all pipes, enabling steel pipe cost per meter to be estimated for all line sizes. Surface area was calculated based on outside diameter of each pipe. This enabled coating cost to be estimated for all line sizes. Inch-kilometers are simply nominal pipe sizes in inches multiplied by pipe length. This enabled construction cost to be estimated. Other and Contingencies are simple percentages based on the sum of piping, coating and construction costs.

The producer price index for Australia was used to convert costs from 2015 to 2022 AUD. Costs were converted from AUD to USD assuming 1.0 AUD equals 0.7 USD. Richardsons construction factors were again used ensure the cost of construction in India is reflected for transport. The Richardsons construction factor for Australia at 1.46 was assumed for the reference location for pipeline costs. As for capture costs, the Richardsons construction factor for Bombay India of 1.01 was used. This resulted in a location adjustment factor of 0.69. As for the capture costs, a cost of capital of 10.5% was applied to the capital costs.

An estimate of 1% of capex was used as the annual fixed operations and maintenance (O&M) operating cost for all pipelines in this study [37]. Pipelines have little or no variable O&M operating costs, so these were assumed to be zero.

To demonstrate the cost benefits that hubs can offer, the overall hub cost is compared to the case an individual cement plant were to transport and store its CO_2 independently. The cement plant considered for the individual case is located at the greatest distance from the storage location.

Transportation costs for the hub and the individual case are shown in Table 21 and Table 22, respectively. Booster compression has not been considered in this analysis.

SEGMENT LENGTH (KM)	CO_2 FLOW (Mtpa CO_2)	# PARALLEL PIPELINES	PIPELINE DIAMETER (mm)	TOTAL CAPITAL COST MUSD	ANNUALISED CAPITAL COSTS MUSD/Y	ANNUAL O&M (MUSD/Y)	TOTAL ANNUALISED COSTS (MUSD/Y)	UNIT COST OF TRANSPORT (USD/TCO_2)
27	0.4	1	125	8.9	0.9	0.1	1.0	2.4
22.7	0.9	1	200	13.4	1.4	0.1	1.5	1.7
7.8	1.5	1	250	6.2	0.7	0.1	0.7	0.5
1.9	0.7	1	200	1.1	0.1	0.0	0.1	0.2
7	1.8	1	300	7.1	0.7	0.1	0.8	0.4
14.7	4.6	1	400	21.1	2.2	0.2	2.4	0.5
23.7	5.9	1	450	40.4	4.2	0.4	4.6	0.8
6.3	0.5	1	150	2.6	0.3	0.0	0.3	0.6
7.6	1.6	1	250	6.1	0.6	0.1	0.7	0.4
6.9	1.0	1	200	4.1	0.4	0.0	0.5	0.5
7	3.9	1	350	8.3	0.9	0.1	1.0	0.2
16	4.7	1	400	23.0	2.4	0.2	2.6	0.6
1	0.4	1	100	0.3	0.0	0.0	0.0	0.1
5.8	1.1	1	250	4.6	0.5	0.0	0.5	0.5
5.2	1.4	1	250	4.1	0.4	0.0	0.5	0.3
5.8	2.2	1	300	5.9	0.6	0.1	0.7	0.3
2	4.4	1	400	2.9	0.3	0.0	0.3	0.1
7.7	8.4	1	500	15.4	1.6	0.2	1.8	0.2
31.3	9.3	1	500	62.4	6.6	0.6	7.2	0.8
80	19.9	2	550	366.0	38.4	3.7	42.1	2.1
287.4	**19.9**			**603.9**	**63.4**	**6.0**	**69.5**	**3.5**

Table 21: Krishna-Godavari hub pipeline segment and overall hub costs

SEGMENT LENGTH (KM)	CO_2 FLOW (Mtpa CO_2)	# PARALLEL PIPELINES	PIPELINE DIAMETER (mm)	TOTAL CAPITAL COST MUSD	ANNUALISED CAPITAL COSTS MUSD/Y	ANNUAL O&M (MUSD/Y)	TOTAL ANNUALISED COSTS (MUSD/Y)	UNIT COST OF TRANSPORT (USD/TCO_2)
130.7	0.43	1	200	154.1	16.2	1.5	17.7	34.7

Table 22: Individual cement plant with carbon capture and storage case pipeline cost

The overall cost of transport for the hub is $3.50 USD/tonne of CO_2. The cost of transport for the cement plant considered in the individual cement plant with carbon capture and storage case as part of the hub is $5.30 USD/tonne of CO_2.

This can be compared to the transport cost for the cement plant if it were to consider a standalone carbon capture and storage project with a much higher cost of $34.70 USD/tonne of CO_2. This represents a considerable cost reduction on transportation by leveraging economies of scale through shared infrastructure. For facilities that are smaller in scale or at a greater distance from suitable storage a hub approach to transport could offer an opportunity to reduce overall carbon capture and storage costs. This model would present a greater opportunity for these facilities to continue to operate while meeting emissions reduction objectives. This applies to not just cement plants, which were the focus on this study, but also other neighboring industries (for example specialty chemicals, refining, fertiliser, power generation) that are often smaller in scale and could consider carbon capture and storage.

As highlighted above, this hub configuration has not been optimised and therefore there is an opportunity for further reductions in transport costs. Optimising the route taken by each pipeline is one avenue; however, CO_2 compression optimisation is another avenue that could be explored to reduce transport costs.

This analysis has assumed all CO_2 transport is under supercritical conditions. As a result, each plant is required to compress its CO_2 to these conditions to enable it to be transported to pipelines aggregating CO_2 from other facilities before reaching the storage location. Like capture plants and pipelines, compression costs can also leverage economies of scale. Compression can also leverage the phase the CO_2 is transported.

Previous work by the GCCSI [29] explored the high-level cost trends associated with CO_2 transport in different phases be it gas phase or dense/supercritical phase transport. The study highlighted that facilities that are in close proximity to each other, an industrial cluster, could use lower cost low pressure gas phase transport to transport the CO_2 from each plant to a common compression hub. The common compression hub could then compress the combined CO_2 to supercritical conditions for further transport to the storage location leveraging economies of scale resulting in an overall compression cost reduction of 15% in the scenario considered in the work. The cost reduction for any hub could be more or less than 15%; however, it highlights the optimisation opportunities with transport design that can be explored to reduce overall carbon capture and storage costs.

11.0 CONCLUSIONS & RECOMMENDATIONS

11.1 Cement industry and carbon capture

Indian cement industry has a total of 333 cement manufacturing units in India, comprising 150 large integrated cement plants, 116 grinding units, 62 mini cement plants, and 5 clinkerisation units. Cement consumption in India is around 260 kg per capita against a global average of 540 kilograms per capita, which shows significant potential for the growth of the industry. Indian cement industry has been working on the issue of its GHG emissions and has brought down the CO_2 emission factor from 1.12 t CO_2/tonne of cement in 1996 to 0.719 t of CO_2 /tonne of cement in 2010. Moreover, the CO_2 emission factor was further reduced to 0.617 t CO_2/tonne of cement by 2020-21 *(Reference NCCBM Compendium of Cement Industry 2022 & GCCA India).*

With India's ambitious plan for net-zero and industry-wide commitment, the momentum to decarbonise cement is significant. This report focusses on identifying the storage potential in terms of oil and gas fields, sedimentary basin, and basalt formations, along with capture and transportation costs.

11.2 Storage

According to this study, sedimentary basins in India have the potential to offer sizeable storage resources for CO_2. Among these basins, those with a high level of hydrocarbon exploration and production maturity (basins in Category 1) present early opportunities for development. Net storage resources of basins in Category 1 totals 1.79 $GtCO_2$ at P10; 9.83 $GTCO_2$ at P50; and 48.06 $GtCO_2$ at P90. The study underscores a significant lack of publicly available data for a more reliable assessment of CO_2 storage resources in saline formations across all basins. Consequently, the reported values in this study and those in the literature, are subject to considerable uncertainty, emphasising the urgent need to take action on gathering and publishing the required subsurface data.

Regarding CO_2 storage in oil and gas fields, the current study reveals that the majority of the studied fields are small, with only five oil and twelve gas fields offering storage resources higher than 20 $MtCO_2$, making them appealing for commercial-scale carbon capture and storage deployment. However, among these fields, only three oil fields are almost depleted and their pore space is ready for storage.

Concerning storage in basalts via in-situ mineral carbonation, there is a lack of data regarding essential parameters required for evaluating the CO_2 storage factor of the studied basalts. Published studies reported here have used a simplistic approach to estimate the storage resources in the Deccan and Rajmahal traps, which, due to multiple geological and geochemical complexities, is not recommended by this study. Hence, this study could not provide insights into the storage resources of the Deccan and Rajmahal traps. Considering the size of these basalt formations, they may hold significant potential for in-situ carbon mineralisation. Therefore, there is a need to conduct specific measurements and geochemical modelling studies to calculate their storage resources.

11.3 Capture and Transport

The analysis of emission source matching to storage opportunities highlights that in India there is a strong potential for cement focused CCUS hubs to develop. Seven cement plant clusters were identified in southeast and central India that could consider a CCUS hub. Of these cement plant clusters two are near potential storage locations; these are clusters V and VII. Cluster V located near the Krishna-Godavari Basin consists of 18 cement plants producing a total of 19.9 Mtpa CO_2 and Cluster VII near the Cauvery Basin includes 8 cement plants producing 11.9 Mtpa CO_2. Due to the tight proximity of the cement plants in the cluster, Cluster V was selected as the hub location for the technoeconomic assessment.

The emissions from the cement plants in Cluster V range from 0.4 Mtpa CO_2 to 2.2 Mtpa CO_2. The cost of capture (including dense phase compression) for the cement plants ranged from 137.30 USD/tCO_2 (for 0.4 Mtpa CO_2) to 85.30 USD/tCO_2 (for 2.2 Mtpa CO_2) using publicly available costs derived from the Feasibility Study for the application of carbon capture and storage to the Edmonton Cement Plant in Edmonton, Canada. Actual cost estimates may vary as these costs are highly dependent on inflation and other parameters, location, local labour and material costs, energy costs etc. Costs are continuously evolving from a technical perspective and will require substantial engineering studies to develop the specific costs for each cement plant.

Capture costs make up a significant component of the carbon capture and storage value chain, however transport of CO_2 can also be a significant cost depending on the design of the transport system. A high-level carbon capture and storage hub pipeline transport concept was developed to derive transport costs and allow this cost to be compared to the case where an individual cement plant were to transport and store its CO_2 independently. The overall cost of transport for the hub is US$3.50/tonne of CO_2. The cost of transport for the cement plant considered in the individual cement plant with carbon capture and storage case as part of the hub is US$5.30/tonne of CO_2. This can be compared to the transport cost for the cement plant if it were to consider a standalone carbon capture and storage project with a much higher cost of US$34.70/tonne of CO_2.

The hub concept represents a considerable cost reduction in transportation by leveraging economies of scale through shared infrastructure. For facilities that are smaller in scale or at a greater distance from suitable storage, a hub approach to transport may offer an opportunity to reduce overall carbon capture and storage costs. In addition, this model would present a greater opportunity to not just cement plants, which were the focus on this study, but also other neighbouring industries (for example specialty chemicals, refining, fertilizer, power generation) that are often smaller in scale and could consider carbon capture and storage.

It should be noted that of the seven potential plants for lighthouse projects included in the analysis, two were found to fall in identified clusters. While these clusters did not proceed to techno-economic analysis in this study they still demonstrate potential for CCUS. Through more detailed engineering design beyond this study, the application of CCUS to these clusters may be technically viable and cost-effective.

Further engineering studies are needed to identify and develop first mover CCUS projects within the CCUS hubs identified, however this analysis provides a good starting point for future work.

11.4 Further Study Phases

The collaboration between the GCCA, GCCSI and CEM CCUS creates the opportunity to fast-track CCUS in the Indian cement industry and deliver real projects/hubs with CO_2 capture, transport, and storage solutions. This paper is the first in a series aiming to discuss relevant issues around the deployment of CCUS in the Indian cement industry and to leverage the momentum for CCUS created through the release of the *'CCUS Policy Framework and its Deployment Mechanism in India'*, in November 2022.

Future papers will build on this first study and explore the enabling policy, regulatory and investment environment that will be crucial for a large-scale deployment of CCUS in India.

12.0 APPENDIX – METHODOLOGIES

12.1 Methodology: Saline Formation Resource Calculation

CO_2 storage resources of saline formations can be estimated using the following equation:

$$M_{CO_2} = A.\ H.Ø.\ E.\rho \quad (1)$$

Where:

- H refers to the thickness of the formation,
- A refers to the areal extent of the formation,
- $Ø$ is the formation average porosity,
- E is the storage efficiency, and
- ρ is the density of CO_2 at reservoir conditions.

Storage efficiency can be calculated using the following equation:

$$E = E_v.E_m.E_{An/At}.\ E_{hn/hg}.E_{Øe/Øtot} \quad (2)$$

Where:

- E_v is the volumetric displacement efficiency,
- E_m is microscopic displacement efficiency,
- $E_{An/At}$ is the fraction of total area suitable for storage,
- $E_{hn/hg}$ is net to gross thickness, and
- $E_{Øe/Øtot}$ is the fraction of effective to net porosity.

Storage efficiency is ''site-specific'' and is influenced by multiple factors including but not limited to saline formation's boundary conditions, injection and pressure management strategies, and structural and stratigraphic confinement types. The most commonly used values for storage efficiency in sandstone saline formations are those reported by the Department of Energy (DOE), with P10 at 0.51%, P50 at 2%, and P90 at 5.4% [38]. However, these values are calculated at the "formation scale". P10, P50, and P90 are the three key percentiles often employed when dealing with the representation of uncertainty through a probability distribution. At the P10 level, there is a 10% probability that the actual outcome or value will be equal to or lower than the estimated value, representing the pessimistic scenario and portraying a more cautious and conservative outlook. Moving to the P50 level, there is a 50% probability that the actual outcome or value will be equal to or lower than the estimated value. Widely considered as the best estimate or the point of highest likelihood, P50 provides a balanced midpoint in the estimated range. Finally, at the P90 level, there is a 90% probability that the actual outcome or value will be equal to or lower than the estimated value. While this estimate offers a more optimistic outlook, it also acknowledges a higher level of uncertainty compared to P50. These percentiles serve to communicate the range of potential outcomes and the associated probabilities, aiding in understanding the variability and risks inherent in the estimation process.

Given the lack of data on saline formations of Indian basins, the storage resources of saline formations at the ''basin scale'' are calculated in this study using the DOE method [38]. However, the DOE values need to be amended for basin scale calculations as $E_{hn/hg}$ (net-to-gross thickness) and $E_{An/At}$ (total area suitable for storage) values will be smaller than those at the saline formation scale.

Therefore, the storage efficiency has been recalculated using P10 = 0.05 and P90 = 0.19 for $E_{hn/hg}$ and P10= 0.05 and P90= 0.2 for $E_{An/At}$. IEA [39] reported these values as P10 = 0.21 and P90 = 0.76 for $E_{hn/hg}$ and P10= 0.2 and P90= 0.8 for $E_{An/At}$ at the saline formation scale.

A log-odds transformation is applied to the P10 and P90 values for each parameter reported in Table 23. Storage efficiency is then calculated using a Monte Carlo simulation and equation 3.

$$E=\frac{1}{1+\exp(-X_v)}\cdot\frac{1}{1+\exp(-X_m)}\cdot\frac{1}{1+\exp(-X_{An/At})}\cdot\frac{1}{1+\exp(-X_{hn/hg})}\cdot\frac{1}{1+\exp(-X_{Øe/Øtot})} \quad (3)$$

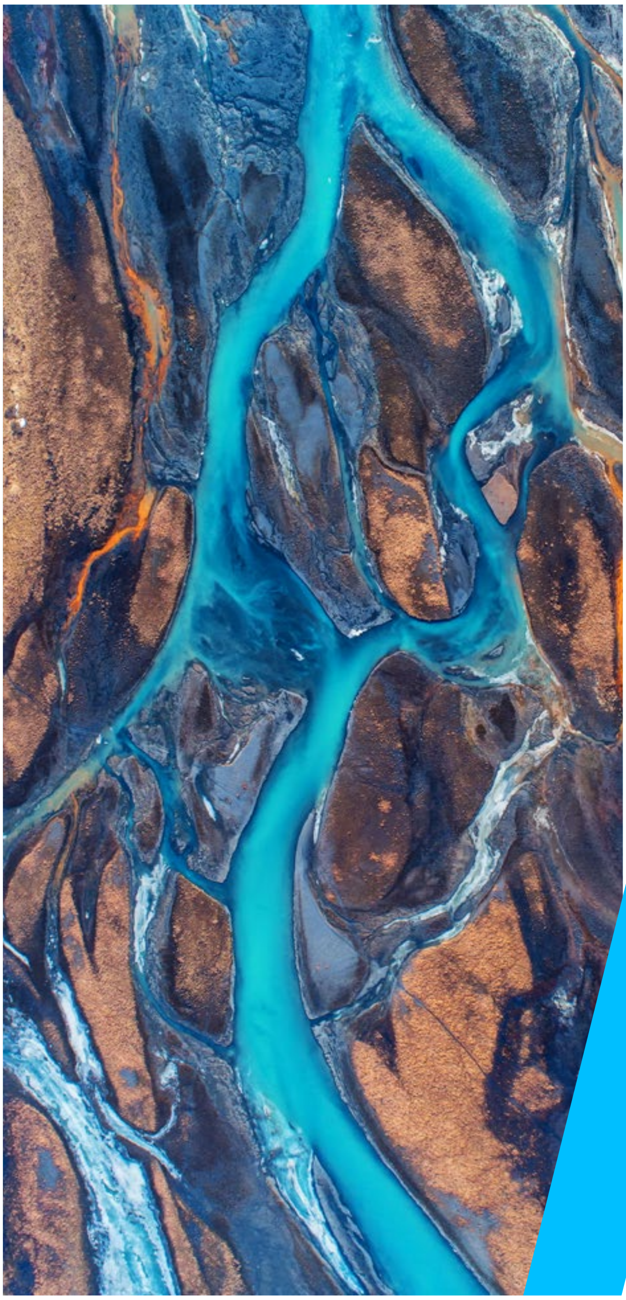
$$X= \ln (P/(1-P)) \quad (4)$$

TERM	P10	P90
$E_{An/At}$	0.05	0.2
$E_{hn/hg}$	0.05	0.19
$E_{Øe/Øtot}$	0.64*	0.77*
E_v	0.16*	0.39*
E_m	0.35*	0.76*

Table 23: Parameters for storage efficiency in saline formations at basin scale. * Values from IEA GHG (2009) [40]

Since the $E_{An/At}$ and $E_{hn/hg}$ values have already been updated to account for calculation at the basin scale, terms A and H in equation 1 can be used as the areal extent and average sedimentary thickness of each basin.

For CO_2 to reach a critical phase, the injection depth should be deeper than 800 meters. While there is no specific reported maximum depth for CO_2 storage, it is crucial to establish an upper limit. This necessity arises from the fact that pressure and temperature increase with depth, and beyond a certain point, the reservoir pressure and temperature become excessively high. As a result, the conditioning of CO_2 at the surface for injection may not be economically viable. In this study, a maximum storage depth of 4000 meters is assumed. It's noteworthy that all existing storage projects in saline formations around the world inject CO_2 at depths well above this maximum value. For instance, the Dupuy saline formation (Gorgon CO_2 storage site) is situated at a depth ranging from 2000 to 2500 meters [41], and the Utsira formation (Sleipner CO_2 storage site) is situated at a depth between 802 to 1093 meters below sea level [42]. Using the optimum injection depth range (from 800-4000 m), a constant gross thickness of 3200 m is assumed for all the studied basins, unless the reported average sedimentary thickness of the basins is less than this value. In such cases, the reported value is utilised.



Due to a lack of data regarding the depth of saline formations and hence their pressure and temperature conditions, and consequently, the range of CO_2 density values, as well as the unknown porosity, a global minimum, maximum, average, and standard deviation values for each parameter have been defined (Refer to Table 24. Values for each parameter are generated using the Gaussian probability distribution. CO_2 density is calculated using the pressure and temperature data.

Utilising the above equations and values for each parameter, a Monte Carlo simulation is employed to estimate the resources of each basin. This simulation involves one thousand iterations, each with a sample size of 500 for every parameter.

	AVERAGE	MIN	MAX	STANDARD DEVIATION
Pressure (psi)	2000	1200	4000	500
Temperature (°C)	100	70	130	10
Porosity	0.2	0.1	0.3	0.05

Table 24: Parameters used in the Monte Carlo simulation to estimate storage resources per basin.

12.2 Methodology: Conventional Oil

The estimated CO_2 storage resources (MCO_2) of the studied fields are calculated using a 1D volumetric approach:

$$M_{CO_2} = (N_o.B_o + N_g.B_g).E.\rho_{CO_2} \quad (5)$$

- Here, E refers to site-specific storage efficiency, which can be determined via reservoir simulations. The storage efficiency value for gas fields is anticipated to surpass that of oil fields. This determination is site-specific and contingent on various parameters, necessitating numerical modelling for accuracy. In the absence of such site-specific data, in this study, it is assumed that the storage efficiency range of gas fields is two times that of oil fields (refer to Table 25). In addition: B_o and B_g are the formation volume factors of the oil and gas, respectively, dependent on oil and gas properties and current reservoir conditions.

- ρ_{CO_2} represents the CO_2 density at reservoir conditions, which is a function of reservoir pressure and temperature.

- N_o and N_g refers to the recoverable volume of the oil and gas in the field. It's important to note that not all the pore space occupied by the recoverable hydrocarbons in the field becomes available for CO_2 storage. Factors such as aquifer encroachment, compaction, water and gas injection during secondary and tertiary injection scenarios, damage to the integrity of the seal and reservoir during depletion - constraining the buildup of pressure to the original reservoir pressure during CO_2 storage, and other factors, negatively impact the pore space available for CO_2. Therefore, storage efficiency is incorporated into equation 5.

Due to a lack of data regarding the current pressure and temperature conditions in each field, and consequently the range of CO_2 density values in each field, as well as the unknown current oil formation volume factors and storage efficiency, global minimum, maximum, average, and standard deviation values for each parameter have been defined (Refer to Table 25). Values for each parameter are generated using the Gaussian probability distribution. CO_2 density is calculated using the pressure and temperature data. B_g is calculated assuming the gas is completely made of CH_4 and using the pressure and temperature data. A Monte Carlo simulation is utilised to estimate the resources, employing one thousand simulations with a sample size of 50 for each parameter in every simulation.

	AVERAGE	MIN	MAX	STANDARD DEVIATION
Pressure (psi)	2000	1200	3000	500
Temperature (°C)	100	70	130	10
B_o	1.5	1	2	0.3
E for oil fields	0.3	0.2	0.4	0.04
E for gas fields	0.6	0.4	0.8	0.08

Table 25: Parameters used in the Monte Carlo simulation to estimate storage resources per field.

13.0 REFERENCES

[1] "Iea 50, India's clean energy transition is rapidly underway, benefiting the entire world." [Online]. Available: https://www.iea.org/commentaries/india-s-clean-energy-transition-is-rapidly-underway-benefiting-the-entire-world

[2] S. Paltsev, A. Gurgel, J. Morris, H. Chen, S. Dey, and S. Marwah, "Economic analysis of the hard-to-abate sectors in India," Energy Econ, vol. 112, p. 106149, Aug. 2022, doi: 10.1016/J.ENECO.2022.106149.

[3] "India: CO_2 Country Profile."

[4] R. G. Prinn et al., "MIT Joint Program on the Science and Policy of Global Economic Analysis of the Hard-to-Abate Sectors in India Economic Analysis of the Hard-to-Abate Sectors in India," 2021. [Online]. Available: http://globalchange.mit.edu/

[5] "Business Today, Can Cement Industry be a growth driver for India."

[6] "Cement Industry: Advancing the nation, one tonne at a time."

[7] Global Cement and Concrete Association India, "BLENDED CEMENT - GREEN, DURABLE & SUSTAINABLE," 2022. [Online]. Available: https://gccassociation.org/wp-content/uploads/2022/04/Report_Blended-Cement-Green-Duratable-Sustainable_13Apr2022.pdf

[8] I. Bhavan, "Indian Minerals Yearbook 2019 58 th Edition CEMENT (ADVANCE RELEASE) GOVERNMENT OF INDIA MINISTRY OF MINES INDIAN BUREAU OF MINES," 2020.

[9] M. of C. and I. D. for P. of I. & I. T. Government of India, "Annual report 2022-23." [Online]. Available: https://dpiit.gov.in/sites/default/files/DPIIT_AnnualReportE_03March2023.pdf

[10] "Directorate general of hydrocarbons." [Online]. Available: https://www.dghindia.gov.in/

[11] "National Data Repository (NDR) of India." [Online]. Available: https://www.ndrdgh.gov.in/NDR/

[12] "A regional assessment of the potential for CO_2 storage in the Indian subcontinent." https://www.globalccsinstitute.com/archive/hub/publications/95746/regional-assessment-potential-co2-storage-indian-subcontinent.pdf

[13] S. Holloway et al., "An assessment of the CO_2 storage potential of the Indian subcontinent," Energy Procedia, vol. 1, no. 1, pp. 2607–2613, Feb. 2009, doi: 10.1016/J.EGYPRO.2009.02.027.

[14] "Building the cost curves for CO_2 storage: European sector," 2005. [Online]. Available: https://www.globalccsinstitute.com/archive/hub/publications/95736/building-cost-curves-CO_2-storage-european-sector.pdf

[15] T. Bakshi, H. Mallya, and D. Yadav, "Assessing India's underground CO 2 storage potential A critical analysis of what lies beyond the theoretical potential," 2023.

[16] A. Singh, V. Mendhe, and A. Garg, CO_2 sequestration potential of geologic formation in India. 2006.

[17] V. Vishal, Y. Verma, D. Chandra, and D. Ashok, "A systematic capacity assessment and classification of geologic CO_2 storage systems in India," International Journal of Greenhouse Gas Control, vol. 111, p. 103458, Oct. 2021, doi: 10.1016/J.IJGGC.2021.103458.

[18] M. Mishra and A. K. Patidar, "Post-drill geophysical characterization of two deep-water wells of Cauvery Basin, East Coast of India," J Pet Explor Prod Technol, vol. 13, no. 1, pp. 275–295, Jan. 2023, doi: 10.1007/s13202-022-01550-w.

[19] S. C. Malviya et al., "Integration of technology & Geological understanding for reservoir characterization-A case study of Ahmedabad-Nandej-Wasna area of Cambay Basin, India,"

[20] P. C. Kumar, J. Kumar, and K. Sain, "Cenozoic tectonic subsidence in the Upper Assam Basin, NE India," Geosystems and Geoenvironment, vol. 3, no. 1, p. 100223, Feb. 2024, doi: 10.1016/J.GEOGEO.2023.100223.

[21] S. K. R. Moulik, H. J. Singh, R. K. Singh Rawat, M. S. Akhtar, S. Mayor, and M. Asthana, "Sand Distribution Pattern and Depositional Model of Kopili Formation (Eocene) with Special Reference to Sequence Stratigraphic Framework from North Assam Shelf, Assam-Arakan Basin, India, #50196 (2009)," 2009.

[22] "Cambay CCS." [Online]. Available: https://www.synergiaenergy.com/india/cambay-ccs

[23] R. Wessel, "Cambay Carbon Capture & Storage Scheme," 2023.

[24] B. P. McGrail, H. T. Schaef, A. M. Ho, Y. J. Chien, J. J. Dooley, and C. L. Davidson, "Potential for carbon dioxide sequestration in flood basalts," J Geophys Res Solid Earth, vol. 111, no. 12, Dec. 2006, doi: 10.1029/2005JB004169.

[25] H. K. Bokka, K. Zhang, and H. C. Lau, "Carbon capture and storage opportunities in the west coast of India," Energy Reports, vol. 8, pp. 3930–3947, Nov. 2022, doi: 10.1016/J.EGYR.2022.03.012.

[26] "Indian planning body proposes CCUS framework eyeing 750 mil mt/year CO_2 capture by 2050 | S&P Global Commodity Insights." [Online]. Available: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/113022-indian-planning-body-proposes-ccus-framework-eyeing-750-mil-mtyear-CO_2-capture-by-2050

[27] "Netra Technology/Scientific Services." [Online]. Available: https://ntpc.co.in/about-us/corporate-functions/netra/technology/flue-gas-CO_2-methanol

[28] "India to have two National Centres of Excellence in Carbon Capture & Utilization at IIT Bombay & JNCASR, Bengaluru, supported by DST." [Online]. Available: https://pib.gov.in/PressReleasePage.aspx?PRID=1797178

[29] J. Minervini, C. Consoli, and D. Kearns, "CCS networks in the circular carbon economy: linking emissions sources to geologic storage sinks," 2021. [Online]. Available: https://www.globalccsinstitute.com/wp-content/uploads/2022/03/CCE-CCS-Networks-22-5.pdf

[30] P. Jain, K. Pathak, and S. Tripathy, "Possible Source-sink Matching for CO_2 Sequestration in Eastern India," Energy Procedia, vol. 37, pp. 3233–3241, Jan. 2013, doi: 10.1016/J.EGYPRO.2013.06.210.

[31] B. Baliga et al., "Integrated high impact innovation in sustainable energy technology - prefeasibility analysis for carbon capture, wutilization and storage (subproject 2)," 2021. [Online]. Available: https://www.adb.org/sites/default/files/project-documents/52041/52041-003-tacr-en.pdf

[32] N. Tkachenko et al., "Global database of cement production assets and upstream suppliers," Sci Data, vol. 10, no. 1, Dec. 2023, doi: 10.1038/s41597-023-02599-w.

[33] "Final outcomes report non-confidential version lehigh cement edmonton CCUS feasibility project." [Online]. Available: https://eralberta.ca/

[34] M. C. Eti, S. O. T. Ogaji, and S. D. Probert, "Reducing the cost of preventive maintenance (PM) through adopting a proactive reliability-focused culture," Appl Energy, vol. 83, no. 11, pp. 1235–1248, Nov. 2006, doi: 10.1016/J.APENERGY.2006.01.002.

[35] "Iea50, Cost of Capital Observatory." [Online]. Available: https://www.iea.org/data-and-statistics/data-tools/cost-of-capital-observatory

[36] "Gas production and transmission costs eastern and south eastern Australia," 2015.

[37] "Australian power generation technology report," 2015. [Online]. Available: www.CO_2crc.com.au/publications

[38] A. Goodman et al., "U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale," International Journal of Greenhouse Gas Control, vol. 5, no. 4, pp. 952–965, Jul. 2011, doi: 10.1016/J.IJGGC.2011.03.010.

[39] "Development of storage coefficients for carbon dioxide storage in deep saline formations." [Online]. Available: www.ieaghg.org

[40] "DEVELOPMENT OF STORAGE COEFFICIENTS FOR CARBON DIOXIDE STORAGE IN DEEP SALINE FORMATIONS Technical Study." [Online]. Available: www.ieaghg.org

[41] M. Flett, J. Brantjes, R. Gurton, J. McKenna, T. Tankersley, and M. Trupp, "Subsurface development of CO_2 disposal for the Gorgon Project," in Energy Procedia, Feb. 2009, pp. 3031–3038. doi: 10.1016/j.egypro.2009.02.081.

[42] V. Singh, S. Asa, and A. Cavanagh, "SPE 134891 Reservoir Modeling of CO 2 Plume Behavior Calibrated Against Monitoring Data From Sleipner, Norway," 2010. [Online]. Available: http://onepetro.org/SPEATCE/proceedings-pdf/10ATCE/All-10ATCE/SPE-134891-MS/1727117/spe-134891-ms.pdf/1

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