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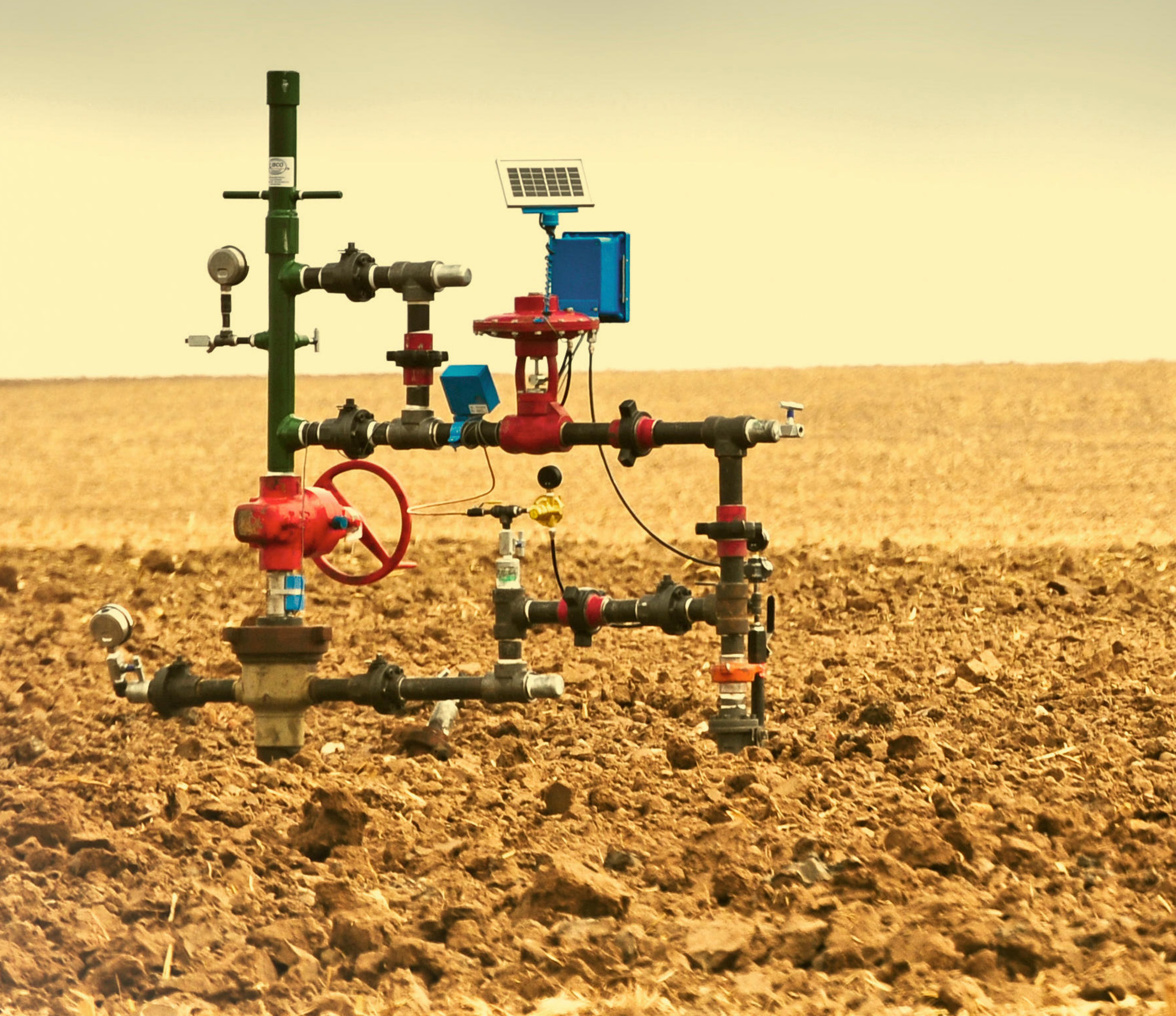
Assessing India's Underground CO_2 Storage Potential

A Critical Analysis of What Lies Beyond the Theoretical Potential

Tuli Bakshi, Hemant Mallya, and Deepak Yadav

Report | April 2023



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Contents

India has extensive basalt formations which could be used to store CO_2.

Image: Alamy

Executive summary

Carbon capture and storage (CCS) is vital for India to be self-reliant, achieve net-zero GHG emissions by 2070, and ensure a just transition. Despite India promoting renewable and alternative energy sources, long-term projections show that to meet the growing energy demand of power systems and industries, fossil fuels will need to remain an integral part of India's energy economy (Malyan and Chaturvedi 2021). Cumulatively, India will have to inject 5.3–10 gigatonnes (Gt) of CO_2 by 2050 to mitigate fossil fuel use–based emissions under 1.5°C temperature increase scenarios (Gambhir et al. 2022; Vishal, Chandra, Singh, and Verma 2021; Garg et al. 2017; Singh, Sharma, and Dunn 2021). **Essentially, CCS can reduce emissions from key sectors of the economy without changing the existing fuel or technology mix**. It could also help reduce the cost of the energy transition significantly, and, to an extent, avoid stranded assets in India in the future.

Geologically, CO_2 can be sequestered in oil and gas reservoirs, unmineable coal beds, deep saline formations, and basalts. The theoretical storage potential[1] of these reserves is 649 Gt (Figure ES 1). Of this, 326 Gt can be stored in deep saline formations and 316 Gt in basalts, while oil fields and coal formations account for 2.6 Gt and 4 Gt, respectively (Figure ES 1). Prior studies suggest that the vast majority of storage potential exists in the sedimentary formations of deep saline aquifers (Singh, Sharma and Dunn 2021). However, few studies have been conducted on basalts, which can be found extensively in the western part of India. Unlike sedimentary formations, basalts are harder due to different origins and chemical assemblage. Basalts act as the basement for other formations in much of the country. In sedimentary rock formations (such as saline aquifers), CO_2 is trapped in pore spaces, whereas basalt can convert the CO_2 into stone through mineralisation. **With one of the most significant onshore basalt formations in the world, India could potentially be a global CCS champion.** However, there is currently only one active basalt CCS pilot project globally, which is located in Iceland, where basalt has been used successfully to store CO_2 due to suitable properties. Every basalt is different; therefore, we need to urgently assess India's basalt formations to evaluate whether these are favourable for CCS.

If Indian basalts have suitable properties, **developing a pilot CCS programme has dual critical benefits**.

i. **Zero leakage and post-injection risk:** It is the least risky of all underground CCS options, since CO_2 is permanently converted to mineral salts when injected into basalt, ensuring no possibility of leakage. This further reduces monitoring costs significantly in the long run, which can make projects commercially viable without requiring long-term liability coverage.

ii. **Monetisation potential:** India's CCS potential is considerably higher than what it requires to achieve its net-zero targets. Hence, the excess CCS potential provides a monetisation opportunity for India to inject CO_2 emissions from other countries into our formations .

This is not to say that saline aquifers are not a promising option. However, from an overall risk–return trade-off perspective, and the fact that exploitation of both saline aquifers and basalt may take the same time and effort, basalt is an option that should not remain unexplored. Through our research, we provide a comprehensive analysis of various CCS options in India, highlighting the measures to be taken and the timeline to unlock these options.

> India could be a global CCS champion, having significant onshore basalt formations.

1 This theoretical capacity calculation is based on liberal assumptions that do not consider various above-ground and underground challenges.

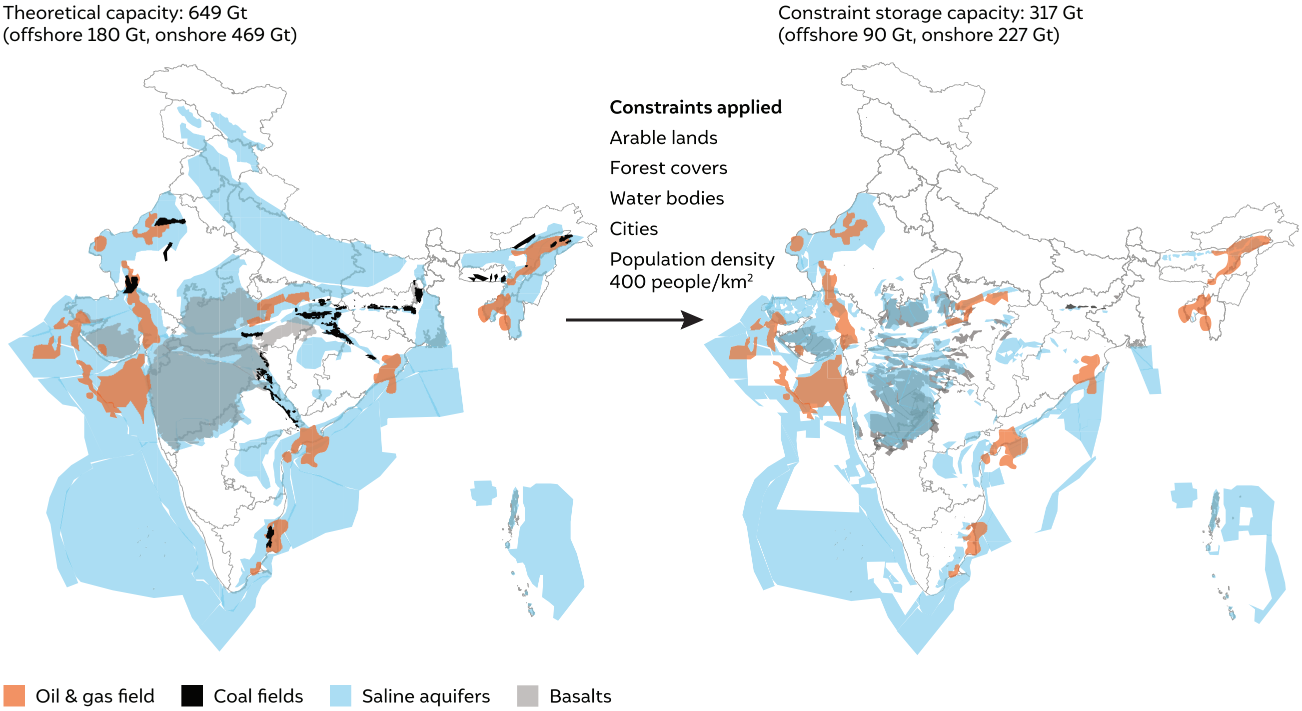
A. Realisable potential in India

CO_2 storage sites exist deep under the Earth's surface. But above them lie arable lands, forests, water bodies, no-go zones, and areas with high population density. These environmental, social, and 'not in my backyard' (NIMBY) factors are termed 'above-ground challenges', which limit operations and significantly reduce the areal extent of storage in India (Figures ES1 and ES2).

Per our analysis, the realisable storage potential tends to be a function of arable lands and population density, as depicted in Figure ES3. This constrained storage potential ranges from 359–101 Gt. The gap between realisable storage and the theoretical potential can be attributed to the challenges mentioned above (Figure ES 2).

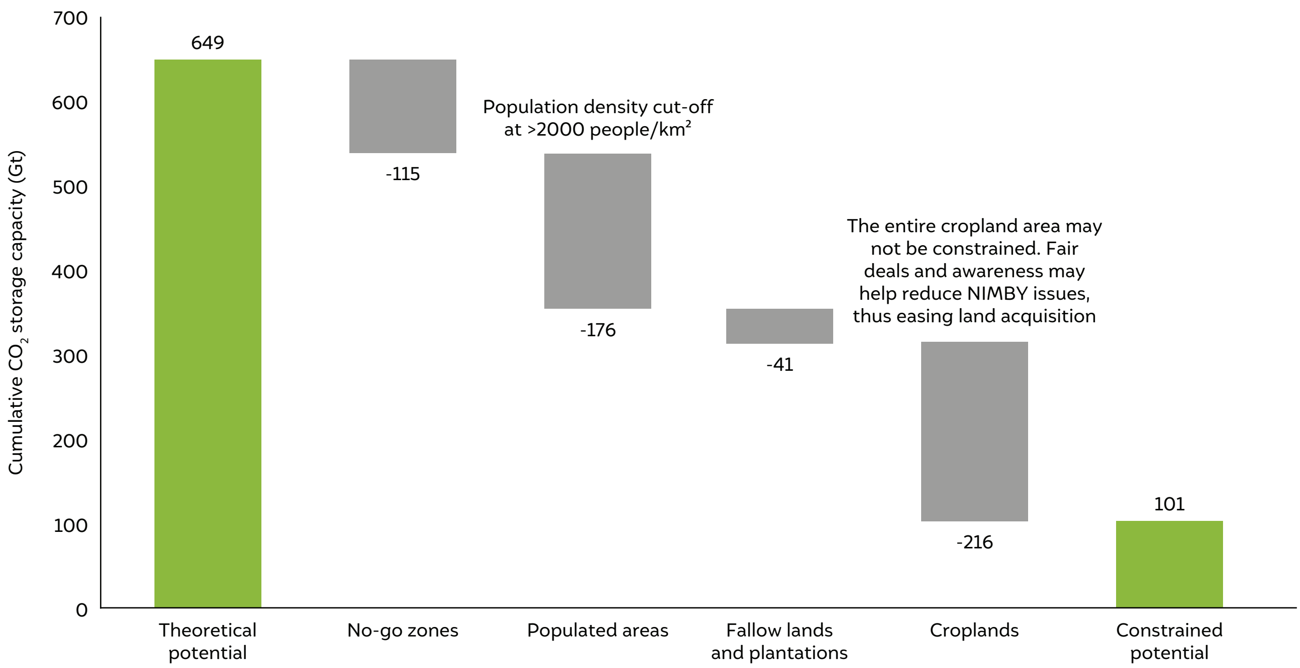
- The exclusion of no-go zones (biodiversity zones, economic zones, armed forces areas, reserve forests, national parks, etc.) reduces the storage potential from 649 Gt to 534 Gt.

Figure ES 1 **Above-ground challenges could significantly reduce the area available for CO_2 storage**



Source: Authors' analysis

Figure ES 2 **The theoretical CO_2 storage potential is constrained due to the presence of no-go zones, human settlements, and croplands**



Source: Authors' analysis

- When we exclude high population density districts (>2000 people/km²) as well, the storage potential reduces to 359 Gt (dark green curve, Figure ES 3).
- It further reduces if plantations and fallow lands are taken as constraints. Here, croplands and wastelands are considered operable (light green curve, Figure ES 3).
- In the extreme scenario, when croplands are deducted and only wastelands are considered, the storage potential becomes 101 Gt (grey curve, Figure ES 3).

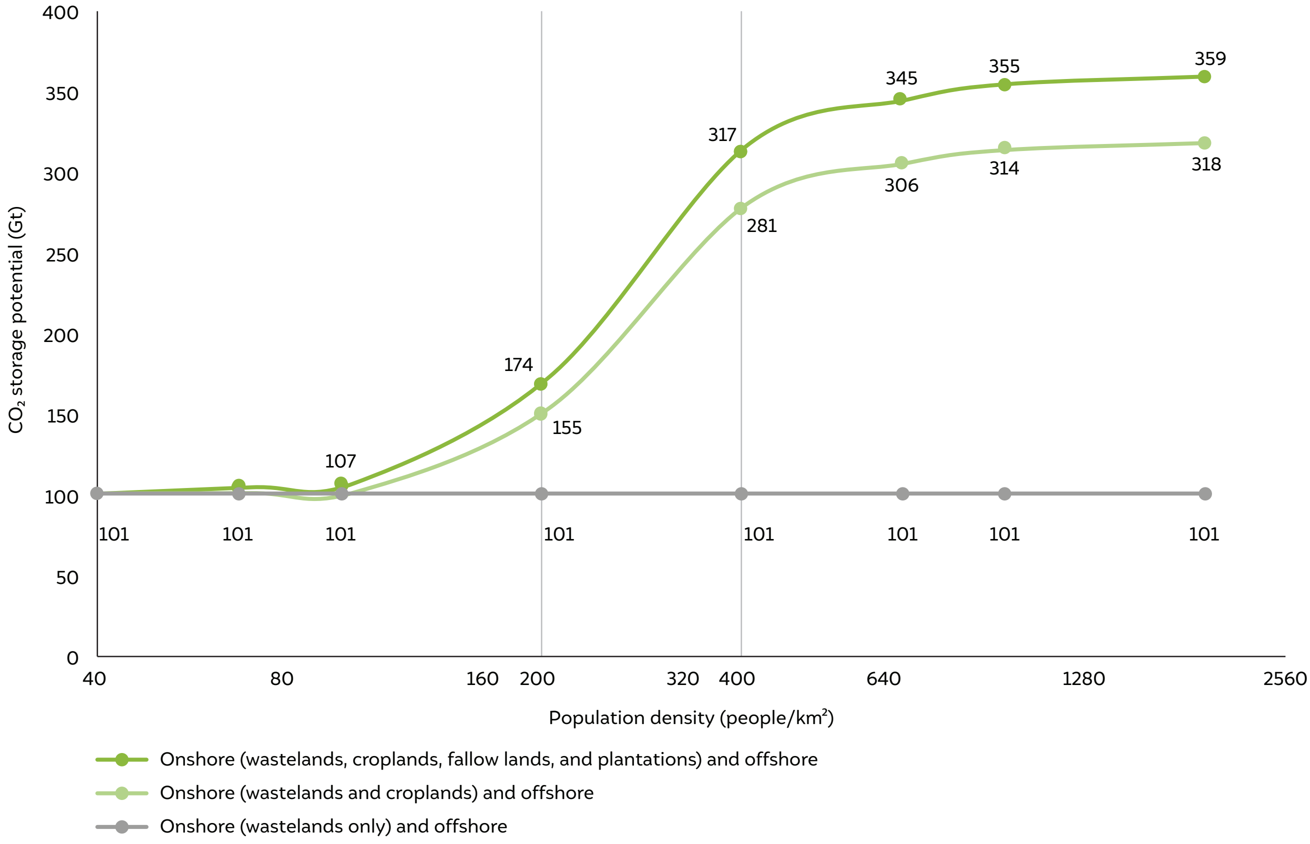
B. Probable timeline for various CCS options

Figure ES4 presents the probable timeline for beginning commercial injection in various reservoir types. India can start with large scale CO_2–enhanced oil recovery (EOR) within ten years. However, injection in other kinds of reservoirs is crucial, since oil and gas fields alone will not be able to meet India's CCS needs to achieve net-zero emissions. Further, the figure demonstrates that the work that needs to be undertaken in the next five years is crucial to ensure that India builds sufficient CCS capacity to meet its net-zero target.

Dedicated research and data generation are needed to explore potential CO_2 storage sites in saline formations and basalts. Technical feasibility studies and other research/data generation on CCS in oil and gas fields and active coal bed methane (CBM) fields might take less time since data already exists for both these resources. However, of India's entire reserves, oil and gas reservoirs contribute to only 2 per cent, while the remaining is contributed by saline formations and basalts combined. Despite this skewed distribution, injection in oil and gas fields is being prioritised for cost recovery through EOR. The first CO_2-EOR project in the depleted Gandhar fields in Gujarat is expected to start injection soon (Business Wire 2022).

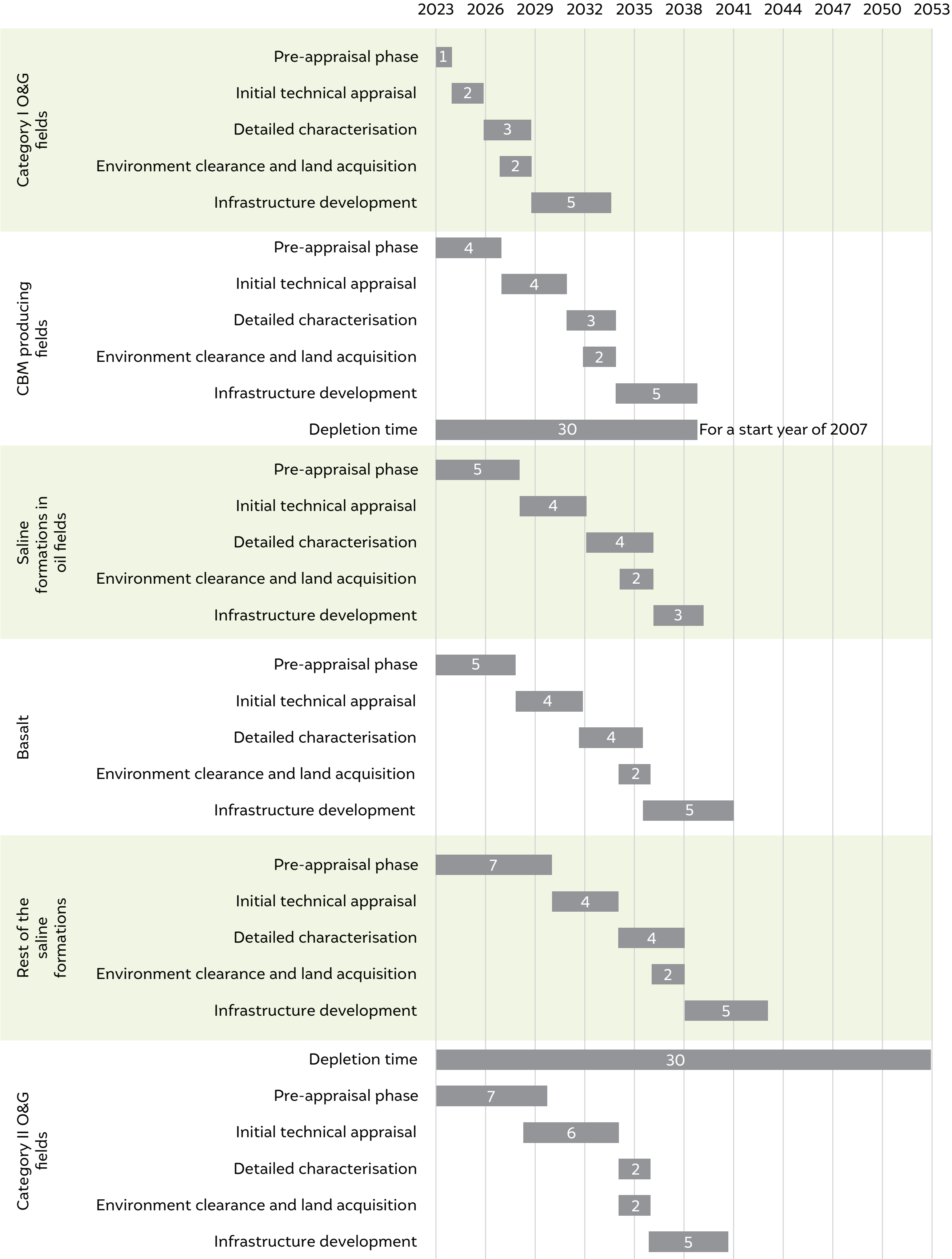
Saline formation and basalt formations are entirely unexplored from the perspective of CCS. Injection could take up to two decades to begin for these wholly untapped, unexplored, yet promising reservoirs unless rigorous research starts at the earliest. To unlock this significant CCS potential, data generation over the next five years is critical. This will set India as a forerunner of CCS in South Asia and unlock monetisation opportunities.

Figure ES 3 The constrained storage potential is a function of the population density and land use



Source: Authors' analysis

Figure ES 4 Timeline depicting initiation of probable commercial injection



Source: Authors' analysis

C. Recommendations

- **Assess and explore basalt resources on priority:** Despite the high theoretical potential, minimal knowledge exists on the disposition of deep-seated basalts and the kinetics of mineralisation in different strata. While EOR is taking place, the Department of Science and Technology (DST), along with the Geological Survey of India and hydrocarbon industries, should initiate a dedicated research programme on CCS in basalt, prioritising detailed mapping and research and development. Although developing this resource to achieve commercial-scale injection could take up to two decades, it promises large-scale potential with low risks.
- **License acreage for CCS development:** The costs of exploring deep saline aquifers and basalt formations for CCS potential could be offset by the Government of India (GoI) taking the initial steps to facilitate surveys, exploration, and research programmes. Alternatively, the GoI could lease out acreage to third parties through a licensing mechanism similar to oil and gas exploration licensing. The government could generate revenues through the CCS licensing mechanism based on the quantum of CO_2 injected, similar to royalties paid on oil and gas production.
  * **Develop CCS as a business potential:** Monetising excess CCS potential (especially in basalts, if research finds it as the right storage sink) can also recover costs and generate revenue. Japan is exploring such an arrangement with Indonesia, albeit in oil and gas reservoirs for EOR (Reuters 2022).
- **Develop and update existing standards and regulations to incorporate CCS:** A thorough assessment is required to identify and develop the necessary standards and regulations for the entire CCS supply chain. The environmental impact assessment must have provisions for clearing CCS projects. Similarly, injection and monitoring need safety standards.
- **Build a collaborative research network:** The DST should build a domestic research network that facilitates collaboration between academia, government institutes, policy think tanks, and industry. It should also establish networks for knowledge transfer with other countries that have successfully implemented CCS projects at a pilot or commercial scale.

1. Introduction

It has been scientifically established that human activities lead to environmental degradation and that ecosystems globally are facing existential threats from anthropogenic greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change (IPCC) report warns that rising temperatures could cause catastrophic effects if global warming exceeds 1.5°C. IPCC models suggest that limiting global warming to 1.5°C and 2°C through negative emissions should be our prime mandate (IPCC 2018; IPCC 2021). Despite the ongoing climate crisis and dwindling carbon budgets, there has been limited progress in achieving deep decarbonisation, especially in hard-to-abate sectors such as steel and cement. As timelines to achieve net-zero GHG emissions tighten, carbon capture and storage (CCS) could play a critical role in India's climate mitigation portfolio and can help it achieve its net-zero targets.

CCS is a process by which anthropogenic CO_2 is captured from different industrial sources (or directly from air in the future), transported to a storage site, and injected underground — into various geological formations — for permanent storage. Besides geological storage, CCS can be combined with enhanced hydrocarbon recovery from oil and gas reservoirs to increase production. Further, hydrogen production from fossil fuels combined with CCS — termed 'blue hydrogen' — can act as a bridge to green hydrogen production. Moreover, bio-energy production combined with CCS (BECCS), regarded as a negative emission technology (NET), may be critical for realising the 1.5°C target (Fajardy and Mac Dowell 2017; Haszeldine et al. 2018).

The IPCC special report, *Global Warming of 1.5 °C*, highlights the significance of reaching net-zero emissions by mid-century and suggests four scenarios (P1, P2, P3, and P4) to prevent further temperature rise. Three of the four scenarios include a wide use of CCS, where the IPCC estimates that 550–1,017 Gt CO_2 would have to be removed, globally, by 2100 (IPCC 2018; Global CCS Institute 2020). The scenario with no utilisation of CCS requires a radical change in human behaviour, which seems unlikely given our current consumption patterns. CCS can play an essential role in realising cost-effective, net-zero emissions by enabling the following: (i) deep decarbonisation in

> **CCS could play a critical role in achieving India's net-zero targets amid tightening timelines**

hard-to-abate industries such as cement, iron and steel and chemicals, (ii) production of low-carbon blue hydrogen at scale, (iii) decarbonisation of legacy fossil fuel-based power plants so that they provide dispatchable and low-carbon electricity for their remaining lives, and (iv) BECCS and direct air carbon capture and storage (DACCS) (Global CCS Institute 2020).

By mobilising research, investments, and support from government and industry stakeholders, countries such as the United States, Canada, China, and Australia have started facilitating CCS deployment. As per the latest CCS database (Global CCS Institute 2020), 135 commercial CCS facilities and 6 CCS hubs are in different stages of development globally. Of these 135 facilities, 27 are operational, of which 22 are for enhanced oil recovery (EOR). However, the operational CCS facilities have an injection potential of only 40 million tonnes per year (Mtpa). The current pipeline of projects has the potential to capture about 220 Mt CO_2 per year by 2030, only a fraction of the 800 Mt CO_2 per year target of the International Energy Agency's (IEA) sustainable development scenario (SDS) (Debarre et al. 2021). Similarly, a significant gap exists between the planned CCS capacity and the potential needed to realise even 2°C targets. So far, only 300 Mt of CO_2 has been injected into different reservoirs worldwide, cumulatively (Global CCS Institute 2020).

In this report, we first estimate India's theoretical CO_2 storage potential based on existing methodologies. Next, we identify different above-ground operational constraints for CO_2 storage in the Indian context (e.g., land-use patterns, population density, no-go zones, etc.). Then, we evaluate the realistic and comprehensive CO_2 storage potential based on the identified constraints. Finally, we estimate the probable timeline for CO_2 injection in different sedimentary basin types, deep saline aquifers, and basalt after assessing the basin readiness and technology readiness level (TRL). This study considers various constraints to highlight the early steps that need to be taken to realise India's full CCS potential. This research can serve as an initial blueprint for preparing carbon storage maps, source–sink matching, and infrastructure development to allow concerned stakeholders to carry out a practicality assessment of storage projects in the coming decades.

1.1 CCS scenario in India

India emitted 2.95 Gt of CO_2 in 2018, which is expected to rise with continued growth (GHG Platform India 2022). With regard to CCS deployment, India is still in the nascent stages compared to forerunners such as the United States, Norway, and China. Studies show that almost 5 to 10 Gt CO_2 must be cumulatively sequestered in India by 2050 to meet the 2°C carbon budget (Shukla et al. 2015; Vishwanathan et al. 2018). However, the Indian economy depends significantly on domestic coal, which supports jobs across several sectors (Ganesan and Narayanaswamy 2021). India also has significant investments tied up in thermal power plants and industries, such as iron and steel, which will be stranded assets if India decarbonises rapidly. An unplanned rapid coal phase-out will likely remove a low-cost, indigenous fuel supply source from India's energy mix and lead to serious economic consequences.

Table 1 Literature provides varying estimates of the underground storage potential of CO_2 in India

	Dooley et al. (2005)	Singh, Mendhe, and Garg (2006)	IEA GHG (2008)	Vishal, Verma, Chandra, and Ashok (2021)
Oil/gas field (Gt)	2	7	3.7–4.6	3.4
Coal field (Gt)	2	5	0.345	3.7
Saline formation (Gt)	102	360	63.3	291
Basalt (Gt)	–	200	–	97–315
Total (Gt)	106	572	64.3–67.3	395.1–613.1

The inclusion of CCS technologies in India's energy portfolio can enable the sustainable use of coal up to 2060, leading to a more relaxed pace of transformation (Vishal, Chandra, Singh, and Verma 2021; Garg et al. 2017; Kanitkar, Banerjee, and Jayaraman 2019). A CEEW analysis suggests that CCS technology is likely to accommodate almost a 30 per cent share of fossil fuels in the primary energy mix in a 2050 net-zero scenario. The share reduces to only five per cent without CCS (Malyan and Chaturvedi 2021). Given India's net-zero commitment by 2070, CCS will only increase the accommodation levels of fossil fuels for a more extended period. Moreover, research indicates that CCS has a mitigation potential of 780 Mt/year at below 60 USD/tCO_2 in a 2°C scenario and 250 Mt/year up to 75 USD/tCO_2 in a below 2°C scenario (Malyan and Chaturvedi 2021). Therefore, CCS might help India achieve its net-zero target while simultaneously easing the pace of transition from fossil energy to renewable sources.

CCS progress in India

The idea of CCS has been dormant in India's decarbonisation conversations for over a decade. It gained momentum as an indispensable technology to attain carbon neutrality in large, fossil fuel-based economies after the ambitious mitigation pledges made at the Paris Agreement. The government, public sector undertakings (PSUs), and Indian industries have already started researching this technology's techno-economic feasibility and scalability (Business Wire 2022). The Oil and Natural Gas Corporation (ONGC) and the Indian Oil Corporation Limited (IOCL) have signed an MoU to establish a CO_2-based EOR system in the Gandhar field, Gujarat, which is expected to begin operations soon (ONGC 2019).

An assessment of CO_2 storage potential in different formations is the foundation for CCS deployment. So far, works by various researchers estimate that almost 68–606 Gt storage reserves exist across different types of sinks (Singh, Mendhe, and Garg 2006; Dooley et al. 2005; Viebahn et al. 2011; IEA GHG 2008; Vishal, Verma, Chandra, and Ashok 2021) (Figure 2). The potential storage sites identified in India are mainly located in onshore sedimentary basins, basalts, and offshore shallow and deep waters up to the exclusive economic zone (EEZ). The Directorate General of Hydrocarbon (DGH) India categorises these sedimentary basins into three categories: I, II, and III (DGH 2020). We have given the definitions of these basins in Annexure I and their locations and geographical extents in Figure A2. There have only been estimations of the theoretical CO_2 storage potential so far and no realistic estimate considering above-ground challenges.

CO_2 storage potential assessments are outdated and limited in the Indian context. We have provided some estimates found in the literature in Table 1. The estimates of different researchers vary due to different methodological approaches, existing resource potential (oil and gas and coal) during the time of the study, and different assumptions. Please refer to Annexure II for further details.

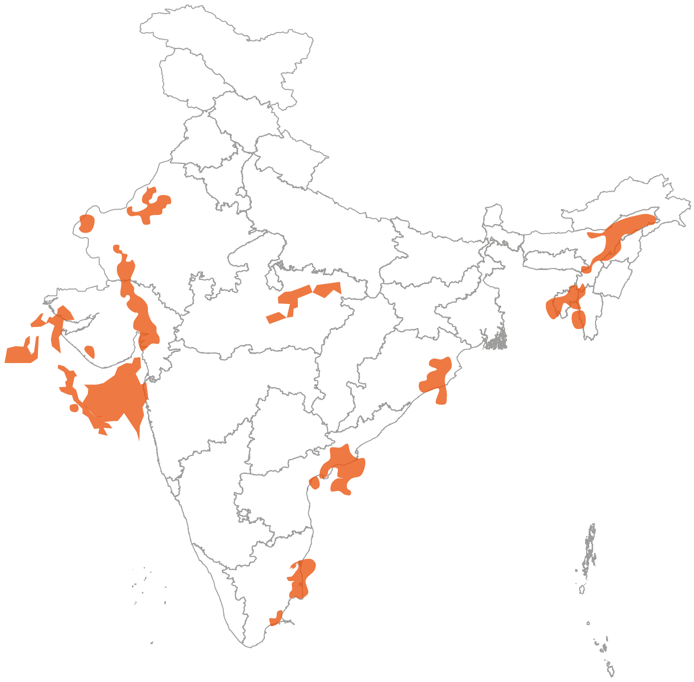
2. CO_2 storage potential of India

To evaluate the potential for CCS in India, we first assess the total CO_2 storage potential in different types of reservoirs without considering any above-ground constraints. This scenario is labelled 'theoretical scenario' for ease of understanding. We have explained the kinds of reservoirs conducive to CCS and their particular characteristics in Annexure I.

2.1 CO_2 storage in oil and gas (O&G) reservoirs

Field-specific reservoir parameters and pore-scale level data are necessary to develop accurate estimates of the CO_2 storage potential of oil and gas fields. However, this information, though available to oil and gas producers, is not available in the public domain. The DGH provides information only on the original oil in place (OOIP) and ultimate recoverable reserves (URR) (DGH 2020). Hence, we made a few assumptions to calculate the storage potential of different basins. We have presented detailed calculations for Category I and II basins in Annexure II. Category III basins only have prospective resources and await discovery (DGH 2021a). Hence, we did not account for them when estimating the storage potential of O&G fields (DGH 2020). Category I and II basins together have a 2.6 Gt storage potential. The storage value in Category II basins is meagre (see Annexure II) and is likely to increase with exploration and development. The 2.6 Gt estimate is close to the values calculated by earlier researchers (Vishal, Verma, Chandra, and Ashok 2021; IEA GHG 2008).

Figure 1 Theoretically, 2.6 Gt and 4 Gt of CO_2 can be stored in India's O&G (Categories I and II) and coal fields, respectively



Oil & gas field ■ Coal fields

Source: Authors' analysis

2.2 CO_2 storage in coal fields

We considered the state-wise total coal bed methane (CBM) resources in the literature (Prabhu and Mallick 2015) to estimate the CO_2 storage potential. We have provided the detailed calculation in Annexure III. India has a coal reserve of about 293.5 billion tonnes, which holds a CBM resource of about 2,600 billion cubic metres (bcm) (MoPNG 2022). Figure 1 shows the distribution of the 4 Gt of CO_2 storage potential in coal fields. The expanding coal resource of India has a 4.64 per cent compound annual growth rate (CAGR) (Vishal, Verma, Chandra, and Ashok 2021). With increased deployment of renewables, coal resources are likely to increase as they will remain unused, leading to increased CBM resource potential. These factors will further increase the CO_2 storage potential.

According to the Ministry of Petroleum and Natural Gas (DGH 2021b), the gas-in-place CBM reserves in Raniganj, Jharia, Bokaro, North Karanpura, and Sohagpur is 296.7 bcm. The CO_2 storage potential through enhanced CBM recovery (ECBMR) is estimated to be 0.13 Gt.

2.3 CO_2 storage in saline formations

Due to a lack of research, surveys, and data acquisition, lithological (rock formation characteristics) data on deep saline formations in Indian sedimentary basins are limited. The detailed data on aquifers obtained during exploration work in Category I O&G basins are only available to oil and gas producers. Also, there have been limited attempts at exploring other areas in these basins. The data for the Category II basins is non-uniform due to a lack of hydrocarbon exploration activity compared to Category I basins. As seen in Figure 2, saline formations are present in both onshore and offshore areas. The total theoretical storage potential in saline formations is 326 Gt. We have explained the methodology for assessing CO_2 storage potential in saline formations in Annexure IV. The theoretical total storage potential offshore is 176 Gt and the remaining 150 Gt is the onshore potential.

Figure 2 **Theoretically, 326 Gt of CO_2 can be stored in India's saline formations**

Source: Authors' analysis

2.4 CO_2 storage in basalt

The 65-million-year-old Deccan basalts occur in the mid-western part of India and are recognised as the most extensive flood basalts on the Earth's surface. They cover an area of 500,000 km². The Rajmahal Trap is 106 million years old and occurs in Jharkhand, covering an area of 18,000 km². Figure 3 shows the areal extent of basalts. Fast volcanic eruptions accompanied by rapid cooling have severely affected these basalts' physical properties, such as density, porosity, and permeability, which could influence the storage of CO_2. Data is limited and not many studies map the porosity, fractures, geomechanics, and storage efficiencies of Indian basalt, all of which significantly impact the potential for CO_2 storage. Hence, further research is needed to identify the desirable areas for storage and quantify storage potential in those areas accurately. Furthermore, the research on storage mechanisms in basalts is in a very nascent stage and severe data gaps exist in the Indian context. Based on high-level assumptions provided in Annexure V, we estimate that India's basaltic area has a theoretical storage potential of 316 Gt.

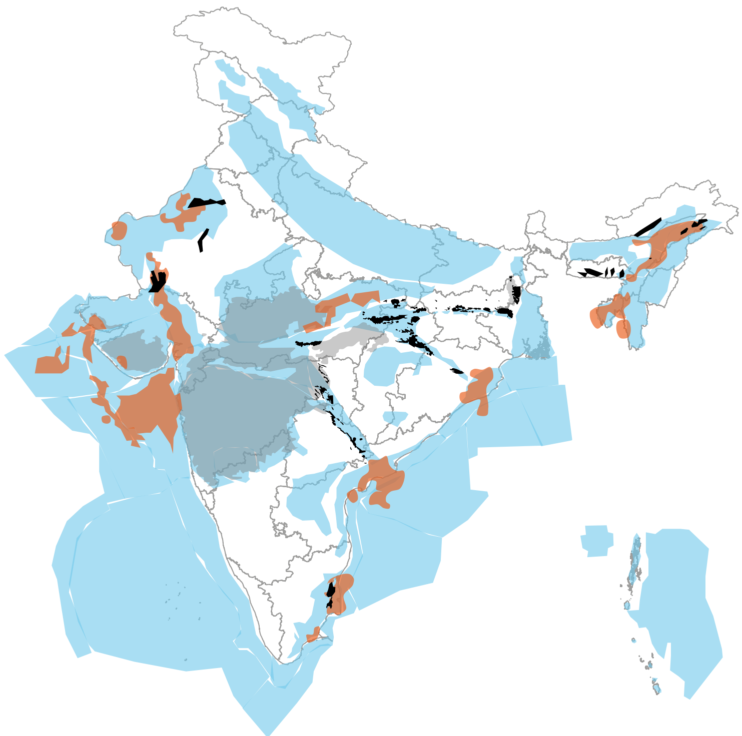
It is important to note that all basalts are different and there are no large-scale CCS projects in basalts globally. There are only two pilot projects. The Wallula basalt pilot in the United States is yet to materialise into a large-scale project. The pilot project in Iceland was successful because the basalts have suitable properties. They have very high permeability and high storage efficiency. Hence, thorough research of Indian basalts is needed to understand the true storage potential.

Figure 3 Theoretically, 316 Gt of CO_2 can be stored in India's basalts

Basalt formations

Source: Authors' analysis

Figure 4 Theoretically, basins in India have a CO_2 storage potential of 649 Gt



Oil & gas field
Coal fields
Saline formations
Basalt

Source: Authors' analysis

Figure 4 shows a consolidated view of the potential sinks in India in a theoretical scenario without any constraints and based on liberal estimates as per the *IEA Greenhouse Gas R&D Programme* (IEA GHG 2008), Prabhu and Mallick (2015), and Vishal, Verma, Chandra, and Ashok (2021). The estimates are liberal either due to the unavailability of actual subsurface data in O&G and coal reservoirs or the lack of research on saline formations and basalts (which, when available, will likely reduce these estimates). We estimate India's cumulative theoretical storage potential of 649 Gt across O&G fields, coal beds, saline formations, and basalts.

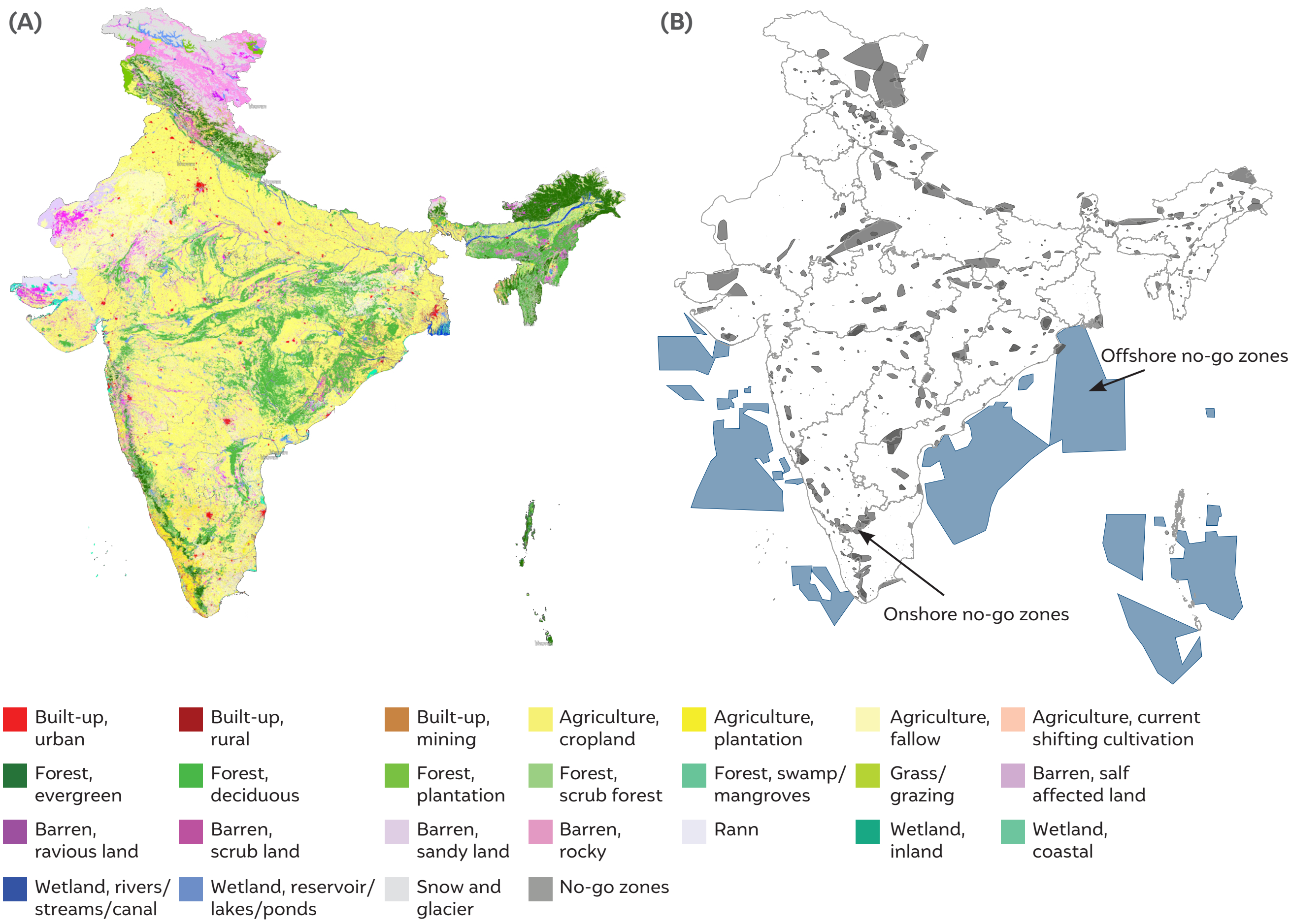
3. Beyond theoretical potential: The influence of different above-ground constraints

Above-ground challenges are critical in deploying CCS and are almost always the deciding factor for the practical deployment of operations. Hence, an analysis of these challenges is necessary for a holistic evaluation of CCS potential. The subsequent sections identify and evaluate the impact of the above-ground barriers in realising CCS potential in India.

3.1 Forest and mangrove cover

The *India State of Forest Report* (FSI 2019) reveals that the country's total forest and tree cover is 807,276 km² (Figure 5). This is almost 24.56 per cent of the geographical area of the country. Reserve forests are a subset of the total forest cover in the country. The same report states that the mangrove cover of the country is 4,975 km², which is 0.15 per cent of the country's geographical extent. Per the Paris Agreement, India has committed to creating a carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent, through additional forest and tree cover, by 2030. To minimise adverse effects on biodiversity and locally dependent livelihoods, and to abide by global commitments, it is fair to assume that CCS projects will not and should not materialise in environmentally sensitive areas.

Figure 5 **Cropland, forests, mangroves, and no-go zones together overlay almost 73% of the total storage potential**



Source: (A) ISRO (2022); (B) DGH (2022)

3.2 No-go zones

Almost 40 per cent of areas in offshore sedimentary basins (1.73 million sq. km.) fall in the 'no-go' zone. The DGH and the Ministry of Petroleum and Natural Gas (MoPNG) designate and demarcate no-go areas in India. All new exploration and development acreages that were previously marked as 'no-go' areas, defence installations, reserve forest/wildlife/eco-sensitive zones (ESZ), or ecologically fragile areas (EFA) (such as mangroves, etc.) are being exhaustively identified by the DGH (DGH 2021). Reserve forests and wildlife sanctuaries are a subset of forest and mangrove cover, but they are also included in 'no-go' zones. Forest and mangrove cover and 'no-go' zones together restrict development and storage operations, thus reducing access under the surface formation for CCS and reduce the storage potential from 649 Gt to 534 Gt (Figure 5).

3.3 Agricultural land

As per World Bank data, India has 155.3 million hectares of arable land, almost 52.3 per cent of its total land area (World Bank 2022) (Figure 5). The net irrigated area is 68.6 million hectares (MoAFW 2021). Hence, developmental activities in agricultural areas tend to face environmental and land acquisition challenges. The CCS potential of the geological rocks (saline formations and basalts) beneath agricultural land is almost 265 Gt.

3.4 Mountains

Areas with high elevations (beyond 1,000 m in height) might be challenging and uneconomic for CCS deployment. Hence, we removed those areas for a realistic assessment. Figure 6 displays the population and elevation map of India.

3.5 Cities, water reservoirs, and earthquake-prone zones

Storage is also challenging in populated cities and water reservoirs. Hence, we excluded these areas when estimating the CCS potential in India. Earthquake-prone zones might not directly harm the reservoir but could be hazardous for surface facilities. Therefore, earthquake-resilient infrastructure is needed to reduce risk and minimise the impact of seismic activities. Protection of potable groundwater is also a big concern. Due to the unavailability of deep hydrological/groundwater data, an analysis of deep freshwater aquifers was not possible.

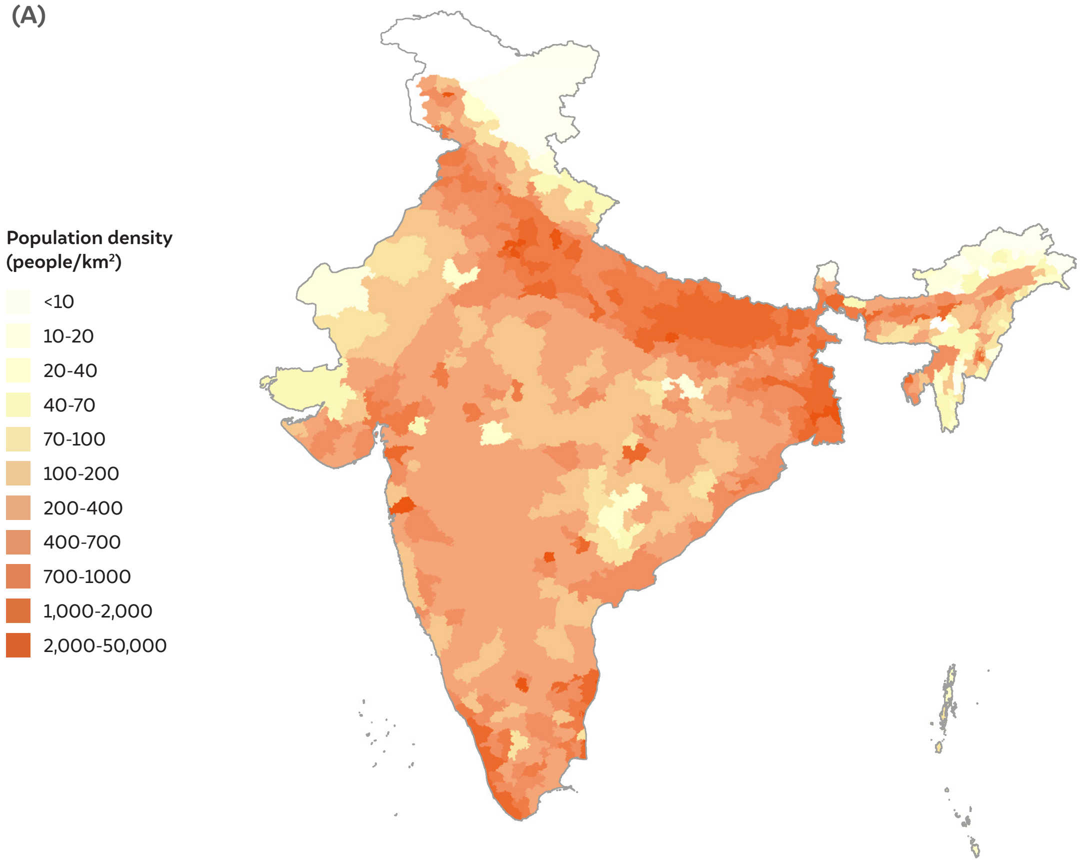
3.6 Population density

Human settlements in densely populated areas are likely to oppose CCS projects due to NIMBY issues. Therefore, population density is a factor that needs ample consideration if the realistic storage potential of India is to be estimated. For ease of evaluation, we divided the population density into 11 segments (50,000–2,000, 2,000–1,000, 1,000–700, 700–400, 400–200, 200–100, 100–70, 70–40, 40–20, 20–10, <10 people/km^2) (Subramanian et al. 2020). We used census data, which provides population density at the district level, to estimate the impact on constrained potential. When we exclude the most densely populated (>2000 people/km^2) areas, the storage potential decreases from 534 Gt to 359 Gt.

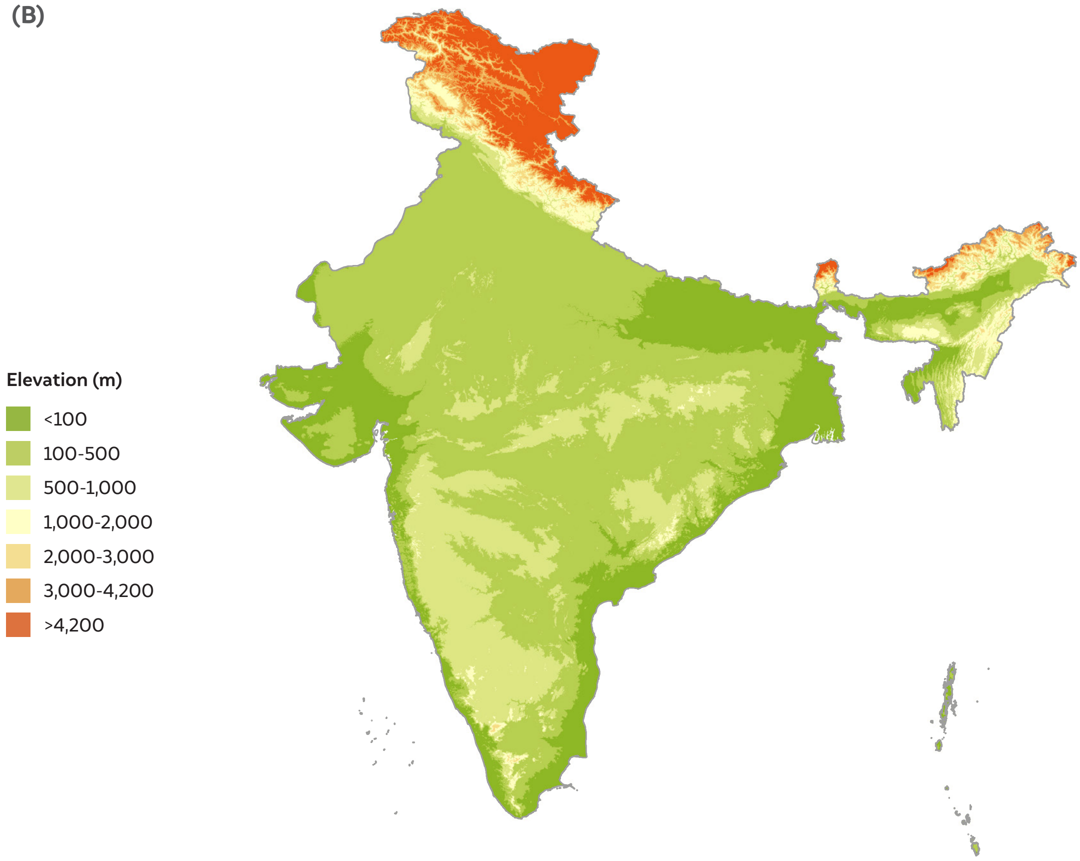
> **Agricultural lands and densely populated areas constrain the CO_2 storage potential considerably.**

Figure 6 CO_2 storage may not be possible in densely populated areas (A) and challenging at heights above 1,000 meters (B)

(A)



(B)



Source: Authors' analysis based on Subramanian et al. (2020) and Reddy et al. (2015)

4. Realisable scenarios for storing CO_2

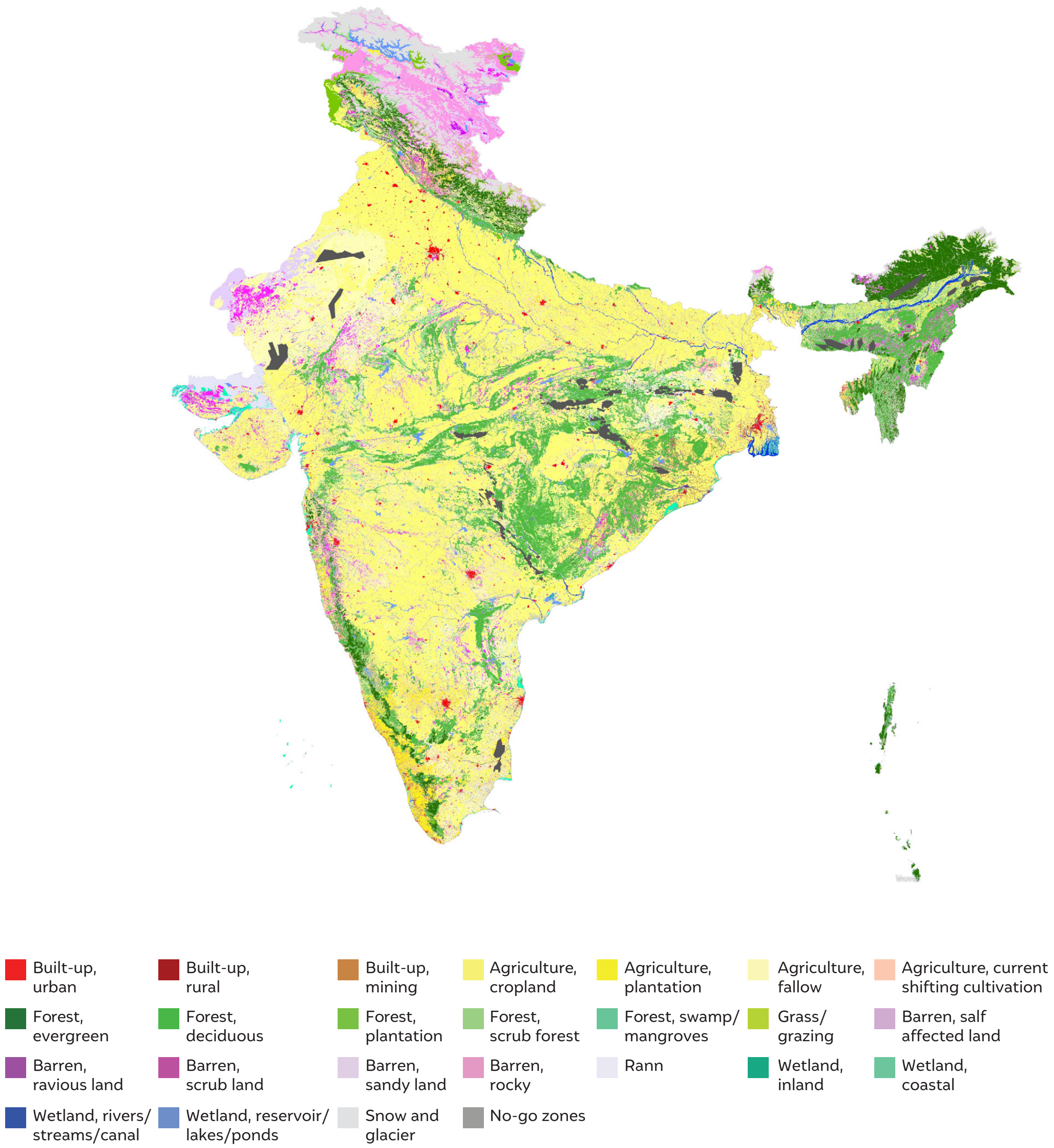
4.1 O&G fields

Storage potential in O&G and coal reservoirs is well understood and established due to existing data and well-characterised formations. Therefore, we did not refine the estimates further based on population density and other above-ground challenges. Any further refinements in estimates will come through a more defined below-ground characterisation of formations and additional data. Also, offshore basins are only influenced by no-go zones. But again, this is not a concern for existing offshore operations in Category I fields.

4.2 Coal fields

Most of the coal fields are in forest areas, as seen in Figure 7, indicating challenges in obtaining environmental clearances. Since the COP21 and Paris Agreement targets are to be fulfilled, we assumed that forested areas are to be left out and only presently operational blocks (Jharia, Bokaro, Raniganj, Karanpura, and Sohagpur) should be considered — leading to a 0.13 CO_2 constrained storage potential.

Figure 7 Coal fields (in grey) are located in heavily forested areas (in green)



Source: ISRO (2022), authors' analysis

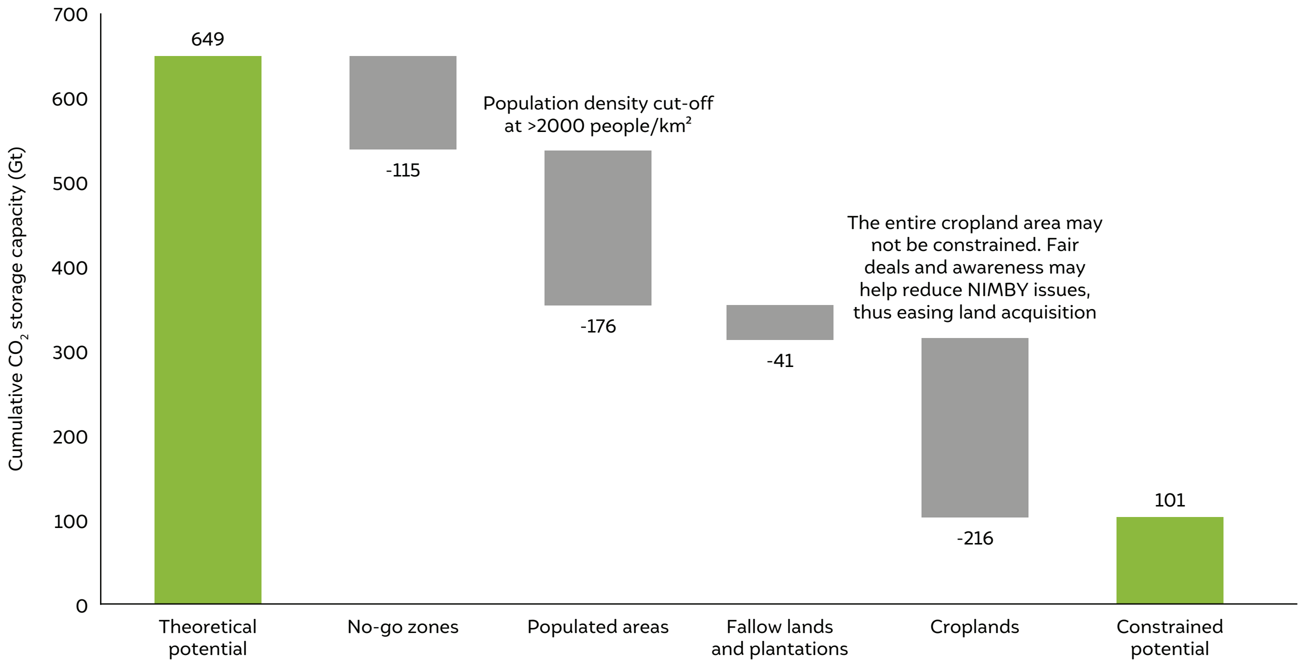
4.3 Saline aquifers and basalts

Saline aquifers and basalt formations can be clubbed together, as the CO_2 storage potential in these reserves is estimated by considering the areal extent. We observe that most of the operable sites on land are in arable zones. Our analysis concludes that the CO_2 storage potential is a function of both population density and arable land, which shows the variation in CO_2 storage potential with respect to changing landmass and population density. We used the national census data, which provides population density at a district level, to estimate the constrained storage potential. We can develop better estimates if population density information is available at a higher resolution.

4.4 Total constrained CCS potential with all above-ground constraints included

When we exclude regions like forests, no-go zones, hilly terrain, etc., and zones with >2,000 people/km², the storage potential decreases from 649 Gt to 359 Gt. At a population density of 2,000 people/km², the maximum potential of 359 Gt further reduces to 318 Gt, when we exclude fallow lands and plantations and include only croplands. After the removal of croplands, the storage becomes 101 Gt. Figure 8 presents the different components of above-ground challenges and their influence on the storage potential.

Figure 8 A theoretical CO_2 storage potential of 649 Gt ultimately reduces to 101 Gt, primarily due to no-go zones, human settlements, and croplands

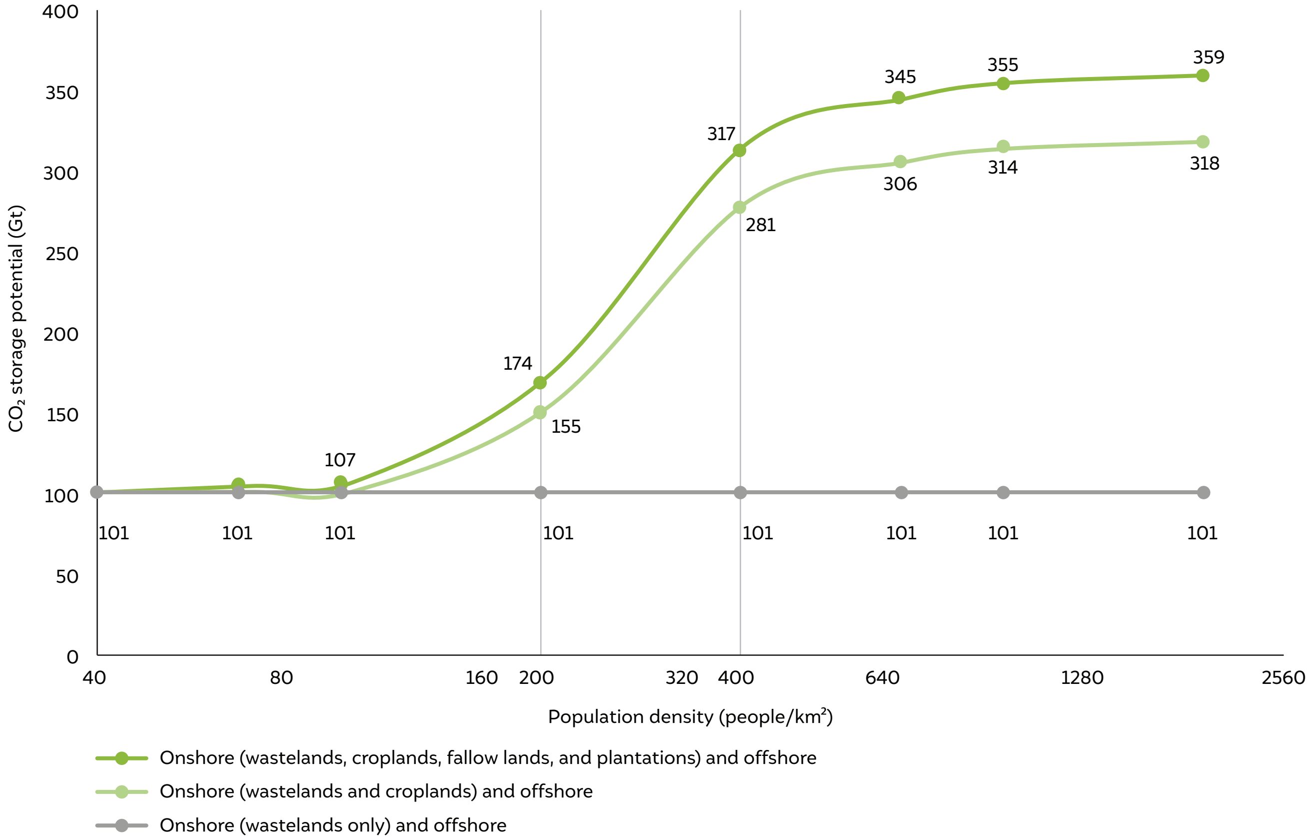


Source: Authors' analysis

Figure 9 is a graphical representation of the varying CO_2 storage potential for population density and land-use patterns. This graph uses different population density filters and land-use patterns to depict the change in storage space. There is no change in storage potential for the wastelands scenario because there is minimal habitation on these lands (population density 40–70 people/km²). Further, if we limit the population density to around 100 people/km², the various scenarios converge at 101 Gt. The 101 Gt storage potential can be considered an extremely 'constrained' scenario. In this constrained scenario, as seen in Figure 9, 91 Gt out of the 101 Gt storage potential is in offshore reserves and the onshore resources are only 11 Gt. The onshore resources are spread across O&G fields and coal fields (approximately 2 Gt), saline formations (6 Gt), and basalts (2 Gt). The constrained scenario is extreme, as CCS facilities can be deployed in locations with population densities similar to those near oil and gas facilities.

A more realistic constrained scenario is with a population density of 400 people/km², which results in a constrained storage potential of 281–317 Gt, depending on whether we include fallow lands and plantations. The onshore reserves are spread across O&G fields and coal fields (3 Gt), saline formations (144 Gt), and basalts (170 Gt).

Figure 9 Realisable CCS potential is a function of available lands and population density

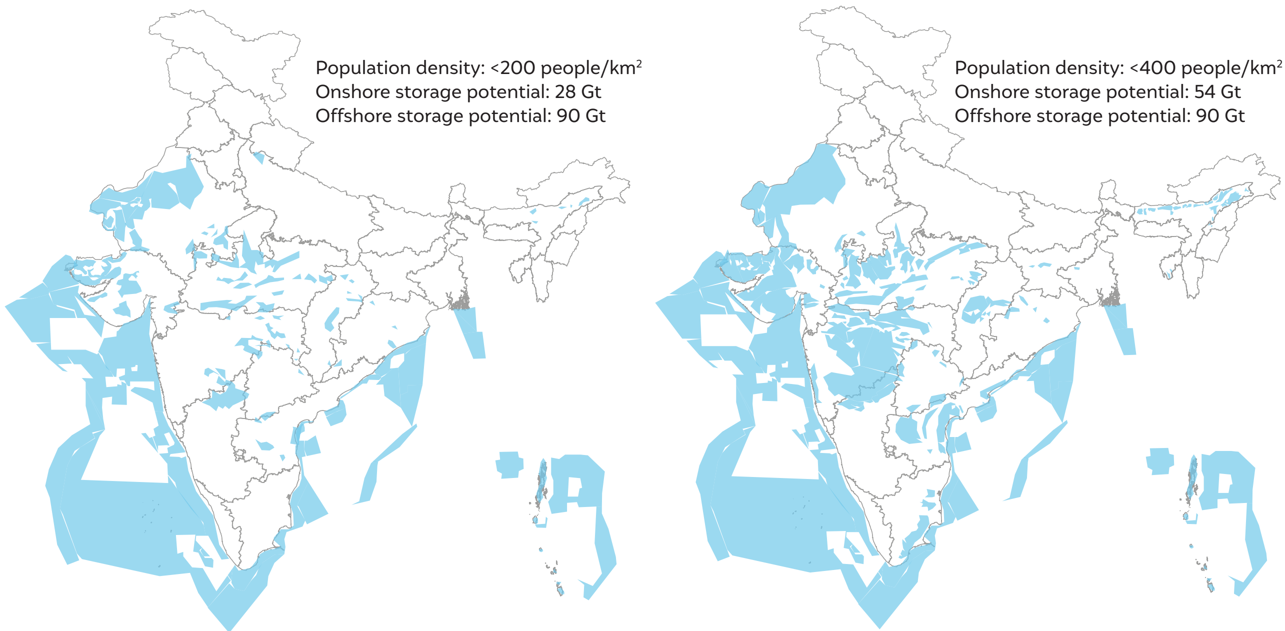


Source: Authors' analysis

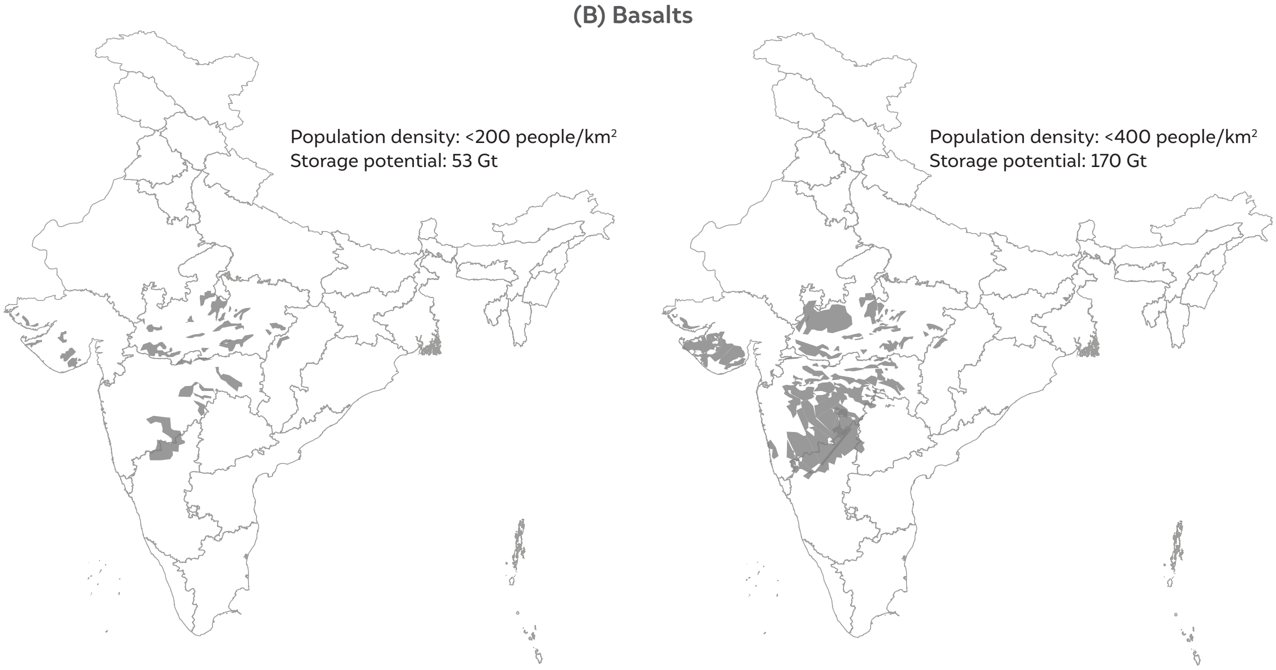
Figure 10 represents the 400 and 200 people/km² population density inflexion points on the CO_2 storage potential curves from Figure 9. Most of the storage potential changes at these two inflexion points are due to the inclusion of a large portion of the landmass with a high population density. When the population density changes from 200 to 400 people/km², almost 143 Gt of capacity is added due to the inclusion of additional storage space. The changes are primarily due to the inclusion of human settlements and croplands. This increases the areal extent of potential sites in saline formations and basalts significantly, increasing the storage potential underneath them. In offshore reserves, the filter of population density is not applicable and the storage remains at 90 Gt in saline aquifers throughout, as only the no-go zone filter is applied.

Figure 10 The realisable potential reduces with the lowering of population density

(A) Saline aquifers



(B) Basalts



Source: Authors' analysis

Note: These maps do not include the storage potential of 3 Gt from O&G and coal formations.

5. How long will it take to start injecting CO_2?

Injecting CO_2 across reservoirs depends on basin size, geology, and multiple other factors. Also, significant time is needed to prepare for CO_2 injection in these reservoirs. Pilots and test projects are essential in shaping perceptions about upcoming technology and processes. There is a need to consider aspects such as pressure management, fault and fracture risk, well integrity, resource optimisation/mobility control, pipeline fracture propagation, and network and hubs planning tools in the CCS domain. The activities involved before actually injecting CO_2 into geological reservoirs are as follows.

- **Pre-appraisal phase:** In this stage, the researchers assess possible storage locations and estimate a ballpark potential from the existing data. This stage primarily involves preliminary research on a regional/basinal scale. Researchers study the available seismic, well-log, and geophysical data, conduct fieldwork to find future storage sites, and assess existing reservoirs as potential storage sites.
- **Initial technical appraisal:** In this stage, the basinal/regional scale/existing estimates are further narrowed down with more data acquisition and data generation — through seismic surveys, geomechanical assessments to check on reservoir strength, refined potential estimations, and preliminary risk assessments through multistakeholder collaboration — to narrow down the potential sites. This stage could take around five years. Usually, the final investment decision is taken after this stage.
- **Technical appraisal/detailed characterisation:** This stage further reduces uncertainties and narrows down the potential storage sites. It involves reservoir characterisation, exploration work (if needed), practical potential estimation, thorough risk assessment and feasibility studies, and research and analysis to understand the techno-economic aspect of varying storage sites. The final due diligence is done at this stage. Depending on the reservoir geology, this stage could take three to seven years.
- **Environmental clearance and land acquisition:** Environmental clearance and land acquisition are carried out before establishing operations and deploying technology. Significant roadblocks can be expected at this stage in deploying CCS in India. While this process can continue simultaneously with the technical appraisal, uncertainties and legal challenges might extend the lead times for the injection to begin.
- **Infrastructure development:** After site characterisation and identification, front-end engineering and design (FEED) are needed to develop the storage reservoirs. Post-FEED study and the acquisition of the required approvals, site construction and equipment installation commence. Finally, actual operation begins with the injection of CO_2. Depending on NIMBY issues, already existing gas pipeline corridors, and infrastructure, this stage can take five to more than ten years (Vidas et al. 2012; Singh, Sharma, and Dunn 2021).

It should be noted that these timelines depend on multiple aspects like the type of reservoir, well economics, the region where the injection is to take place, time taken for clearances, and infrastructure. Table 2 presents the details of a few global CCS projects for which timelines are available. The duration from conceptualisation to injection varies across projects. This is not to suggest that CCS in India would take the shortest or the longest duration, but instead, indicates that significant planning is required for deploying a successful CCS project.

Table 2 Lead time for CCS projects depends on technical and policy considerations

Project	Country	Storage type	Injection (Mt/year)	Time taken from conceptualisation (years)	Status of capture potential (Mt/year)
Gorgon	Australia	Saline aquifer	2.3 (Lewis 2022)	21	3–4
Snohvit	Norway	Saline aquifer	0.7	17	0.7
Quest	Canada	Saline aquifer and EOR	1	10	Exceeded target while lowering costs
Uthmania	Saudi Arabia	EOR	0.8	9	–
Carbfix	Iceland	Basalt	0.04	7	
Wallulla	USA	Basalt	IGCC/Pre-combustion	8	Pilot project, currently non-operational

Source: IISD (2015); Heiskanen (2006); Shell (2020); Rock et al. (2017); McGrail et al. (2006); Sigurdur et al. (2018)

5.1 Category I O&G fields

Category I O&G fields in India are in mature stages of operation and their infrastructure development took place across decades of exploration and oil and gas production. Hence, these fields can support the infrastructure deployment for enhanced oil recovery and store substantial amounts of CO_2. Aggressive research works, faster clearance of projects, government support, and efficient supply chain linkages could help initiate the injection of CO_2 in Category I O&G fields through EOR within approximately ten years (Figures ES 4 and 11 and Table A4).

As per recent developments, the Gandhar oil field CCUS project is in an advanced stage and CO_2 injection will begin soon. In this project, almost 0.7 Mtpa CO_2 will be captured from a steam methane reforming (SMR) unit, which produces hydrogen, and will be injected into the Gandhar oilfield for EOR (Business Wire 2022). The amount of CO_2 that is permanently sequestered will depend on if and when the reservoir is shut after EOR operations. Any revival of production post-EOR operations can release some of the CO_2 injected during the EOR.

5.2 Coal bed methane

Presently, CBM production occurs in the Raniganj, Bokaro, Karanpura, and Jharia coalfields. However, the evaluations of coal adsorption ability, different reservoir parameters (fracture, flow mechanics, porosity, etc.), and technical feasibility studies have not been conducted comprehensively from the perspective of CCS. A thorough evaluation is paramount for screening the storage sites, as the properties vary with the quality of the coal bed (Sun et al. 2018). So far, the technology readiness level of CO_2-ECBMR is low and not mature enough for commercial operation.

CBM reservoirs contain water along with methane. Methane is extracted after the dewatering of coal seams. Over time, water production decreases, leading to a gradual loss of methane production, opening up space for CO_2 injection. Considering that CBM production in India started around 2007, CO_2 injection and enhanced methane production can only begin in the next 15 years as some of these coal beds go into the depletion phase (Essar n.d.; Singh, Sharma, and Dunn 2021).

5.3 Saline formation in O&G fields

Oil and gas operators might have primary seismic and well data for saline aquifers associated with their fields, which could help in the preliminary identification of these reservoirs. Hence, saline aquifers in existing oil and gas fields might have better development prospects than other completely unexplored saline aquifers. Our analysis suggests that almost 29 Gt of CO_2 can be sequestered in the saline formations that exist above and below oil and gas-bearing fields. However, thorough technical research to identify storage sites and feasibility analyses is needed before CO_2 injection. Hence, injection could take another 17 years (Figures ES 4 and 11 and Table A4 in Annexure VI), provided preliminary research and data collection begin now and possible storage spaces are identified in the next 5 years. However, if the saline aquifers are already mapped in operating oil and gas fields, the injection can begin in as early as five to six years.

5.4 Basalt and unexplored saline formations

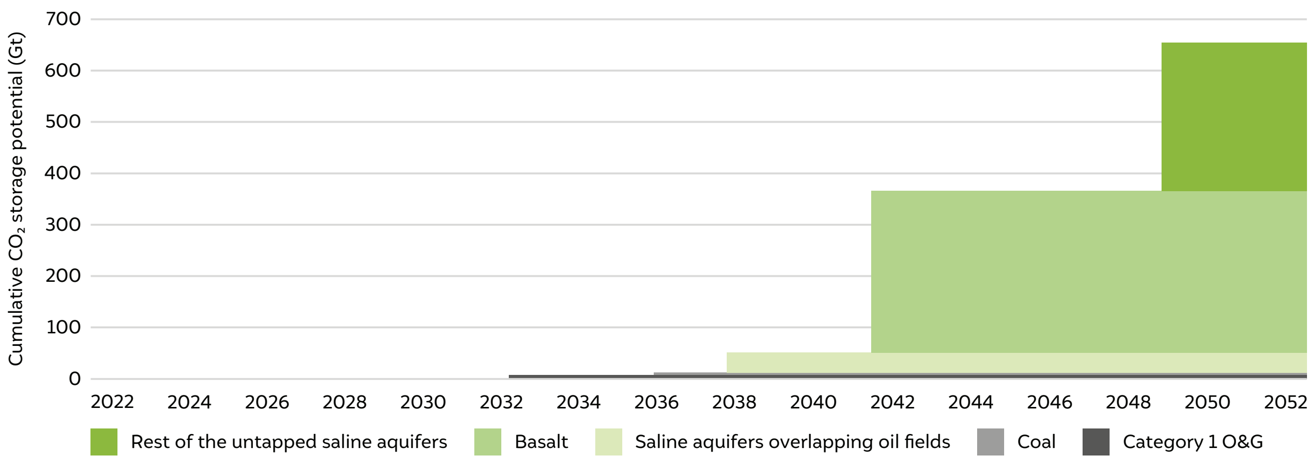
Despite having potentially significant storage potential, saline formations (not in existing oil and gas fields) and basalts are yet to be explored for CO_2 storage. The existing knowledge gap demands thorough research from a storage perspective to assess the characteristics and viability of these reservoirs as probable sinks in the Indian context. Seismic, gravity-magnetic, remote sensing, well-log, geochemical, core, and different geological data should be generated for a detailed study. If this immense opportunity is addressed in the coming five years through data generation and research, the injection could begin in identified sites around 2042.

5.5 Category II O&G fields

Category II O&G fields are less developed than Category I fields. Hence, efforts should be directed at developing capabilities for CO_2 injection. Research and feasibility studies on CO_2 storage potential in these fields must be carried out in parallel. The learnings from injection in Category I O&G and coal fields would lead to faster deployment in Category II fields. The studies might take over 20 years, considering that such fields have not yet been fully explored and developed. While exploration and development occur, these fields can be studied and researched for prospective storage sites, such that when they go into the depletion phase, the EOR can be implemented without delay. Considering 20–25 years of well life for primary recovery, commercial EOR can only occur around 2048 (Figures ES 4 and 11 and Table A4 in Annexure VI) when these fields go into depletion.

The next five years of research could help unlock a theoretical cumulative storage potential of 2.6 Gt storage by 2032, by initiating injection in Category I O&G fields, and almost 6.6 Gt by 2037, through injection in coal fields. Further, a cumulative theoretical potential of 358 Gt by 2039-2042 can be made accessible by tapping into saline formations associated with O&G fields and basalts. The total 649 Gt storage theoretical potential can be made accessible by 2048 by initiating exploration of other saline formations and Category II O&G fields, respectively (Figures ES 4 and 11 and Table A4 in Annexure VI). However, the corresponding unlocked potential reduces significantly in a constrained scenario.

Figure 11 Large-scale storage potential with saline formations and basalt will only be unlocked post 2035



Source: Authors' analysis[2]

2 Category II basins are not included as they have contingent resources and are yet to be developed. Hence, the depletion phases of these reservoirs, following production, could take more than 25 years. Thus, these are not included in this figure.

Figures ES 4 and 11 provides a summary view of the time taken for the development of each of the CCS resource types. Concerted efforts are required in the near term to establish a credible amount of storage capacity in the long-term post 2035.

6. Uncertainties in the CCS potential estimates

The CCS estimates in this study, especially for saline formations and basalts, have significant uncertainties as discussed below.

- **Assumptions to compensate for the lack of critical data:** Of the total CCS storage potential, 98 per cent lies in deep saline formations (326 Gt) and basalts (316 Gt). A substantial lack of data and research on saline formations and basalts requires that we make assumptions in estimating the CCS potential, resulting in high uncertainty in the estimates.

  Since groundwater surveys in India have been restricted to primarily potable and agricultural water resources, no large-scale, deep saline formation has been mapped. The current storage potential is calculated based on assumptions due to insufficient knowledge about reservoir parameters. The storage estimates only consider the areal extent of the basin, assuming that 50 per cent of that area can store CO_2 (IEA GHG 2008). This assumption could be a gross overestimation due to a lack of pore-scale data. Also, the storage potential is subject to change with the changing percentage of the area.

  Similarly, there is no information on the basalt's formation thickness and underground extent. We relied on the areal extent of the basalt formations here as well, which could result in high uncertainty. An assumption of a formation thickness of 100 meters is based on published literature (Vishal, Verma, Chandra, and Ashok 2021), which affects the estimate significantly. Thickness is a significant factor that influences storage potential directly. The CO_2 storage potential increases with the increasing thickness of a formation and vice versa.

- **Uncertainty resulting from a simpler estimation methodology:** The widely used U.S. DOE method is based on volumetric estimates that depend on different geological properties (area, thickness, porosity of formations, pore volume, and gas/fluid flow from laboratory-derived datasets) measured in the laboratory (Goodman et al. 2011). The inaccessibility of these reservoir data made it difficult to generate conservative estimates; thus, we had to consider the liberal assumptions of the *IEA Greenhouse Gas R&D Programme* (IEA GHG 2008). In this report, Holloway did not establish a formula for basalt; hence, we used the U.S. DOE method. However, a lack of research and laboratory facilities led us to assume the formation thickness and storage efficiencies from the results of researchers outside India.

- **Uncertainty of population density:** After excluding no-go zones, forest and tree cover, highlands, waterbodies, and cities, the on-land storage potential primarily falls over farmlands. Thus, in a more realistic scenario, the storage capacity is a function of both population density and farmland occupancy. However, this farmland occupancy is again dependent on liberal assumptions and calculations by taking area as a factor and is, hence, subject to change. Moreover, population density used here is a district-wise density — when applied, it excludes entire districts. However, less populated operational blocks/*tehsils* might exist in densely populated districts. Hence, a block-wise/*tehsil*-level survey is necessary before operations and will possibly increase the storage capacity.

We note that, ultimately, reservoir parameters will determine the effective storage capacity. However, inaccessibility to promising reservoirs can be a challenge, which is what we have tried to identify in our analysis.

> **Of the total CCS storage potential, 98% lies in deep saline formations (326 Gt) and basalts (316 Gt).**

7. Policy recommendations

- **Assess and explore basalt resources on priority:** India has one of the most extensive onshore basalt formations globally. Thus, this provides significant potential for CCS, orders of magnitude greater than the CCS potential of oil and gas reservoirs and coal seams combined. Besides, basalt offers one critical benefit over all other underground CCS options: CO_2 is permanently converted to mineral salts when injected into basalt. However, minimal knowledge exists on the disposition of deep-seated basalts and the kinetics of mineralisation in different strata. If found as the ideal storage sink, developing basalt for CO_2 storage reduces monitoring costs in the long run as well as the overall risk of deploying CCS. The development of this resource to achieve the scale of commercial injection could take up to two decades, but with promising prospects of large-scale potential at low risk.

  The knowledge and resources from EOR projects would help in developing a national programme on pilot-scale CCS in basalt. Therefore, the DST, Ministry of Earth Sciences, and the Geological Survey of India, along with hydrocarbon companies and the Central Ground Water Board, should exclusively initiate national and international research programmes for CCS in basalt. Such programmes can prioritise detailed mapping, research, and development that would facilitate the injection of CO_2 in basalts in the longer term.

- **License acreage for CCS development:** CCS deployment in India, with a primary focus on oil and gas, is at a nascent stage, mainly because candidate oil and gas reservoirs have been studied and understood for petroleum exploitation. This is not the case with saline formations and basalt formations. Exploring these formations for CCS potential will be an expensive proposition. One way is for the GoI to take the initial steps to facilitate surveys, exploration, and research programmes. Another opportunity may be to lease out acreage to third parties through a licensing mechanism similar to oil and gas exploration licensing. The government could generate revenue through the CCS licensing mechanism based on the quantum of CO_2 injected, similar to the royalties paid on oil and gas production. This will also allow multiple CCS exploratory projects to manifest simultaneously.

  * **Develop CCS as a business potential:** The CCS potential in India, especially for basalts, is significantly higher than what the country needs to achieve its net-zero targets. The excess CCS potential provides a monetisation opportunity for India to inject the CO_2 emissions from other countries into our formations. Japan is exploring such an arrangement with Indonesia, albeit in oil and gas reservoirs for EOR. We should note that CCS might be required only for another half century while fossil fuel–based technologies are phased out.

- **Develop and update existing standards and regulations to incorporate CCS:** CCS is new to India and we need standards and regulations for the entire supply chain, including for capture, transportation, injection, and monitoring. For example, the environmental impact assessment does not have provisions for clearing CCS projects. Similarly, injection and monitoring need safety standards. A thorough assessment is required to identify and develop the necessary standards and regulations across the entire supply chain.

- **Build a collaborative research network:** A key challenge in developing CCS potential in India is the lack of data and analytical capabilities that spans technical and policy areas. However, a collaboration between academia, government institutes, policy think tanks, and industry can overcome this deficiency and help accelerate the identification and piloting of CCS in India. Therefore, the DST should build a domestic and international collaborative research network that interacts with networks in other countries that have successfully implemented CCS projects either at a pilot or commercial scale. The learnings on CCS deployment in other countries, especially on basalt formations, can accelerate the timelines for deploying CCS in India.

> **Basalt formations must be assessed on priority to allow CO_2 injection within two decades.**

Annexures

Annexure I

Different types of CO_2 storage reservoirs

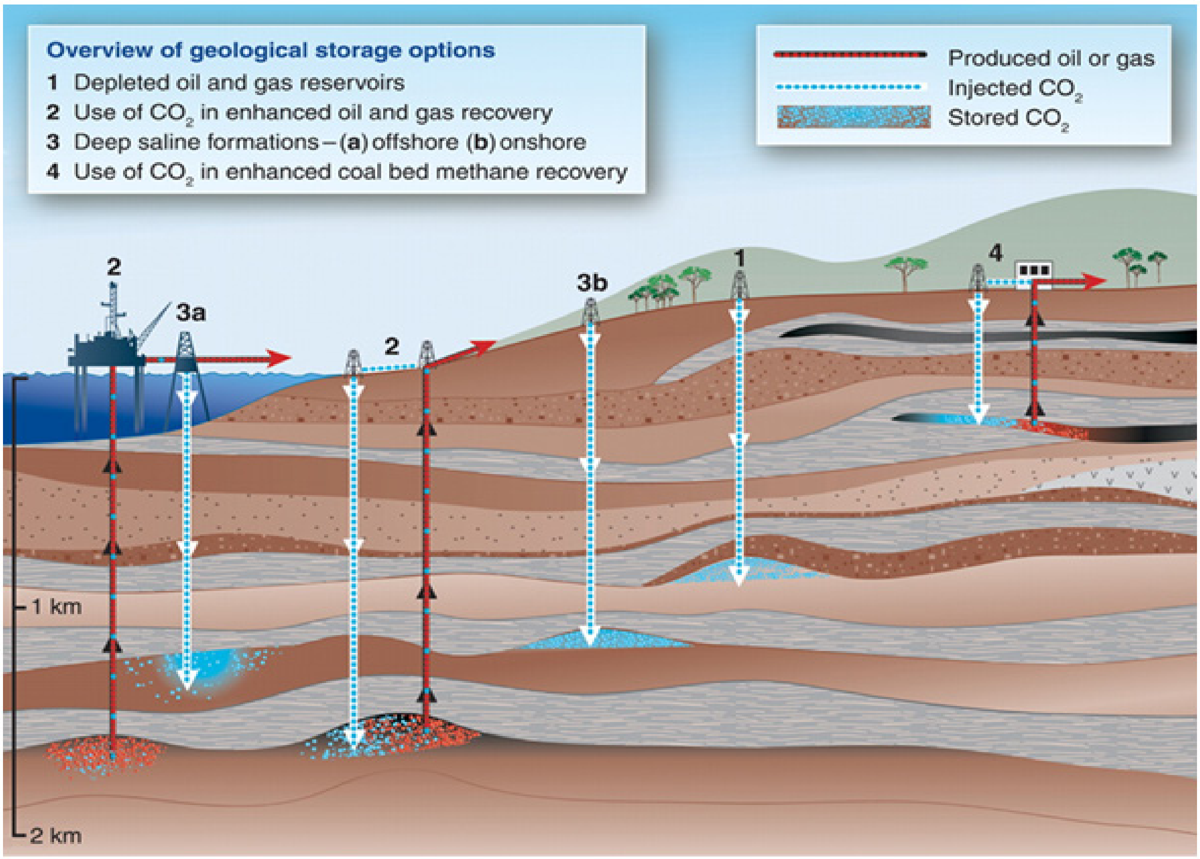
CO_2 can be stored in oil and gas reservoirs, coal seams that cannot be mined, deep saline formations, and basalts. The different types of storage are explained in Figure A1.

Storage in oil and gas reservoirs

The storage of CO_2 in depleted oil and gas reservoirs is an economically viable option because CO_2 capture and transport costs are partly offset by the value created by enhanced oil recovery (EOR), i.e., an increase in oil production relative to conventional production without EOR. In depleting oil and gas fields, the volume previously occupied by produced oil makes space for injected CO_2. Oil and gas reservoirs are attractive geologic storage sites because they have held hydrocarbons for millennia. These fields and basins are widely researched and have extensive infrastructure built for exploration and production, saving on exploration and feasibility costs for CO_2 storage. In this scenario, CO_2 storage and injection depend upon reservoir characteristics such as pressure, temperature, original gas or oil in place, recoverable hydrocarbon reserves, etc.

There are many operational CO_2 storage sites at oil and gas reservoirs globally. A notable aspect of this alternative is that only a portion of the CO_2 is retained in the reservoir as long as it is operational, i.e., the CO_2 dissolved in the oil returns to the surface and is recycled as long as production continues. Permanent storage happens only when the reservoir is shut down and production is discontinued. Although the CO_2 is retained in the reservoir once it has been shut down, it does not decompose chemically. Hence, any breach in the reservoir structure or the wells can result in leakages to the atmosphere — a key concern raised against CO_2 storage in hydrocarbon reservoirs.

Figure A1 Viable options for CO_2 storage



Source: Benson and Cook (2005)

Coal beds/enhanced coal bed methane recovery (ECBMR)

Coal contains varying amounts of methane, which is adsorbed on its pores. The coal surface has a chemical attraction for the adsorption of CO_2, which displaces the existing CBM (Vishal et al. 2013). For every molecule of methane displaced, three molecules of CO_2 can be adsorbed. This strong adsorption affinity helps coal beds adsorb CO_2 when injected, leading to methane desorption and enhancing methane recovery.

Coalfields have numerous large-scale thermal power plants in their vicinity. These provide opportunities for injecting captured CO_2 into depleted CBM reservoirs for CBM recovery in unmineable coal beds at nominal transportation costs and higher methane-recovery rates (Vishal, Chandra, Singh, and Verma 2021). A total of 12 pilot-scale ECBMR projects have been completed in China and USA (Pan et al. 2017). The most extensive pilot was the San Juan ECBMR project in the USA, where almost 18,000 tonnes of CO_2 were injected. However, there are no active ECBMR projects in the world (Global CCS Institute 2021). Similar to CO_2 storage in oil and gas reservoirs, CO_2 in coal beds does not chemically react into a stable compound and the risk of leakage remains.

Deep saline formation/saline aquifers

Sedimentary rocks, such as sandstone and limestone have interconnected voids inside them which are filled with oil/water/gas. Layers of non-porous rock overlie these rocks, ensuring that no CO_2 leaks into the atmosphere. Worldwide, deep saline formations are widespread and have enormous potential for storing CO_2 compared to other storage sites.

CO_2 gets trapped in saline aquifers through various trapping mechanisms when injected into saline reservoirs. In one mechanism, the stored CO_2 moves upward, gathers underneath a cap rock, and remains trapped (Hoefner and Fogler 1988). In another trapping mechanism, the high-density CO_2 solution travels downward and stays there (Boot-Handford et al. 2014). This density-driven convection increases CO_2 storage and decreases the hazard of CO_2 leaks (Jiang et al. 2019). CO_2 also tends to react with brine water and form new minerals. Today, large-scale carbon capture and storage (CCS) projects, such as the Sleipner project in Norway and the Gorgon project in Australia, are operational globally (Viebahn et al. 2011).

Basalt

Basalts are widespread, dark-coloured rocks found off- and on-shore on every continent. When injected, the CO_2 reacts with the abundant cations (Ca^{2+}, Mg^{2+}, and Fe^{2+}) in these rocks to form carbonate minerals. Basalt formations are attractive sinks for CCS because the chemical reactions lead to the formation of stable solid carbonate minerals, resulting in the permanent storage of CO_2. Basalt formations are abundant on the Earth's surface and, hence, are considered a promising alternative for environmentally safe and permanent storage of CO_2.

Trial projects in Iceland and Washington State, USA, show encouraging results, exhibiting rapid carbon mineralisation in basalt reservoirs. The duration varies from one to five years (Keleman et al. 2019). Nonetheless, these are pilot-scale projects and transitioning them into industrial operations could be highly uncertain, as basalt is heterogeneous, and the chemical composition varies with location. This heterogeneity affects the creation of the fractures that govern the CO_2-water-basalt interaction.

Type of oil and gas basins

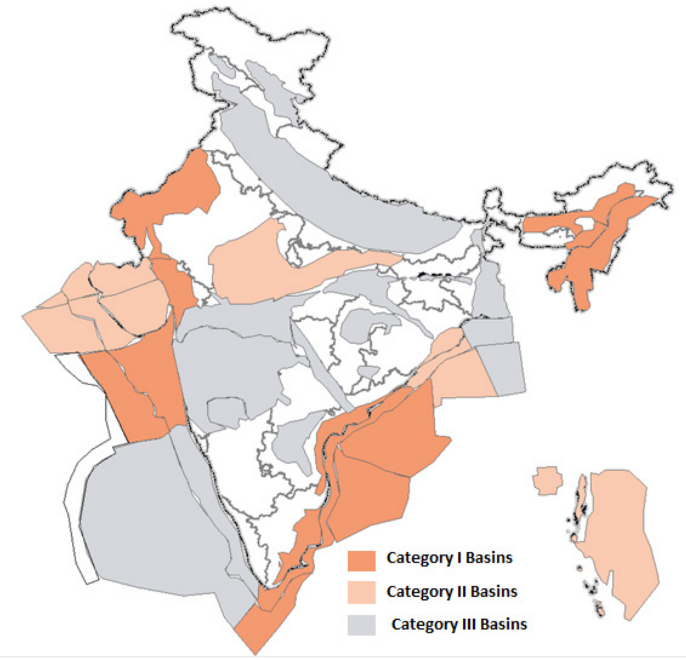
Oil and gas basins are classified into Categories I, II, and III.

Category I: These basins have discovered hydrocarbon-in-place that is commercially recoverable. In other words, these basins produce hydrocarbons and have reserves that can be exploited as they support quick recovery. Additionally, these basins have exploitable resources for the future. There are seven basins under this category: Krishna–Godavari, Cauvery, Mumbai offshore, Cambay, Rajasthan, the Assam Shelf, and the Assam–Arakan Fold Belt.

Category II: These basins have discovered and recoverable hydrocarbon-in-place but are yet to be thoroughly appraised, developed, and put into commercial production. Additionally, these basins have prospective resources but no reserves, i.e., an accurate assessment of commercially viable production volumes is yet to be made. The five basins under this category are Kutch, Vindhyan, Mahanadi, Andaman, and Saurashtra. These basins have good prospects for CCS and will become potential targets once the storage resources in Category I have been fully utilised.

Category III: These basins require extensive exploratory efforts. Here, hydrocarbons are entirely undiscovered and only prospective resources exist, which need to be explored and discovered. Therefore, Category III basins are unattractive for CCS in the medium term.

Figure A2 Sedimentary basins in India



Source: Modified from DGH (2021a).

Annexure II

Methodology for calculating CO_2 storage in oil and gas basins

We obtained the methodology for estimating CO_2 storage potential in hydrocarbon basins from the literature (IEA GHG 2008). In the *Theoretical Scenario*, the volumes of discovered (proved and recoverable) as well as undiscovered oil-in-place (potentially recoverable based on indicative prospects) are considered. Then, CO_2 storage is calculated according to equation 1. We considered only Category I and II basins for calculation purposes, as Category III basins are still elusive (DGH 2020). Theoretically, the total CO_2 storage potential is 2.6 Gt. Categories I and II oil and gas fields are presented in Figure 1.

We calculated the CO_2 storage potential (M_{CO_2}) following the methodology of Holloway in the *IEA Greenhouse Gas R&D Programme* report (IEA GHG 2008).

$$M_{CO2}(Mt) = (V_{oil}(stp).B_o).\rho_{CO2} \quad \text{(i)}$$

M_{CO_2} is the CO_2 storage potential, V_{Oil} *(stp)* is the volume of ultimately recoverable oil at stp (m^3), stp is standard temperature and pressure, B_o is the oil formation volume factor (the ratio between a volume of oil and the dissolved gas that it contains at reservoir temperature and pressure and the volume of the oil alone at stp), ρ_{CO_2} is the density of CO_2 (kg/m^3).

We then discounted the pore space occupied by the ultimate recoverable reserve (URR) by 35 per cent to allow for water invasion into the reservoir and/or water injection into oil and gas fields for secondary recovery.

Table A1 shows India's basin-wise CO_2 storage potential through EOR. The low storage value in Category II basins is likely to increase with future exploration and development and, hence, the CO_2 storage capacity will change/increase.

Annexure III

Methodology for calculating CO_2 storage in coal fields

India has a huge coal resource of about 293.5 billion tonnes with a CBM resource of almost 2,600 billion cubic metres (bcm) (DGH 2021) (MoPNG 2022). Our methodology considers the state-wise total CBM resources to estimate the CO_2 storage potential (Prabhu and Mallick 2015). Studies indicate that 3 Mt CO_2 can be sequestered for every bcm of CBM extracted (Vishal et al. 2013). Coal resources below 300 m cannot be extracted through the conventional mining process, making them uneconomical. These resources should be targeted for ECBMR instead (Prabhu and Mallick 2015). About 57 per cent and 38.9 per cent of methane can be recovered through ECBMR at a depth higher than 300 m for bituminous coal and lignite, respectively (Prabhu and Mallick 2015). These uneconomical coals could be the prime targets for CO_2 storage.

Table A1 Basin-wise storage potential in oil and gas fields

Basin number	Category I basins	CO_2 storage potential considering only discovered-oil-in-place (Gt)
1	Krishna–Godavari	0.43
2	Bombay Offshore	1.04
3	Assam Shelf	0.40
4	Rajasthan	0.20
5	Cauvery	0.06
6	Assam–Arakan fold belt	0.04
7	Cambay	0.39
	Category II Basins	
8	Saurashtra	0.0147
9	Kutch	0.0051
10	Vindhyan	0.0002
11	Mahanadi	0.0167
12	Andaman	0.0004
	Total	**2.60**

Source: DGH (2020); Authors' analysis

Table A2 State-wise CBM resources and CO_2 storage potential

State	Estimated CBM Resources (bcm)	CO_2 storage potential (Gt)
Jharkhand	722.08	1.23
Rajasthan	359.62	0.42
Gujarat	351.13	0.41
Orissa	243.52	0.42
Chhattisgarh	240.69	0.41
Madhya Pradesh	218.04	0.37
West Bengal	218.04	0.37
Tamil Nadu	104.77	0.12
Andhra Pradesh	99.11	0.17
Maharashtra	33.98	0.06
Northeast	8.50	0.01
Total	**2,599.48**	**4.00**

Source: MoPNG (2022); Authors' analysis

The CBM potential is estimated by:

- Assessing the mass of unmineable coal for each coalfield.
- Calculating the average volume of CH_4 (V_{gas}) stored in a given coal reservoir (using an adsorption coefficient and following the Langmuir isotherm method).
- Multiplying the aforementioned with (density of CO_2) to derive the methane potential for each field.

The ability of CO_2 entrapment to recover methane depends on the physicochemical properties of coal. Typically, it is assumed that CO_2 amounting to thrice the volume of methane adsorbed can be injected into the coal bed. (Vishal et al. 2013; Vishal et al. 2015). Multiplying the total CBM potential by three and the density of CO_2 gives the total storage potential of a particular field. The state-wise CBM resource and corresponding CO_2 storage potential are shown in Table A3.

$$M_{CO2} = 3 * V_{gas\ (total\ mass\ of\ coal)} * \rho_{CO2} \text{.......................} \text{(ii)}$$

M_{CO_2} is the CO_2 storage potential (Mt), V_{gas} is the total volume of gas (m^3) stored in a given coal reservoir, and ρ_{CO_2} is the density of CO_2. (tonne/m^3).

The total CO_2 storage potential is found to be 4 Gt, which is very close to the studies done by Vishal, Verma, Chandra, and Ashok (2021) and Singh, Mendhe, and Garg (2006).

Annexure IV

Methodology for calculating CO_2 storage in a saline formation

The CO_2 storage potential in saline formations is estimated from the literature (IEA Greenhouse Gas R&D Programme (IEA GHG) 2008). Since we do not know the reservoir thickness, porosity, and distribution in these reservoirs in the Indian context, we made the following assumptions to develop approximate estimates of India's storage potential:

i. Storage-worthy deep saline formations are present in 50 per cent of the basin.

ii. 0.2 x 10^6 tonnes of CO_2 are stored per km^2 in the area mentioned above.

$$M_{CO2} = A * 0.2 \text{ x } 10^6 \text{ ....} \text{ (iii)}$$

M_{CO_2} is the CO_2 storage potential (Mt) and A is the areal extent (km^2).

Multiplying the two assumed values (equation III) gives a rough estimate of the CO_2 storage potential (Table A3). It may be that storage-worthy deep saline aquifers are present in 25 per cent of the basin; the storage potential then changes to 123 Gt.

The assumptions regarding saline formation are very liberal due to a lack of data availability. Hence, a thorough reservoir scale study is vital to understand the effective storage potential.

Table A3 Basin-wise, deep saline formation and corresponding CO_2 storage potential

Basin	Areal extent (km^2)	CO_2 storage potential (Gt)
Rajasthan	126,000	12.6
Saurashtra	194,144	19.4
Mumbai offshore	212,000	21.2
Cambay	53,500	5.4
Kutch	58,554	5.9
Vindhyan	202,888	20.3
Krishna Godavari	230,000	23.0
Mahanadi	99,500	10.0
Cauvery	240,000	24.0
Assam	136,825	13.7
Andaman	225,918	22.6
Bengal	121,914	12.2
Satpura–South Rewa–Damodar	57,180	5.7
Ganga	304,000	30.4
Kerala Konkan	580,000	58.0
Narmada	95,215	9.5
Pranhita Godavari	30,000	3.0
Deccan Syneclise	237,500	23.8
Spiti-Zanskar	32,000	3.2
Bhima–Kaladgi	14,100	1.4
Bastar	5,360	0.5
Total area	**3,256,598**	**325.8**

Source: Vishal, Verma, Chandra, and Ashok (2021); Authors' analysis

Annexure V

Methodology for calculating CO_2 storage in basalts

A standardised methodology for storage potential does not exist for basalts, especially in India. Since no porosity (φ) or storage efficiency (E_{CO_2}) (CO_2 storage per unit volume of basalt) is known for Indian basalts, we took values from the published literature (McGrail et al. 2006), where the storage efficiency is 40.65 kg/m³ and the porosity value is 0.15. Although on the higher side, this porosity is close to the reported porosity of the Deccan basalts (Pandey, Vedanti, and Ganguly 2016). Nonetheless, the research is limited and a deeper enquiry is needed to find an effective capacity.

We calculated the total CO_2 storage potential for a workable thickness (*h*) of 100 meters using the following equation (Vishal, Chandra, Singh, and Verma 2021):

$$M_{CO2} = A.h.\phi.E_{CO2} \text{ .... (iv)}$$

M_{CO_2} is the CO_2 storage potential (Mt), A is the areal extent of basalt (m²), h is the thickness of formation (m), φ (per cent) is the porosity, and E_{CO_2} (kg/m³) is the storage efficiency.

We estimated that India's theoretical total CO_2 storage potential is primarily provided by the Deccan volcanoes (305 Gt) and a nominal amount by the Rajmahal traps (11 Gt).

Annexure VI

Probable timeline of injection

Table A4 describes the probable sequence of the injection in different reservoir types. The injection in a particular kind of reservoir marks the opening of the entire storage space of that specific type of reservoir. The timelines here display the sequence of events before injection. This was assessed for India as per the technology readiness level (TRL) of the different storage types. Globally, the commercial recovery of CO_2-EOR has been going on for over three decades. However, this technology came to India only when IOCL and ONGC signed an MoU for a CO_2-based EOR system (ONGC 2019). The existing data and built infrastructure in matured and depleted Category I fields make the injection more manageable and smoother in terms of time consumption.

Table A4 Lead times of CO_2 injection across reservoirs depends on the readiness

Type of field	Pre-appraisal phase	Initial technical appraisal	Technical appraisal	Environmental clearance/land acquisition	Design and development	Total time estimated
Category I O&G fields	<1 year (A large amount of existing data)	3 years (Considering the existing set of data)	3 years	2 years (Can happen simultaneously with feasibility study)	5 years	11–12 years
CBM-producing fields	2 years (Conceptualisation and data generation for reservoir mapping)	5 years (Reservoirs are not mapped from a CCS perspective)	4 years	3 years (Can happen simultaneously with feasibility study)	5 years	16 years
Saline formations in O&G fields	5 years (Data generation, conceptualisation, and planning)	5 years (New type of reservoir; rigorous research is needed)	4 years (New type of reservoir; rigorous technical appraisal is needed)	2 years (Can happen simultaneously with feasibility study)	3 years	17 years
Basalt	5 years (As no data is available, a large amount of data needs to be generated before initial research)	4 years (Initial research, data generation, conceptualisation, and planning)	4 years (Site selection and risk analysis should be made in detail as new lithotype)	2 years (Can happen simultaneously with feasibility study)	5 years (New type of formation and lithology)	18 years
Rest of the saline formations	8–10 years (As no data is available, a large amount of data needs to be generated before initial research)	5 years (Initial research, data generation, conceptualisation and planning)	6 years (As no data is available, site selection and risk analysis should be conducted in detail)	4 years (Can happen simultaneously with feasibility study)	7 years	>25 years
Category II O&G fields	25 years (Commercial exploration and maturation time)	5 years (Research can happen simultaneously with commercial field appraisal, development, and production)	<2 years (Most of the research can be done in an earlier phase during exploration and development phase)	3 years (Can happen simultaneously with feasibility study)	5 years	>25 years

Source: Authors' analysis

Note: If the saline aquifers are already mapped and assessed, the injection can begin in 5–6 years with existing technologies.

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Acronyms

bcm	billion cubic metres
BECSS	bioenergy with carbon capture and storage
CAGR	compound annual growth rate
CBM	coal bed methane
CCS	carbon capture and storage
CCUS	carbon capture utilisation and storage
DACSS	direct air capture with carbon storage
DST	Department of Science and Technology
ECBMR	enhanced coal bed methane recovery
EFR	ecologically fragile areas
EOR	enhanced oil recovery
ESG	environmental, social, and governance
ESZ	eco-sensitive zones
FEED	front-end engineering and design
FSI	Forest Survey of India
GHG	greenhouse gas
Gt	gigatonne
HC	hydrocarbon
IEA	International Energy Agency
IEA GHG	IEA Greenhouse Gas R&D Programme
IPCC	Intergovernmental Panel on Climate Change
MoAFW	Ministry of Agriculture and Farmers Welfare
MoEFCC	Ministry of Environment, Forests and Climate Change
MoPNG	Ministry of Petroleum and Natural Gas
Mt	million tonnes
Mtpa	million tonnes per annum
NET	negative emission technology
NIMBY	not in my back yard
ONGC	Oil and Natural Gas Corporation
OOIP	original oil in place
O&G	oil and gas
PSU	public sector undertaking
SDS	sustainable development scenario
SF	saline formation
TRL	technology readiness level
UN	United Nations
UNEP	UN Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
URR	ultimate recoverable reserve

Useful definitions

Basalt: A type of rock that comes from volcanoes. It is low in silica content, dark in colour, and comparatively rich in iron and magnesium. It occurs in parts of Maharashtra, Gujarat, MP, and Jharkhand.

CCS: Carbon capture and storage (CCS) is a process by which anthropogenic CO_2 is captured from different emissions sources, then transported to a storage site, and finally injected underground (in various types of formations) so that it does not re-enter the atmosphere.

CCU: In carbon capture and utilisation (CCU), CO_2 is captured from concentrated point sources such as power plants and industrial plants that use either fossil fuels or biomass for fuel and is recycled again for use in various applications, such as fuels and chemicals.

Deccan Trap or Deccan Basalts: A vast region of thick basaltic rock in west-central India associated with one of the largest volcanic eruptions in the Earth's history. The eruption took place approximately 65 million years ago.

Deep saline formation: An aquifer is an underground body of porous rock or sediment saturated with water. Deep saline formations are porous rock formations typically 1–3 kilometres below the surface and contain saline water with high salt (sodium, calcium, magnesium, etc.) content (Breunig, et al. 2013).

Forest Cover: Forest cover is defined as an area of more than 1 hectare (ha) in extent and having a tree canopy (as measured considering the crown of trees) of more than 10 per cent, irrespective of ownership and legal status. Such land may not necessarily be a recorded forest area. It also includes orchards, bamboo, and palm (MoEFCC 2022).

Geological formations: A geological formation is a rock unit with distinctive physical characteristics that differentiate it from the surrounding rock layers.

NIMBY (not in my back yard): Opposition to locating something considered undesirable (such as a prison or incinerator) in one's neighbourhood.

Resource and reserve: A resource is a naturally occurring material of economic value that exists in both discovered and undiscovered deposits. Reserves are a known amount of a resource that has been discovered and can be exploited economically. Factors that affect economic exploitation are demand, market price, exploitation costs, transportation costs, new technologies that can extract the material at a lower price, taxes, environmental laws, and government price controls. As these factors change, a resource or reserve's economic value can change with time.

Reservoir: A subsurface body of rock having sufficient porosity and permeability to store fluids/gas.

Sedimentary basin: A low-lying area on the Earth's surface formed by tectonic activity, in which sediments accumulate. Continued subsidence of the area causes continuous sedimentation. As the sediments are buried, they are subjected to increasing pressure and temperature, resulting in several physical and chemical changes that transform them into the sedimentary rock that comprises these basins and may hold oil/gas/coal inside them. Hydrocarbons form primarily in sedimentary basins.

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Tuli was a consultant in the Industrial Sustainability team at the Council. Her primary domain of work is industrial decarbonisation through carbon capture utilisation and storage. She completed her postdoctoral education at the Department of Earth Sciences, IIT Bombay, and her doctorate at the Department of Mining Engineering, IIT Kharagpur. Tuli is a geologist and did her master's at IIT Bombay. Her current work areas are carbon capture utilisation and storage and industrial decarbonisation.

"Basalts in western India are key to our CCS ambitions and should be investigated soon. With the right efforts, a significant share of our CO_2 could be injected and mineralised."

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Hemant leads the Industrial Sustainability team at CEEW in four broad areas – energy transition and industrial decarbonisation; carbon management; circular economy and innovation; and R&D. Hemant holds a dual MS in industrial engineering and operations research from Pennsylvania State University, United States and a BE in production engineering from Mumbai University.

"New operational and revenue sharing models should be explored to accelerate and monetise CCS potential in India, similar to oil and gas exploration and licensing."

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Deepak works on the sustainability analysis of low-carbon and renewable technologies for industrial decarbonisation. At the Council, his work involves developing a roadmap for hard-to-decarbonise industrial sectors, engaging with industry partners on carbon mitigation strategies and supporting policy-making with insightful analysis. Deepak is currently focussing on alternative fuels, renewable hydrogen, and low-carbon energy sources such as natural gas for mitigating industrial emissions. Deepak holds a doctorate and a master's degree from the Department of Energy Science and Engineering, IIT Bombay.

"While India has adequate realisable storage potential to meet its climate goals, unlocking it would need urgent intervention and prioritisation from all stakeholders."

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