Revisiting Geologic Storage Potential in Unconventional Formations Is Key to Proactive Decision Making on CCS in India

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Global energy modeling exercises project significant deployment of CO_2 capture and storage (CCS) to bridge the gap between India's pledged climate commitments and the 1.5°C target. Despite advances in laboratory analyses and process modeling, the information on geologic storage potential in India is limited. Prior studies indicate that the vast majority of storage potential exists in saline aquifers (50–300 Gt-CO_2); though, this might be overestimated. These estimates also estimate the theoretical potential in coal seams to be <5 Gt-CO_2 while shale basins have not been evaluated as geologic CO_2 sinks on a systems level. Based on several recent climate developments and CCS best practices, we suggest revisiting these potential estimates. We demonstrate how revisiting some assumptions might enhance the coal repository available as a sink by a factor of 7–8. We also present proof-of-concept analysis to show that Indian shale reservoirs might have suitable CO_2 adsorption capacity. With detailed recommendations for revising these estimates, we present a methodological framework for incorporating the best practices for coal seam and shale basin storage potential. Based on source-sink mapping exercises, we also argue that unconventional basins in India are especially relevant because of their proximity to large point sources of CO_2.

Keywords: geologic sequestration of CO_2, unconventional formations, India, storage potential, coalbed methane, shale reservoir

INTRODUCTION

CO_2 capture and storage (CCS) is projected to be an important part of India's future energy mix. While the current commitments of the Government of India within the Paris Agreement framework do not explicitly mention this technology, more ambitious targets would near-certainly require large-scale CCS. A consensus of integrated assessment modeling (IAM) studies indicate that 7–10 Gt-CO_2 would be need to be cumulatively sequestered by 2050 for meeting the 2°C national carbon budget (Shukla et al., 2015; Vishwanathan and Garg, 2020). These exercises project that CO_2 could be captured from a wide-variety of sectors—coal and gas power, steel, cement, refineries, and lately, bioenergy and ambient air—but they do not have similar representation in detail for the storage of CO_2.

Based on the perceived importance of CCS outlined above, a number of country-specific studies have appeared looking at policy approaches (Gupta and Paul, 2019; Hiremath et al., 2021; IEA CCC, 2021), costs and energy penalty for CO_2 capture (Yadav et al., 2016; Singh et al., 2017) and source-sink mapping (Garg et al., 2017). However, the literature on the downstream end of the CCS life cycle i.e., geologic sequestration is limited. While the laboratory-scale studies on the geomechanics of CO_2 injection have continued to evolve, storage potential assessment has not been carried out post-2009 in India. These decade-old assessments (Singh et al., 2006; Holloway et al., 2009) were subject to large uncertainties, as acknowledged by the authors (Wuppertal, 2012), and indicated an overwhelming majority of geologic sink availability in saline aquifers.

Objectives and Organization of This Perspective

We see opportunities for research, ideally that is collaborative between industry and academic researchers, that could correct the ambiguities in storage potential and evaluate the realistic potential of CCS for emissions reductions commitments for India. This research would start with the re-evaluation of core assumptions in existing evaluations of CCS potential in coal beds/seams that would improve these estimates based on the latest projections on energy scenarios. It would then advance to new evaluations of the CCS potential in shale gas reservoirs. We also describe opportunities for matchmaking between emissions sources and CCS sites that can inform policy making.

We point out in "Prior studies and the need to look at unconventional formations" that the strategy of emphasizing saline aquifers could be reworked by prioritizing unconventional formations (coal and shale reservoirs) for geologic sequestration based on updated data availability and economic lucrativeness on part of the coal and hydrocarbon industries. We discuss coal and shale formations as potential CO_2 sinks individually in "Storage potential considerations in coal seams" and "Storage potential considerations in shale formations" along with an approach to revise the first-order theoretical storage potential estimates for these reservoirs. These reservoirs are discussed separately because of their differing geologic conditions and level of understanding in India. For example, coal basins have been explored as potential CO_2 sinks in existing literature (Singh et al., 2006; Holloway et al., 2009). In "Storage potential considerations in coal seams," however, we indicate the need for reworking of particular assumptions compared to what previous studies assume. To our knowledge, no similar study has been performed for Indian shale basins. That said, our understanding indicates that primary data from past studies could be reformulated for improved estimation for CO_2 storage in both coal and shale formations. Once these considerations have been discussed, we provide recommendations for narrowing the CO_2 storage estimates for coal and shale basins based on geographical and engineering criteria in "Moving beyond theoretical potential." Overall, we investigate the hypothesis that existing studies could be dramatically underestimating the potential for CCS in India by excluding coal and shale reservoirs.

It may be noted here that some studies indicate basalt formations as an unconventional reservoir, which is outside the scope of this paper. Here, we focus solely on coal and shale reservoirs. That said, basalt formations are an important thrust area in CO_2 storage and significant work has been carried out in India and internationally (del Real and Vishal, 2016).

PRIOR STUDIES AND THE NEED TO LOOK AT UNCONVENTIONAL FORMATIONS

The initial estimates of geologic storage potential in India were presented by Dooley et al. (2005) and Singh et al. (2006). Both these studies revealed that the vast majority (>95%) of sink availability was in saline aquifers. The cumulative potential within coal, oil and gas reservoirs was <10 Gt-CO_2, which is equivalent to about 4 years of India's CO_2 emissions from point sources. This has led several policy-makers to see CCS apprehensively because aquifer storage is financially less appealing and poses risks to groundwater resources. For instance, IAM analyses—which are influential in policy-making—consider the previously published results as indicative of low CCS feasibility in such formations in India (Garg et al., 2017; Selosse and Ricci, 2017). A closer look, however, reveals that these projections of low CCS potential in India could be partially apportioned to contradictory assumptions about pore space availability.

On one hand, the assumptions about saline aquifers were very liberal due to lack of data availability. The storage potential for saline aquifers in the prior Indian studies were similar to the US DOE Carbon Storage Atlas methodology, where volumetric equation was a product of area, thickness, porosity, density and efficiency factor (DOE, 2015). In particular, the depth, porosity and thickness of reservoirs, which determine aquifers' potential as a CO_2 sink, where characterized with global default values, not values that were specific to individual aquifers. For instance, the porosity was selected as 0.5% based on global defaults. This is because Indian groundwater surveys have been restricted to shallow depths (<800 m) with an emphasis on potable and agricultural water resources. As such, no large-scale brine collection has been carried out to gauge reservoir parameters, as has been done, say, by the USGS Brine Database in the United States (Blondes et al., 2016). This has led to some obvious ambiguities. For instance, default theoretical estimates show that the Ganga Basin has a large theoretical storage potential (~80 Gt-CO_2) based on its geographical area. However, experts suggest that it might be 1–2 orders of magnitude less than estimated due to low salinity and unpredictable caprock availability. In fact, the authors of these studies have themselves pointed out that associated errors may be very significant and that these estimates were a function of the best data available at that time (Wuppertal, 2012).

Contrastingly, the storage potential in coal formations was estimated conservatively. While geological data was plentiful, these data were coupled with extremely restrictive economic and regulatory assumptions. For instance, it was assumed that coking coal, which is used for steel manufacturing would be mined out

and therefore the mines from which it is sourced would not qualify for CO_2 storage regardless of depth. The assumptions around coking coal particularly deserve attention due to falling steel production in India. In 2020, India's steel production reduced disproportionately by 10.6% even as the global reduction was <1%. Thus, there are strong indications that prior works have overestimated the extractability as well as demand of coking coal. Similarly, other reserves were considered mineable up to 600–800 m based on lucrative coal pricing structure of the time. It should be noted that further studies placed increasingly restrictive parameters of 90% storage efficiency (Singh and Mohanty, 2015) and removing lignite fields (Holloway et al., 2009) from consideration which reduced the sink availability from 5 to 4.5 Gt-CO_2 and 0.4 Gt-CO_2, respectively.

Recent evidence as well as new scientific literature indicates that these assumptions might require reframing. For instance, coal demand is increasingly scarce in 2/1.5°C scenarios, thus countermanding prior assumptions on most coking and non-coking coal being mined out and therefore, being unavailable for CO_2 sequestration (Vishwanathan and Garg, 2020). These studies parallelly suggest increased demand for natural gas as a substitute for coal, which could be supplemented to some degree by enhanced methane recovery via CO_2 injection in unconventional reservoirs. According to some media reports (Chaudhary et al., 2021) and expert "op-eds" (Garg, 2021; Parikh and Parikh, 2021), the Indian Government is mulling an aggressive net-zero target by 2050 which could further reduce future coal use. Recent statements by Coal India Limited, the state-owned coal company responsible for >80% of India's coal production indicate that they foresee solar overtaking coal as India's primary power producer. Coal pricing is already less lucrative with a $6–7/$t$-$CO_2$ coal "cess" or surcharge (Spencer et al., 2018; Malik et al., 2020). If less coal from higher depths is extracted, greater reservoir will be available for CO_2 storage. In other words, earlier assumptions about these reservoirs being unavailable may have led to significant underestimation of storage potential in coal formations. Even if coal use were to continue, recent years have shown coal companies are apprehensive about underground mining due to safety concerns. Instead, they opt for near-surface deposits (Singh and Kumar, 2016).

Due to these emerging circumstances, we suggest a reframing of assumptions as well as policy narratives regarding unconventional formations as CO_2 sinks (in subsequent sections). Moreover, to avoid internally inconsistent assumptions, we suggest that future studies should use the storage potential pyramid (**Supplementary Figure 1** of the SI) as a way of making *apples-to-apples* comparisons. These practices suggest that in the first step, the theoretical potential may be calculated, which is indicative of pore space availability. This could be constrained based on geologic, engineering, economic and ultimately, source-sink mapping considerations which reduces the actual capacity to 10–20% of the theoretical capacity (Yu et al., 2019). As we demonstrated, prior estimates for saline aquifers correspond to theoretical potential (bottom of the pyramid) while those for coal reservoirs have a mix of inbuilt geologic and economic assumptions, which might have prevented a robust theoretical estimate for unconventional

formations. An increased focus on unconventional formations could also increase business opportunities for CCS in India. Across the world, enhanced hydrocarbon recovery has been the preferred sink for existing and upcoming CCS projects (Global CCS Institute, 2020). A sustained focus on unconventional basins could similarly provide business lucrativeness to both public and private extractive industries to pursue CCS.

STORAGE POTENTIAL CONSIDERATIONS IN COAL SEAMS

Coal seams are an often-discussed storage formation for CO_2 especially since publication of the IPCC Special Report on CCS (Benson et al., 2005). They have the potential to offer injectability at much shallower depths (as low as 300 m) because of coal's highly adsorptive structure which differs from other formations considered suitable for CO_2 storage (ARI, 1998; Das and Dutta, 2017). Primarily, injection in coal seams is considered for enhanced coalbed methane recovery (ECBM) where CO_2 sequestration leads to improved productivity in coalbed methane (CBM) fields where production might be tapering. While ECBM has not demonstrated similar maturity as enhanced oil recovery (EOR), it offers comparable theoretical potential. For instance, the US Carbon Storage Atlas (DOE, 2015) estimates that the sequestration potential in coal seams in the US is 54–113 Gt-CO_2, which is about half of that available in oil and gas reservoirs (188–232 Gt-CO_2). Results from pilot studies in the US, China and Australia have also shown increased CBM production accompanying reliable retention of CO_2 with no discernible groundwater hazards (Zhou et al., 2013; Pashin et al., 2015).

In India, ECBM potential has been gauged at 0.3–5 Gt-CO_2 despite the overall coal resource being similar to that of the US. As stated in "Prior studies and the need to look at unconventional formations," this was a function of highly constraining assumptions around depth criteria based on economic considerations of 1.5 decades ago. We have already demonstrated that these assumptions might need to reframed based on aggressive climate constraints and technological issues surrounding extraction of deep-seated coal deposits. Here, we look at the coal resources from a quantitative viewpoint (**Supplementary Table 1** of the SI).

First, prior analyses assume that all coking coal and superior grade non-coking coal would be treated as extractable up to depths of 1,200 m (thus not treated as a storage site). Even for inferior grade non-coking coal, they assumed that extraction would occur up to depths of 600 m. This leads to a coal repository suitable for sequestration at about 15 Gt. However, once we consider the non-coking coal in the depth 300–600 m, this substantially increases the coal repository available to 106 Gt. This means that even if only the depth criteria around non-coking coal is relaxed, the coal repository increases by a factor of 7. Once coking coal in the depth 300–1,200 m is included in this repository, it further increases to 120 Gt (i.e., an overall increase by a factor of 8). It is true that storage at shallower depths may not offer similar adsorption capacity as depths of more than 600 m (Mahanta and Vishal, 2020). That said, it is widely recognized

that the mechanism of CO_2 storage in coal seams is different from that in aquifers or oil and gas reservoirs (i.e., free reservoirs). Coal has an extraordinarily high rate of adsorption due to its dual-cleat structure which means that storage might be possible at much shallower depths than the standard of 800 m considered for other deposits. Indeed, based on field measurements in the Damodar Valley coalfields of eastern India, suitable adsorption capacity has been noted in various coal blocks at the depth interval of 200–600 m (Singh and Hajra, 2018). Thus, we suggest updating the resource base that could be treated as storage sites based on the inventory data.

Reframing the criteria around storage depths will also lead to meaningful changes and improve industrial outlook for CBM production. Existing CBM production in India has been prominent in the coalfields of Raniganj, Jharia and East Bokaro. These coalfields have extensive deposits of coking coal (>13 Gt), which were not considered in prior studies. CO_2 injection has a greater business opportunity when introduced later in the CBM well lifetime. If CO_2 injection begins at year 15–20 since the inception of the well, it can improve productivity and lead to recovery of otherwise unrecoverable methane. As such, CBM production in these coalfields started in the early 2010s. The most recent biennial update report of the Indian Government to the United Nations Framework Convention of Climate Change (UNFCCC) indicates that CBM is being deployed as a clean coal technology within the government's decarbonization efforts. They indicate that fugitive methane emissions from coal mining and post-mining activities amounted to 17 Mt-CO_2e (MOEFCC, 2021). As significant pre-mining drainage and deployment of CBM in virgin basins occur, it may also lead to a co-benefit of reduced fugitive emissions (Singh and Colosi, 2019). This means that significant ECBM opportunities might arise in this region around 2025–2030. Effective government policy-making and revised storage potential estimates based on our recommendations would, therefore, lead to heightened interest in the CBM fields in the region encouraging earlier CCS adoption.

STORAGE POTENTIAL CONSIDERATIONS

Shale gas production and utilization have dramatically transformed the North American and global natural gas landscape. Shale formations and their associated hydrocarbons have been found to be internationally abundant based on US EIA studies, although extraction largely depends on availability of massive fracturing equipment. Lately, work has also emerged looking at the viability of CO_2 injection in such formations which could utilize their vast potential pore space. For instance, analyses in the mid-western US have shown considerable economic viability with this pathway, which results in 6–10% cost savings as compared to storage in saline aquifers (Bielicki et al., 2018). Similarly, life-cycle analyses have shown that gross injection of 1 ton of CO_2 results in net sequestration of 0.96 ton of CO_2 (Middleton et al., 2014; Menefee and Ellis, 2020), which reflects high viability with respect to the net-zero target. The life-cycle emissions here pertain to the upstream

energy requirements in construction of the pipeline and storage infrastructure, as well as leakage involved.

There have been no nationwide or basinwide estimates of CO_2 sequestration potential in India's shale reservoirs. But studies based in the United States showed a maximum theoretical storage capacity of 1.12 Mt-CO_2 per square kilometer of area (Godec et al., 2013). The overall area of Indian shale basins is close to 1,00,000 km^2 (Sain et al., 2014), which could result in comparable storage capacity as saline aquifers. However, estimating this is more difficult than that in coal seams because there is no commercial extraction of shale gas or oil in India. Moreover, the last of the prior sequestration potential estimates was carried out in 2008 and lab/field scale exploration of Indian shale basins began after that. That said, first-order potential estimates show 96–584 TCF of commercially-recoverable shale gas, as compared to only 92 TCF of CBM. Thus, we use the total organic carbon (TOC) of the shale formation as a proof-of-concept for the possibility of CO_2 sequestration in Indian shale formations. Tao and Clarens (2013) have shown the CO_2 adsorption capacity is linearly related to TOC and accordingly could be treated as a proxy for understanding CCS viability. **Figure 1A** shows that the TOC for India's Damodar and Cambay basins is comparable or higher than the Eagle Ford basin where geologic injection has been deemed viable (Psarras et al., 2017). Damodar Valley shales exhibit an average TOC content of 8% by weight, with several outlier samples showing much higher values. The pore volumes of these shales have been found to be large and the adsorption ratio (CO_2-CH_4) is also substantial at 2.6–6:1 (Bakshi et al., 2020). As we discuss in "Moving beyond theoretical potential," these factors are further complemented by geographical circumstances making the Damodar Valley an excellent candidate for localized storage. On the flip side, the area of this basin is limited (3,600 km^2).

The methodology illustrated in **Figure 1B** should also be followed for other basins with lower geological and engineering feasibility for obtaining a technical estimate of the storage potential. The Krishna-Godaveri basin has the largest prospective volume (~1,460 km^3) of shale spread across depths of 4,000–16,400 m, however, its lower TOC content limits the CO_2 storage capacity. Similar is the case for Cauvery basin. The relatively lower TOC content in these basins is due to the presence of silt from nearby Krishna-Godaveri river deltas and relatively high sea-levels in case of Cauvery basin (Nagendra et al., 2014; Mani et al., 2016). Though the adsorption capacity per unit volume of shales is lower for Krishna-Godaveri and Cauveri basins, the larger area may mean cumulatively significant pore volume for CO_2 storage.

While storage in shale formations is being considered as an alternative, there are two major inhibiting considerations. First, shale has been traditionally considered as the caprock for CO_2 that may be stored in saline aquifers in the future (Song and Zhang, 2013). If the shale formation is itself considered a sink, it may affect the integrity of CO_2 storage in underlying aquifers. Moreover, the geographic placement of CO_2 injection wells may influence prospective gas production wells, which may affect overall economic prospects of the natural gas industry (Tao and Clarens, 2013).
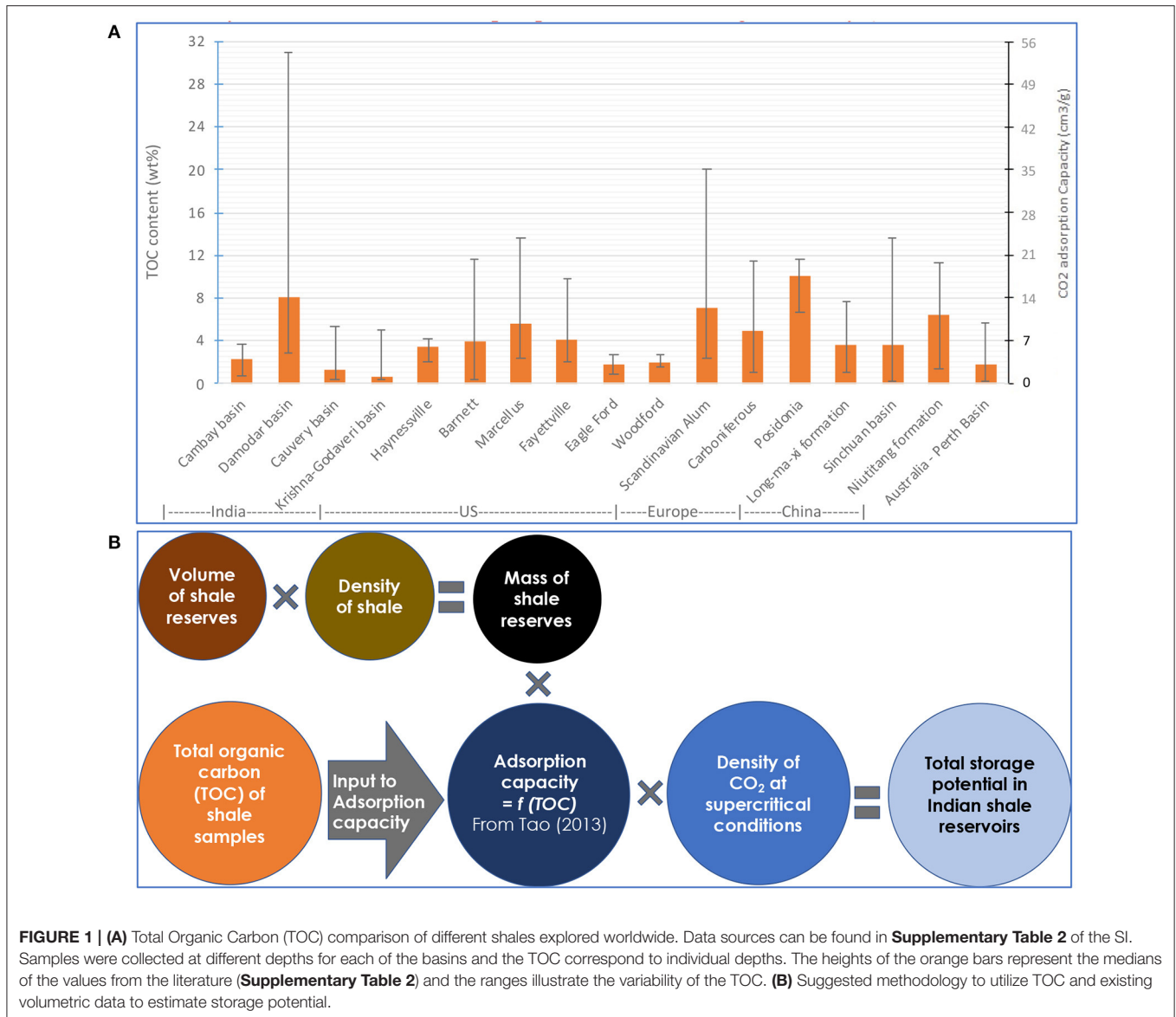
FIGURE 1 | (A) Total Organic Carbon (TOC) comparison of different shales explored worldwide. Data sources can be found in **Supplementary Table 2** of the SI. Samples were collected at different depths for each of the basins and the TOC correspond to individual depths. The heights of the orange bars represent the medians of the values from the literature (**Supplementary Table 2**) and the ranges illustrate the variability of the TOC. **(B)** Suggested methodology to utilize TOC and existing volumetric data to estimate storage potential.

Figure 1A also shows that the variation in TOC is very high depending on the depth. Similar heterogeneity may be seen in other parameters as well. As such, the uncertainty in estimation of storage potential may be very high and range in several orders of magnitude. Thus, the storage potential in the Marcellus basin as calculated by Tao and Clarens (2013) is 10–18 Gt-CO_2 while Edwards et al. (2015) estimate it at <10 Gt-CO_2. It should also be noted that the methodology provided in Tao and Clarens (2013) is identified as a screening mechanism at a national/regional scale estimation. In basins with greater detail of exploration, these have been further resolved using reservoir simulation to understand localized conditions. Notably, adsorption isotherm data can be utilized to understand the relative adsorption of methane and CO_2 on shale structure. Gamma-ray and density log "cut off" are also used to understand pay zones where CO_2 injection and

gas recovery may be carried out economically. This, however, is subject to large uncertainty due to: limited isotherm data, lack of sustained production data, as well as representation of fractures in the simulations (Godec et al., 2013). It is also noteworthy that pilot-scale trials have not been carried out for CO_2 injection in shales as opposed to coal seams. However, based on laboratory studies, some potential constraints in caprock seal efficiency, porosity reduction and reduced tensile strength have been noted (Fatah et al., 2020).

MOVING BEYOND THEORETICAL POTENTIAL

While we provide recommendations for revisiting the theoretical potential in unconventional formations, CCS best practices
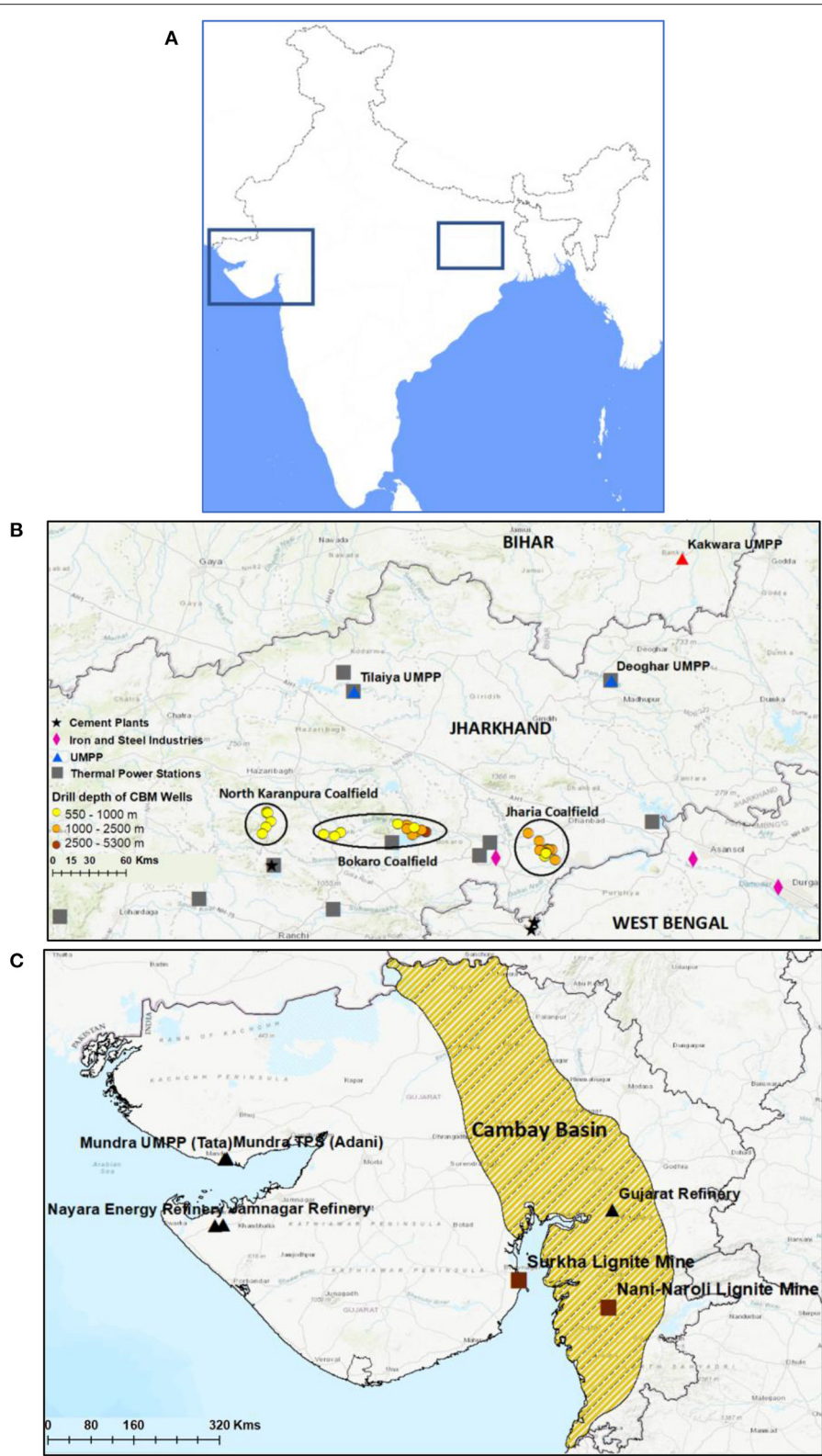
FIGURE 2 | Prospective CCS hubs could be centered around unconventional formations on the map of India **(A)** with insets showing eastern **(B)** and western India **(C)**. UMPP: Ultra-mega power plant.

(**Supplementary Figure 1** of the SI) require its constraining with engineering, economic and source-sink mapping factors. It is important to understand the information that can be gathered using the studies already carried out and how it is distinct from proprietary industrial surveys. For instance, the primary issue with coal seam storage is induced swelling with CO_2 injection i.e., reduction of permeability. A number of lab scale studies have been carried out to gauge these impacts. These studies reveal that while an initial exponential loss in permeability is seen due to CO_2 injection, this could be managed by co-injection of nitrogen as well (Vishal, 2017a). Similarly, sorption time has been calculated for both shale and coal samples, which could provide an indication of the injectivity associated with these formations (Vishal, 2017b; Chandra et al., 2020). We suggest that initial studies could look at theoretical potential based on the recommendations presented in section Storage potential considerations in coal seams and then narrow it using factors such as swelling data, as these are publicly available.

Another area where academic research could focus on is the implications of source-sink mapping on storage potential. In the US, it has been pointed out that there are so-called "CO_2 deserts," regions where sequestration sites are abundant but they are present far from the sources of CO_2 (Middleton et al., 2014). This is not commonly seen in India due to high infrastructure density in selected industrial hubs. The two most prominent regions for CO_2 storage in eastern and western India are seen in **Figure 2**. Eastern India has two upcoming ultra-mega power plants (power plants of 4 GW each) which are anticipated to emit ~25 Mt-CO_2 every year. This is in addition to several existing steel plants and smaller power plants. The proximity of these large point sources is useful since around 10% of India's large-point sources' CO_2 emissions are found in this region (**Figure 2B**). However, the only prominent source-sink study carried out for this region did not assume storage in the coal or the shale formations of the Damodar Valley owing to insufficient storage pointed out by prior studies (Garg et al., 2017). The two major regional hubs shown in **Figure 2** (Damodar and Cambay basins) along with two additional shale basins (Cauvery and Krishna-Godavari) are in close proximity to point-sources with annual CO_2 emissions of 328 Mt-CO_2 as detailed in **Supplementary Table 3** of the SI. Thus, for these basins to be considered as long-term sinks over a period of 30 years, their viable storage potential should be of the order of 10 Gt-CO_2. If the viable potential is an order of magnitude less than the theoretical potential, the theoretical potential required in these basins is 100 Gt-CO_2. Note that the point-sources are based on coal combustion and processing. In the future, if coal consumption declines, there may be some leeway in the required theoretical storage potential.

As pointed out in this paper, once the assumptions are reframed (section Storage potential considerations in coal seams) and shale basins are considered (section Storage potential considerations in shale formations), the storage in unconventional formations could increase by an order of magnitude. Similar fortuitous geographical conditions are present in the western part of the country in the Cambay Basin (**Figure 2C**). This region has two large power plants with emissions higher than 25 Mt-CO_2/year each. The Jamnagar refinery in this region is the largest operating refinery in the world, which could provide low-cost CO_2 capture opportunities. This refinery is already poised to received net-zero oil from the Permian Basin in the US (produced by coupling direct air capture with EOR) (Gupte and VanLaningham, 2021) and the downstream emissions could further be reduced by sequestration in Cambay basin shales. The lignite blocks in this region are also very suitable for underground coal gasification, which could again be a source of high-purity CO_2. The government decarbonization efforts focus on coal gasification and creation of a methanol economy. As such, there is a targeted investment of $53 billion for gasifying 100 Mt-coal by 2030 (MOEFCC, 2021). Global focus is increasingly shifting toward conceiving CO_2 storage hubs or clusters which are areas with abundant sequestration potential and large concentration of large point sources (Global CCS Institute, 2020). The proof-of-concept maps here (**Figure 2**) show that these two regions could become hubs if the lucrative storage opportunities in unconventional formations are considered.

Other geologic factors are very dependent on the local injection conditions. For instance, caprock availability above the injection site is necessary to avoid CO_2 migration and its interfering with groundwater. Moreover, when injection planning is done, it is desirable that the direction of the drilling is perpendicular to the natural fractures for reliable retention. While the stratigraphic data may not be publicly available, these are present as part of the investigation carried out by coal and oil companies. For instance, Coal India and ONGC have carried out detailed regional exploration of coalbed methane at the Jharia coalfield. Therefore, collaborations between the industry and academia could open up pathways to more detailed storage potential.

It may be also noted that this study aims at providing a systems level perspective for the CO_2 storage potential in India. As such, it does not consider some of the field-level geologic parameters that affect overall geologic potential. When we refer to global studies such as Yu et al. (2019), it is noted that the actual storage potential may be an order of magnitude less than the theoretical storage potential. Our perspective does not delve into the engineering conditions that limit the storage potential because of the lack of large-scale CO_2 injection field trials (Pashin et al., 2015). As and when the data from such trials become available, they may be combined with the primary data presented in this paper to arrive at a more refined storage potential. Further, in context of the proof-of-concept maps presented in **Figure 2**, we do not present a *one-to-one correspondence* between sources and sinks as studies in some other countries have attempted (Middleton et al., 2020). This is due to limited information in the Indian context about the prospective pipeline lengths. It would, therefore, be prudent for future studies to analyze the realistic costs of pipeline construction and operation to propose CCS clusters or hubs.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

US and JD contributed to framing of this paper. US and NS designed the figures. US wrote the first draft of the manuscript. NS and JD revised the draft. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.708320/full#supplementary-material

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