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Title Page

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Optimal source-sink matching and prospective hub-cluster configurations for CO2 capture and storage in India

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Abstract

At COP-26, India announced strong climate commitments of reaching net-zero greenhouse gas emissions by 2070. Meeting this target would likely require substantial deployment of CO_2 capture and storage (CCS) to decarbonize existing large point sources of CO_2. This study attempts to evaluate opportunities for deployment of CCS in India in the forthcoming decades. A GIS based approach was adopted for mapping existing sources of CO_2 with the sinks. The results show that regionally-appropriate ways of moving towards CCS at scale exist in both the power and industrial sectors. Coupled analysis of these sectors with sinks shows that 8 clusters may be developed throughout the country to sequester 403 Mt-CO_2 annually. These clusters are concentrated near Category-I oil basins and the Category-I coalfields (Damodar valley), which may also create suitable financial incentives by incremental oil and coalbed methane recovery respectively. Furthermore, a first-order costing analysis evaluates that the cost of avoidance across basins may range from \$31 to \$107/t-CO_2, depending on the type of storage reservoir and the proximity to large point sources. A total of 12 suitable hubs and clusters were created based on annual emissions above 1 Mt of each large point source and their proximity with geological sinks.

1. Introduction

India's CO_2 emissions have risen from 980 Mt-CO_2 in 2000 to 2630 Mt-CO_2 in 2019. This represents a cumulative average growth rate (CAGR) of 5.3 % over the past two decades (Garg et al., 2017a). Capacity addition in electricity generation and large-point industrial sources such as iron and steel, cement, fertilisers, and refineries have largely contributed to this increase. In order to achieve sustained economic and societal growth, a similar trajectory in such infrastructure could be anticipated.

An increase in energy and industrial production alongside rapid reductions in CO_2 emissions requires a number of technological platforms for decarbonisation. India's nationally determined resolutions, which were submitted during the Paris Climate Agreement in 2015, committed the nation to the reducing of the greenhouse intensity of the economy (the ratio of GHG emissions to gross domestic product) by 33–35 %. The pledged reductions were primarily based on potential additions to renewable-energy capacities by 2022. The capacity addition goals have been met before time (Busby and Shidore, 2021). However, the Prime Minister of India recently committed at the Glasgow Climate Summit that India would reach net-zero CO_2 emissions by 2070. In light of this committment, India would likely need a much steeper decline in CO_2 emissions, which will require the decarbonisation of existing large-point sources. Integrated assessment modelling literature shows that a key feature of energy transitions that are compatible with net-zero emissions is the integration of such infrastructure with CO_2 capture and storage (CCS) (Davis et al., 2018; Fennell et al., 2021; Vishal et al., 2021a; Vishal and Singh, 2016). Analyses by the modelling community show that CCS would be responsible for at least 15% of reductions in CO_2 emissions in net-zero energy systems (Baik et al., 2021; Gabrielli et al., 2020). Currently operational CCS facilities can permanently store 40 Mt of CO_2 every year, which is far from the minimum 6000 Mtpa that is needed to meet net-zero targets (Haszeldine et al., 2018). A massive gap seems to exist globally between the current global CCS provision and that which is required to meet the anticipated CCS targets.

In the context of Indian energy systems, modelling exercises further suggest that CCS deployment in the power sector alone could be as high as ~850 Mt-CO_2/year in 2 °C scenarios and ~1000 Mt-CO_2/year in 1.5 °C scenarios in peak years (Vishwanathan et al., 2021; Vishwanathan and Garg, 2020). When combined with the CCS of the industry sector, this would lead to a requirement of 7–10 Gt-CO_2 cumulatively by 2050 (Denis et al., 2018). In addition to the decarbonisation benefits of CCS, there are other value additions. (Vishal et al., 2021a) quantitatively highlight the projected benefits that CCS could provide through enhanced energy security, grid resilience and reduced risks of stranded assets. Moreover, the Glasgow agreement focuses on a ‘phase down’ of coal instead of a ‘phase out’ (Andreoni, 2022). In the light of this, CCS could play a pivotal role in the gradual reduction of emissions from the coal sector, particularly coal-fired power plants which account for 44 % of India’s CO_2 emissions.

Academic literature about India’s CCS readiness is large, diversified and includes policy outlooks (Viebahn et al., 2015; Vishal et al., 2021a), assessment of the potential for geologic storage (Singh et al., 2006, 2021; Vishal et al., 2021b), and retrofitability of existing infrastructure. A critical gap here is system integration through source-sink mapping for which only a single study exists (Garg et al., 2017b). On the basis of India’s 2015 large-point sources and geologic sink locations, Garg et al (2017) proposed clusters in which siting future powerplants would be viable. Subsequently, there have been several developments that could help evolve this exercise. First, the Garg et al. (2017) analysis did not consider the actual storage potential in individual sinks due to data limitations at that point. Lately, our group has developed newer estimates for such sinks (Vishal et al., 2021b). Second, nine ultra-mega powerplants (UMPPs) of a capacity of 4 GW each were considered as the central locations around which these clusters would be developed. However, assessments of economic, regulatory and climate risks have led to the cancelling or postponing of several of these UMPPs. Finally, there is an increased drive from the NTPC (previously referred as National Thermal Power Corporation) to blend biomass in existing coal-fired powerplants. This could be an avenue for carbon dioxide removal (CDR) for India.

To address these gaps, this study undertakes a new source-sink mapping, which incorporates new potential estimates, bio-infrastructure and investment decisions that were made after 2015. In line with global literature, we also seek to inform policy-making through the design of the hubs-and-cluster concept. A second novelty of this study is that it incorporates key costing parameters to address the economic versus storage readiness of individual hubs and clusters. Countries such as India, which have no operational commercial facilities and limited hydrocarbon reserves, could benefit from a hubs-and-clusters strategy that promotes the implementation of this CCS technology. The CCS hubs-and-clusters operations effectively connect a number of nearby CO_2 emitters and storage sites by using shared transportation facilities, which would expedite the development of CCS (Sun et al., 2021a). This appreciably reduces the overall costs and risks when compared to those of standalone projects. Examples of proposed/conceptualized CCS clusters include the Northern Lights facility in Northern Europe (Gough and Mander, 2022) and industrial hubs in the Permian Basin in Texas, United States (Singh and Dunn, 2022).

2. Methods

As discussed above, our analysis focuses on evolving the past source-sink mapping work that was carried out by Garg et al. (2017); we also introduce several methodological improvements. Figure 1 shows the overarching framework that has been used in this study. The following paragraphs describe the process of the identification of key CO_2 sources, the sinks that were mapped out in this analysis, the data sources for the location, and the characterisation of these sources and sinks. Furthermore, we discuss approaches for the demarcation of hubs and clusters based on defined criteria and the costing methodology that has been used in the analysis to prioritise the defined clusters.

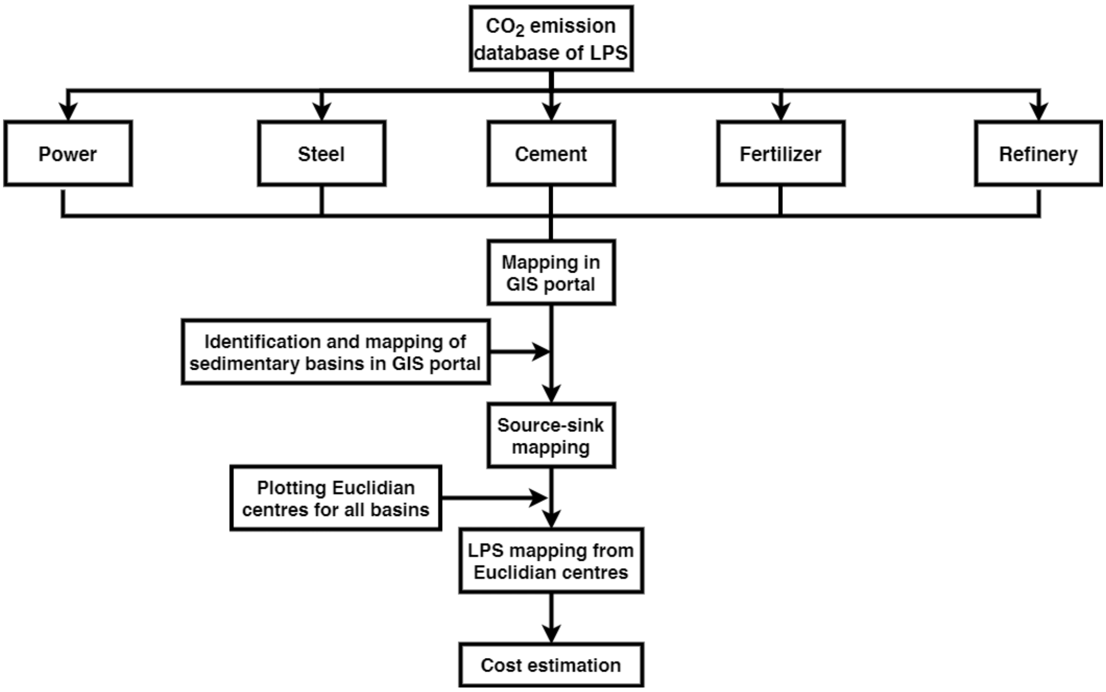

Figure 1: Methodological framework for this analysis

2.1. Identifying large point sources of India

In line with the previous study by Garg et al (2017), we focussed on five types of large point sources (LPS). These were power, steel, cement, fertilizers and refineries. These sectors represent an estimated 69% of India's CO_2 emissions spread out across 23 states. Considering the wide range of sources with disparate emissions, a geographic information system (GIS) platform was soft-linked to estimation of emissions associated with such infrastructure.

Initially, the basemap of India was downloaded from the Bharat Maps portal. Subsequently, layers for LPS and storage sites were added onto it.

The power sector has been accompanied by several key changes since the past source-sink analysis was published. One major policy initiative is the increased penetration of biopower plants: both through blending as well as in standalone plants. As such, we mapped out biopower plants in addition to coal and gas fired power plants. Note that CO_2 emissions from biopower plants and other biogenic sources are considered as zero. However, in the CCS clusters, they do emit CO_2 emissions, capturing and storing which then entail so-called "negative emissions" (Bui et al., 2018; Muratori et al., 2020). The data for the locations and the capacity for power plants was downloaded from the World Resources Institute. This dataset was filtered on the basis of primary fuel type. The capacity of these power plants was multiplied by a capacity factor of 81.5%, based on the average utilization rate published by the Central Electricity Authority (CEA). Some plants also have a lower capacity factor due to intermittent fuel shortages, cooling water scarcity and so forth. However, Singh et al., (2017) have estimated that CCS power plants with capacity factors lower than 80% will not be financially appealing even with a carbon price of >\$100/t-CO_2. As such, the aforementioned capacity factor is assumed as the standard value for all power plants. Use of a constant capacity factor also allows for ease of comparison with the past analyses. A total of 192 LPSs were identified and mapped on the basis of their CO_2 emission in Arc-GIS. The data sources were identified from previously published work of Garg et al., (2017a) and other web sources (CIS, 2021; IBM, 2020; OGIS, 2022; PDIL, 2022; WRI, 2021). These LPSs include powerplants, cement, fertilizer, steel, biomass plants and refineries. For the source clustering, only LPSs having more than 1 Mt annual CO_2 emission were considered, whereas for source-sink matching, all 192 LPSs were considered. The emission factors from the IPCC Emission Factor Database are used to estimate net-emissions.

Once the geospatial data for all the sources were collected and overlayed on the basemap, the emissions associated with individual sources were calculated. This was done by multiplying the production of the relevant product of the facility by the emission factors shown in Table 1. A notable feature of the emission factors assumed in Table 1 is that they correspond to national averages in India for the key sectors, which may be different from global averages. For instance, the higher-efficiency, low-emission plants in China have an average emission factor of <0.8 t-CO_2/MWh. However, because of higher-ash coal and lower plant efficiency in older

Indian coal-fired plants, the emission factors here correspond more accurately to the area of interest in this study.

Table 1: Key characteristics of large point sources considered in this analysis

LPS type	Unit Generation	Emission per unit generation ($t-CO_2$)	Reference
Coal-fired power	1 MWh	0.98	CEA, (2019)
Gas-fired power	1 MWh	0.43	CEA, (2019)
Biomass-fired power	1 MWh	0.80	Singh et al., (2021)
Steel	1 t	1.85	Garg et al., (2017a)
Cement	1 t	0.9	
Refinery	1 t	1.1	
Fertilizers	1 bbl	48.5	Jing et al., (2020)

2.2. Identifying CO_2 sinks

CO_2 storage is considered in three type of formations: saline aquifers, enhanced oil recovery (EOR) and enhanced coalbed methane (ECBM), in this study. While other analyses do project a substantial basalt storage capacity in India, it is not considered due to lower technological readiness. A total of 26 sedimentary basins that cover an area of 3.4 million sq. km (DGH, 2020) represent enormous CO_2 storage potential in India. However, only seven are deemed at a high storage readiness level (Vishal et al., 2021b). The accurate estimation of the storage potential of any reservoir depends on the volume of data available; therefore, the cumulative CO_2 storage capacity in India has varied over time. Previous studies have indicated storage capacities of between 105 and 572 Gt across saline aquifers, basalts and depleted oil and gas reservoirs in India (Dooley et al., 2005; Holloway et al., 2008; Kearns et al., 2017; Singh et al., 2006). However, our recent analysis has indicated 291 Gt of effective CO_2 storage capacity in saline aquifers and 97–316 Gt in basalt formations, which is significant. EOR and ECBM could provide an additional 2.9 Gt and 3.7 Gt of CO_2 can be stored in depleted oil and unminable coal reservoirs, respectively (Vishal et al., 2021b). Although these capacities are significantly lower than those of saline aquifers (Table 2), the financial incentives and ready infrastructure that is available for storage through these pathways render them much more lucrative as sinks. Even the CCUS Roadmap for India by the Technology Information, Forecasting and Assessment Council (TIFAC, 2018) has recommended CO_2-enhanced oil recovery (EOR) and enhanced coalbed methane (ECBM) recovery as the primary drivers to implement CCS at a large scale in India. The more recent 2030 Roadmap for CCUS for oil and gas sector in India lists several policy reocmmendations in short, medium and long term and also identify key projects on EOR and ECBMR for CO_2 storage with/without petroleum recovery (MoPNG, 2022).

Storage reservoirs are often spread across large geographical areas with volumes >2000 km^3. As such, the Euclidean centres for these reservoirs are considered at the location of injection in this source-sink analysis. In order to locate the Euclidean centre for the reservoirs, the reservoir shapefiles were adapted from our previous work (Vishal et al, 2021b) and the "Find Centroid" tool was used in ArcGIS. Vishal et al (2021b) and others (Holloway et al., 2009) have reported that locations with promising saline aquifers are often co-located with oil and gas reservoirs. Thus, the key sedimentary basins analyzed in our study are shown in Table 1. These basins were selected because they have active oil and gas extraction being carried out for the past several decades. CO_2-EOR operations generally commence when the primary and secondary extraction approaches have been used, and CO_2 could be instrumental in recovering residual oil in place. Vishal et al (2021b) concluded that these seven basins have 3.4 Gt-CO_2 sequestration capacity within oil and gas reservoirs. The cumulative hydrocarbon in place in these basins is 11023 MMTOE and the above capacity is estimated by assuming that 10% of this repository could be extracted with CO_2 injection.

While the above basins are prominent for oil and gas extraction, they are also considered as "Category I" basins for storage in saline aquifers. These basins have adequate reservoir data available for the hydrocarbon industry and also the Directorate General of Hydrocarbons. The cumulative CO_2 storage capacity in these basins is 108.66 Gt-CO_2. Note that there are an additional 19 "Category II" and "Category III" basins where another 182 Gt-CO_2 may be stored in saline aquifers. However, these basins are not incorporated into our analysis due to large data uncertainty, low storage prospectivity and often, lower storage capacities in many of these basins.

Table 2: Sedimentary basins with CO_2 storage potential via EOR as well as aquifer injection considered in this study (data adapted from Vishal et al, 2021b)

Basins	EOR	Saline aquifers

	EOR (at 10%) (MMTOE)	CO_2 storage capacity (Mt)	Depth classification	Lithology	Volume	CO_2 storage capacity (Gt-CO_2)
Krishna–Godavari	197.7	658.69	Median	Sandstone	6,900.00	13.39
Mumbai	479.4	1597.24	Median	Limestone	6,360.00	9.26
Assam shelf	186.8	667.48	Deep	Sandstone	2,520.00	14.16
Rajasthan	93.8	312.52	Median	Sandstone	3,780.00	7.34
Cauvery	29.2	99.5	Median	Shale	8,100.00	16.08
Assam–Arakan	17.8	67.01	Deep	Sandstone	5,455.69	32.3
Cambay	180	657.25	Deep	Sandstone	2,808.75	16.13

Coal in India occurs through more than 16 operational coalfields and several unallotted coal blocks. While initial expert elicitations showed the coalbed methane (CBM) extraction could be feasible in several of these, on-the-ground operations have revealed that only four of these have appealing resources: Raniganj, Jharia, East Bokaro and North Karanpura. Incidentally, these coalfields are all located within proximity of each other (within a 300 km radius) and are considered within the Damodar Valley basin. Thus, the entire basin is considered as a single reservoir. The cumulative storage capacity - based on relative methane and CO_2 sorption capacities – of these coalfields is 57 TCF or 1.42 Gt-CO_2. It may be noted that these estimates vary widely based on the methodology used and assumptions surrounding the rate of coal extraction in such coalfields.

We selected the four coalfields in the Damodar Valley basin as the only potential sinks for ECBM recovery. This was done because existing literature shows that only these coalfields satisfy the technical criteria for profitable CBM operations on the basis of depth, porosity, permeability and gas resources (Singh and Hajra, 2018). This is also reflected in the field experience of CBM extraction, where a vast majority of production has taken place in these coalfields (Kelafant, 2020). Extensive experimental studies have been carried out to understand the flow-deformation attributes of liquid and supercrticial CO2 in coal from these basins (Vishal et al., 2013c; Vishal 2017a, 2017b; Vishal and Singh, 2015). Preliminary numerical models for Jharia and Raniganj coalfields indicate high potential for these coal to uptake CO_2 with/without CBM recovery (Vishal, 2017a, 2017b; Vishal et al., 2015b, 2013a; Vishal and Singh, 2015). Indeed, the tertiary coalfields in northeastern India generally occur at a shallower depth (<300m) (Mishra and Ghosh, 1996). And while the Cambay Basin and Barmer-Sanchor coalfields in Eastern India might be viable candidate purely from a geographical standpoint, these are mostly lignite reserves with low gas production potential.

2.3. Source-sink mapping

Once sources and sinks of CO_2 are separately mapped out on ArcGIS, we consider the "hubs and clusters" concept for demarcation of suitable regions with high CCS potential. This concept essentially demarcates "clusters", i.e., regions with high density of LPS and adjoining CO_2 storage locations. In some cases, the storage location may not be conveniently located in close proximity to the sources. These cases require dedicated "hubs", which are locations where CO_2 from all the LPS may be transported to, and then cumulatively transported to the storage location to introduce economies of scale. In some regions, the storage location may be fortituously located near the centre of the LPS and it may automatically be designated as the "hub".

In our analysis, we did not consider sector-specific clusters. Instead, all sectors were assumed to potentially contribute to a particular cluster. This is because the Garg et al (2017b) work already showed that integrated clusters showed a cost optimization of \$10/t-CO_2 over sector-specific clusters. We used the "Shortest route" function in ArcGIS for each cluster in different combinatorial sink locations and the storage locations were demarcated as the following (Garg et al., 2017b):

$$X_{storage} = \sum_{S=1}^{5} \left(\frac{\sum x_i e_i}{\sum e_i}\right) + \Delta_x \qquad \text{Eq. 1}$$

$$Y_{storage} = \sum_{S=1}^{5} \left(\frac{\sum y_i e_i}{\sum e_i}\right) + \Delta_y \qquad \text{Eq. 2}$$

Here, $S = 1$ to 5 denotes the LPS sectors: power, steel, cement, fertilizer and refinery. The e_i values denote the emissions associated with an LPS, i while x_i and y_i are the associated longitude and latitude. The Δ_x and Δ_y values denote the distance between the hub and the storage location of that cluster. Based on expert elicitations, it was assumed that the radii of these clusters would not exceed 150 km. This was due to large multiple infrastructural challenges associated with pipeline construction. As such, the number of sources within 50 km, 100 km and 150 km radii of each of the sinks were located.

2.4. Costing analysis

The cost estimation was carried out for each of the clusters visualized based on the aforementioned methods. The cost components estimated here are: cost of CO_2 capture, cost of CO_2 transportation, costs associated with CO_2 storage (including injection and monitoring) and also, any revenues (negative costs) based on additional resource recovery in the case of EOR and ECBM. All the costs are estimated based on a per t-CO_2 basis with the relevant parameters shown in Table 3.

Table 3: Cost parameter assumptions for CCS supply chain

Parameter	Cost	Reference
CO_2 capture (values in \$/t-CO_2)		
Coal-fired power plant	54	(Singh et al., 2017b)
Gas-fired power plant	120	(Rubin and Zhai, 2012; Singh and Sharma, 2016)
Biopower plant	200	(Muratori et al., 2017)
Steel plant	74	(Global CCS Institute, 2017)
Cement plant	129	
Fertilizer	28	
Refinery	65	(Yao et al., 2018)
CO_2 transport (\$/t-CO_2/km)		
Pipeline transport	0.01	(Singh et al., 2020)
CO_2 storage (\$/t-CO_2)		
Saline aquifers	9-30	Based on reservoir parameters; calculated in IECM framework
EOR	Negative (15-31)	
ECBM	Negative (5.2)	

Depending on the point source, the costs of CO_2 capture may be similar or higher for the Indian context, as compared to global analogues. For instance, the capture cost for a coal-fired power plant (\$54/t-CO_2) is nearly the same as those based in the United States (Pilorgé et al., 2020). However, the capture costs for gas-fired power plants is about 50% higher in India due to historically lower capacity factors for such plants and increased costs of imported natural gas (Singh and Sharma, 2016). In the case of sectors where considerable CCS experience already exists in India – such as fertilizers – the capture costs are close to the lower bounds of global averages.

The costs for CO_2 capture and storage were adapted from the literature, as shown in Table 3. Storage costs were calculated separately for each basin. The Integrated Environmental Control Model (IECM), developed at the Carnegie Mellon University, was used for these estimations. IECM is a graphical-user interface software and accepts the reservoir parameters (thickness, depth, temperature, porosity and permeability) to yield the storage costs. For EOR and ECBM, we also assumed that the market price of crude oil and methane are \$60/bbl and \$6/mmBtu.

3. Results and Discussion

3.1. Evaluating CO_2 capture prospects from large point sources

3.1.1. Power sector

We describe the power sector and industrial sources separately due to a number of reasons. First, most of the existing costing literature on CCS in India is related to the power sector (Singh et al., 2017a; Yadav et al., 2016), which provides lesser uncertainty to the cost parameters assumed in Table 3. Second, the power sector has a disproportionately large share of LPS emissions in India due to a higher share of coal in the energy mix. This is different from economies such as the United States, where the transport sector is the highest CO_2 emitter. Third, because of the regulatory structure of the Indian government, the power sector's control is exercised by a single ministry, whereas the industrial sector comes within the oversight of several different ministries (Garg et al, 2017). Finally, the capture technologies associated within the power sector may be different from say, the refinery sector, where the CO_2 stream is derived from multiple different unit operations (Yao et al, 2017).

Figure 2 shows the locations and emission intensity associated with key large point sources in India. The maps deliver several pieces of interesting insights. For instance, there is a concentration of large number of coal-fired power plants in the central India. Gas-fired power plants, on the other hand, are located towards northern India as air pollution concerns have created a momentum towards coal phasedown in the region. For instance, the Badarpur power station was shut down as 30-40 % of Delhi's air pollution could be attributed to it. Some pockets of gas-fired plant clusters may also be seen in the western, northeastern and east coastal parts of India due to proximity to indigenous gas resources. The capacity of bioenergy power plants has also been notable with total emissions of 6 Mt-CO_2. This is largely due to co-firing with coal power plants in western India, though such trends are likely to intensify in the future (section 2.4). Currently, there is a presence of biopower infrastructure in Maharashtra, Karanataka, Haryana and Gujarat, in addition to smaller units in other states.

As noted earlier, India's annual CO_2 emissions were 2.6 Gt-CO_2 in 2019. Large point sources emit around 80% of this CO_2, which makes CCS retrofitting an appealing possibility. In our analysis, we did not consider all types of LPS due to data limitations. Specifically, our analysis accounts for 1.88 Gt-CO_2 emissions or more than 96% of the LPS emissions. Our analysis shows the relative influence of the power sector in India's GHG emission inventory. For instance, coal-fired power plants alone emit 1.43 Gt-CO_2. This trend has intensified since prior national analysis of GHG inventory, due to commissioning of several new subcritical and supercritical units in existing coal-fired power plants. Moreover, there has been a thrust on larger power plants to increase their capacity factors. Consider the case of the Vindhyachal Super Thermal Power Station in Madhya Pradesh, which is the largest LPS in the county with a capacity of 4,760 MW. The power plant registered a 100% capacity factor last year and the last unit addition for the plant occurred in 2015. As such, the emissions associated with the plant have increased both due to increased capacity and capacity factor. Other large power plants with capacity factors above 90% include: Kahalgaon, Sipat, Talcher and Sasan. This is relevant because expert elicitations indicate that while capacity additions of coal may slow down, increased utilization of existing facilities may add the use of 300 Mt-coal over the next decade. This corresponds to increased CO_2 emissions of 860 Mt-CO_2 by 2030. Interestingly, most of these plants are towards the central part of the country, which has interesting ramifications in terms of hubs and cluster formation, as discussed later.

Gas-fired power plants in India currently do not indicate a major source for CCS in India by themselves. Even though a substantial capacity for gas plants exists (26 GW), the operational capacity factor is low, i.e. 22.6%. This may partly be attributed to the low gas availability. For instance, the 2017 gas requirement for these power plants 117 MMSCMD. However, the actual gas supply remained at 31 MMSCMD or about 26% of this demand. That said, the development of CCS hubs and clusters could lead to a financial incentive for CCS for two reasons. First, many such plants could become part of integrated clusters close to larger coal power plants, thus reducing the transport costs and infrastructural liability if they choose to retrofit with CCS. Moreover, many CCS clusters might come around sites which could increase gas production through ECBM (discussed in section 2.4).

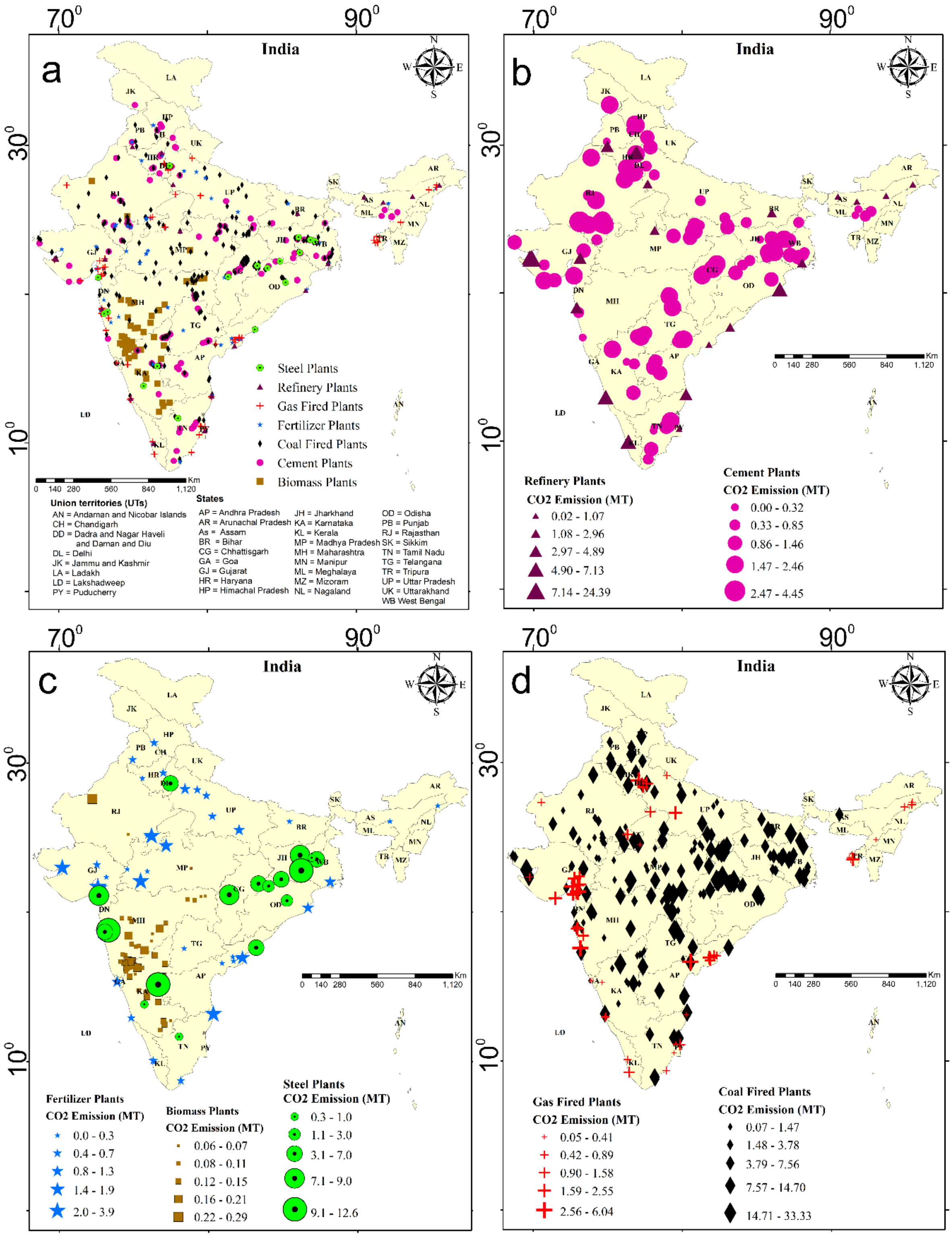

Figure 2: Locations and CO_2 emission intensities of all large point sources in India. (b) only for cement industries and refineries. (c) only for steel plants, biomass and fertilizer plants. (d) only for coal and gas-fired power plants

3.1.2. Industrial sector

In addition to the power sector, industrial sectors (steel, cement, fertilizer, refinery) emitted ~600 Mt of CO_2 into the atmosphere. The global CCS literature has provided prominent coverage to industrial sources of CO_2, particularly in developed economies. For instance, Pilorge et al (2020) estimate a CO_2 avoidance potential of 69 Mt-CO_2 at <\$40/t-CO_2. The avoidance potential here may be defined as the reduction in CO_2 emissions without changing the total produced power/commodity at a given cost. One of the reasons here is the decreasing emissions of power sector CO_2 emissions in such countries, which is not the case for India. Nevertheless, our analysis does provide locations where such conditions may be feasible. For instance, steel plants are largely concentrated in eastern and western India due to ease of sourcing of indigenous and imported coking coal respectively. Cement and fertilizer plants, on the other hand, are present throughout the country due to the ubiquitous demand for these products.

In India, several key opportunities for industrial CO_2 capture do exist. For instance, we estimate 47 Mt-CO_2 from the fertilizer sector. The Indian fertilizer market is anticipated to register a 11% CAGR in production over the next five years, with the government considering an additional subsidy of \$3.8 billion. This sector also exhibits a technological readiness for CO_2 capture with the Jagdishpur fertilizer plant capturing 150 t-CO_2 daily for internal reuse. With a lower cost of CO_2 capture, there may be a possibility for this sector to pivot to CCS. Other opportunities may exist in the cement sector which emit close to 148 Mt-CO_2 based on our analysis. The Dalmia cement group recently announced plans to retrofit one of their facilities to capture 0.5 Mt-CO_2. The steel sector emits 180 Mt-CO_2 based on a total capacity of 144 Mt. This is anticipated to almost double based on government policy initiatives over the next decade. While the cost of CO_2 capture in this sector is similar to the power sector, there has been a recent industrial breakthrough with Tata Steel commissioning a modular 5 t-CO_2/day capture facility. India also ranks first and second in sponge iron and crude steel production, respectively, which is a result of a rapid increase in high-capacity steel plants since 2005. However, since the efficiency of the plants has increased over time, the CO_2 emission per ton of steel produced has steadily decreased, and it currently stands at 2.5 tCO_2/ton of crude steel. This has resulted in a decreasing cumulative emission of CO_2 from the steel sector since 2015 (MoS, 2020).

Emissions from refineries and other fuel production sectors contribute 89 Mt CO_2e annually. The greenhouse gas (GHG) emission from refineries in India has increased 150 % between 2005 and 2019 due to the rapidly increasing capacity for refining. Of particular interest here is the Jamnagar refinery, which is the world’s largest refinery and emits 24 Mt-CO_2 annually. While we discuss the geographical context of this LPS later, it has been deemed as a facility that could enhance the blue hydrogen production at \$1.2-1.5/kg-H_2. This could reduce significant CO_2 emissions here. However, refineries are composed of several CO_2 streams in addition to steam methane reformation (where hydrogen is produced). Particularly, the catalytic cracking unit leads to the largest process emissions within a refinery. Multiple CO_2 emissions add an addition layer of complexity to CO_2 capture from refineries.

3.2. Identifying potential CCS clusters based on source-sink matching

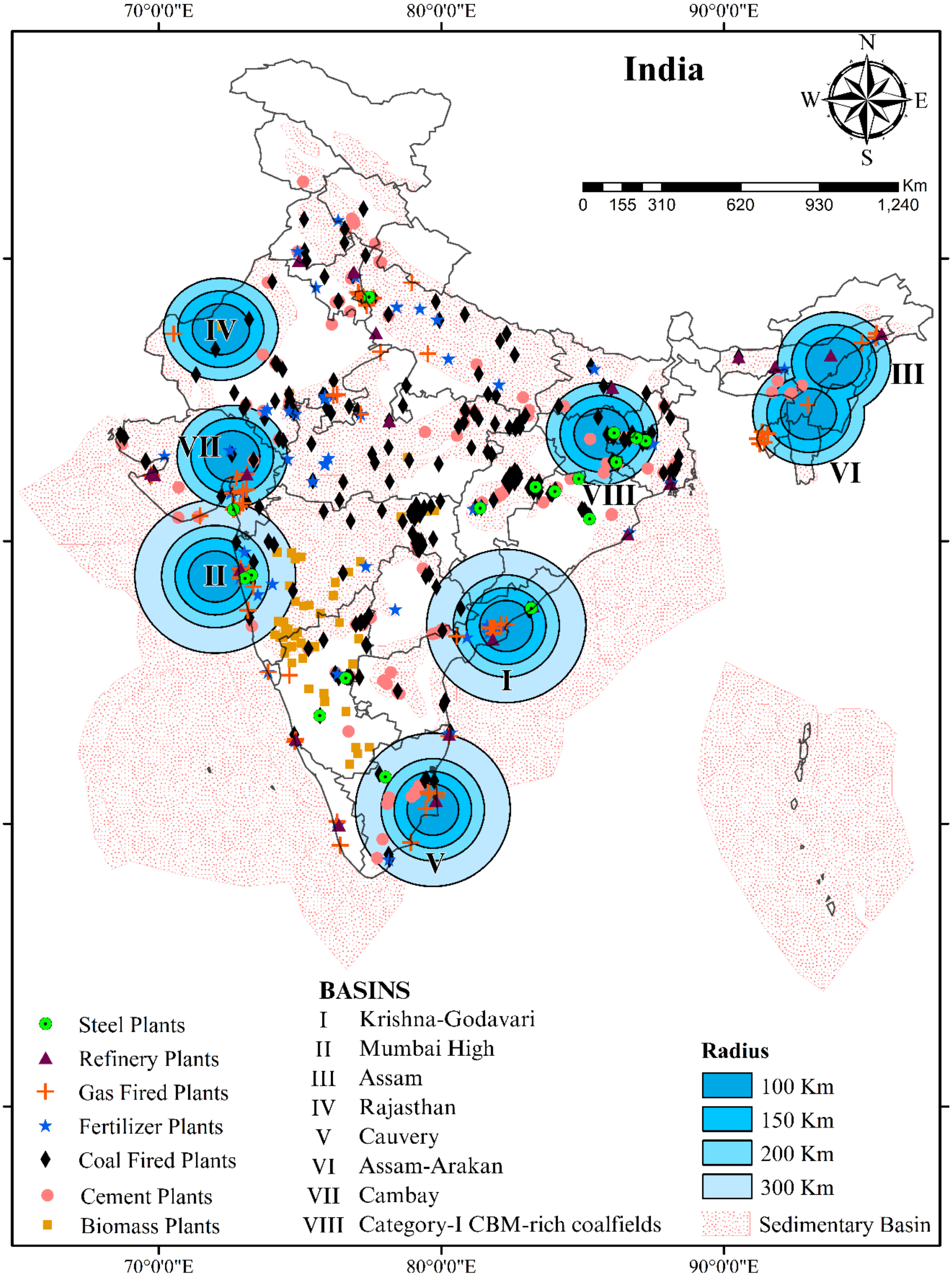

Figure 3: Identified source-sink clusters for key sedimentary basins and coalfields in India. The concentric circles represent radial distance from the eucledian center of each sink.

As discussed above, source-sink clusters in this study were designed in such a way that optimized the transport cost by reducing the CO_2 transport distance. Having a large number of emission intensive sources also reduced the storage cost due to economies of scale. It was observed that the formation of integrated clusters enabled cost optimisation through sectoral collaboration of industrial partners. Seven clusters were identified in this study around EOR basins and saline aquifers (which occur at similar locations due to their occurrence in sedminentary basin). Based on the abundance of CO_2 sources and their proximity to sink reservoirs, a total of 244 LPSs and seven Category I sedimentary basins (four onshore and three offshore basins) were considered as part of these sinks. By definition, these Category I reservoirs have a higher accessible volume, which implies a higher CO_2 storage capacity. Additionally, extensive studies on these basins have rendered the feasibility assessment of these basins for CO_2 storage easier. For this study, we considered clusters of LPSs that were present within certain distances from the sinks. For the onshore basins, we considered LPSs within 200 km of the sink. In contrast, we considered LPSs within 300 km for offshore basins, because the offshore basins had a higher reservoir capacity than their onshore counterparts. Our study shows that 62 LPSs (32%) of the sources are within a distance of 100 km from the sinks in these seven clusters, whereas 85 LPSs (43%) and 55 LPSs (25%) are within 100–200 km and 200–300 km, as shown in Figure 3 and Supplementary Figure 1. It was observed that coal-fired powerplants were significant contributors to the LPS frequency and to the total annual emission in each cluster.

Table 4: Summary of potential CCS clusters based on matching LPS and theoretical sinks

Basin	**Emissions (Mt-CO_2/year)**	**Number of LPS**	**Average distance of LPS to sink (km)**	**Emissions from power sector (%)**	**Percent of sequestration possible with additional resource recovery (%)**	**Storage potential needed for 30 years (Gt-CO_2)**
Sedimentary basins (Category I oil and gas basins)						
Mumbai High	81	33	160	49	65	2.43
Krishna-Godavari	72	27	114	78	30	2.16
Cauvery	65	25	148	85	5	1.95
Cambay	49	23	119	78	45	1.47
Rajasthan	12	6	125	93	88	0.36
Assam-Arakar Fold Belt	2.0	6	102	22	100	0.06
Assam	1.7	2	82	38	100	0.05
Coalfields (Category I CBM basins)						

Damodar Valley	120	29	116	71	39	3.60

Analysis of these clusters reveals several interesting insights (Table 4). First, the maximum abundance of emissions occurs near the Mumbai High basin (81 Mt-CO_2/year). This cluster contains 33 LPS and is actually dominated by industrial sources which contribute to 51% of the emissions here. Particularly, three steel plants near the basin emit 25 Mt-CO_2. This basin is an offshore basin, due to which the distance of most LPS is high, with the average LPS being 152 km away from the Euclidean centre of the basin. This necessitates creation of an onshore hub, where the CO_2 streams from various LPS may be assembled and then cumulatively sequestered. The Krishna-Godavari basin may also be treated as a promising cluster with adjoining emissions of 72 Mt-CO_2. Out of these, 78% emissions are from the power sector. Analysis by Garg et al (2017) found that the emission clusters would develop around large UMPPs with each of such plants emitting 28-29 Mt-CO_2. Because of evolving conditions of lesser new plants coming online and addition of newer units on existing plants, this may not always be the case. Thus, the Krishna-Godavari basins has 14 power plants in close proximity, which emit an average of 4 Mt-CO_2. This is a major change in the ways clusters are likely to be designed in the Indian context. Similar trends are seen in the Cauvery and Cambay basins where adjoining emissions are 65 Mt-CO_2/year and 49 Mt-CO_2/year respectively. Again, the average emission from a power plant in these clusters is only 3.5 Mt-CO_2/year and 2.5 Mt-CO_2/year respectively, thus highlighting the increasing importance of several mid-sized power plants to the formation of clusters.

Onshore basins are associated with lower emissions in close proximity. This is partly due to lower density of infrastructure around the states considered (e.g. Assam) and also because of more restrictive assumption around such clusters. Emissions around the Assam Basin and the Assam Arakan basins are cumulatively only 3.7 Mt-CO_2. At such rates, the cost of emissions are likely to be higher. Even though there is an opportunity for ~700 Mt-CO_2 sequestration via EOR, it may not be utilized because there are minimal CO_2 sources nearby. This is similar to the concept of "CO_2 deserts" proposed by Middleton et al. (2014), where there is a source-sink "mismatch" at some locations.

The Damodar Valley coal basin in eastern India, particularly with four key coalfields (Raniganj, Jharia, East Bokaro and North Karanpura) may be very suitable for formation of clusters and sub-clusters. This was also suggested by Garg et al (2017), though there analysis hinged on provision of CO_2 from three UMPPs (Deoghar, Banka and Tilaiya). As such, they estimated the availability of 218 Mt-CO_2/year in close proximity to the region. Our analysis shows that even in the absence of these UMPPs, this cluster still has 120 Mt-CO_2/year in proximity. This includes annual emissions of 85 Mt-CO_2 from power plants and the remaining 35 Mt-CO_2 from the industrial sector, thus depicting large diversity of sources.

3.2.1. Costs of CCS deployment at scale

The costs of capture, transport, storage and additional revenue (for EOR and ECBM) were calculated for each cluster on a \$/t-CO_2 basis (Figure 4). One of the key features of this study is that we have developed a more detailed estimate of the storage costs as compared to past work, where a default value was assigned to the parameter.

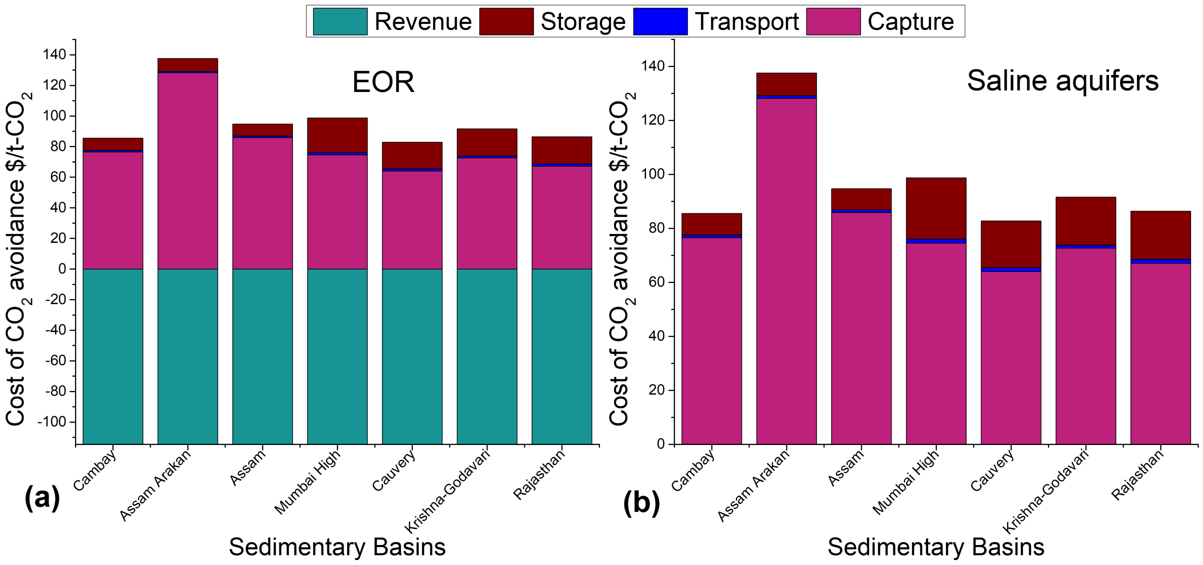

Figure 4: Overall system cost of avoidance for sedimentary basins for storage in (a) EOR reservoirs and (b) saline aquifers

The results for saline aquifers show that the overall cost for CCS in India is substantially higher than global averages (Clarke et al, 2022). This is, in part, due to higher capture costs at coal-fired power plants due to high ash content and lower efficiency. If we exclude the Assam Arakan Basin due to low emission sources in proximity, the costs of CO_2 avoidance are \$87-107/t-CO_2. This is notably due to higher storage cost (\$9-30/t-CO_2) of Indian aquifers. These aquifers often occur at a higher depth and a lower thickness. Moreover, the permeability is assumed at a default value of 40 mD, which is a conservative estimate. The economic prospects, however, change when EOR system costs are evaluated. The past study by Garg et al (2017) assumed a low crude oil price of \$15/bbl, and accordingly EOR storage costs were around \$-

16/t-CO_2. Our analysis assumes a crude oil price of $60/bbl based on current market conditions and an EOR effectiveness of 1.91 bbl/t-CO_2. This makes the overall system profitable by reducing the total system costs to negative $31-15/t-$CO_2$. The system costs present an interesting tradeoff. For instance, we discussed that the Mumbai High basin has a suitable prospect for EOR based on proximity to LPS. However, this cluster has a higher avoidance cost due to a low storage coefficient of 1.5%. Storage in coal basins is somewhat towards the middle of the two sedimentary basin cases and offers a overall system cost of $60/t-$CO_2$. We do caveat these results by saying that data limitations have led us to assume default values for critical parameters. As such, these metrics may be treated as indicative and we suggest further refinements based on field data.

3.3. Key opportunities for CCS deployment in proposed clusters

One aspect in which we have helped evolve the findings of Garg et al (2017) is by incorporating the actual storage potential estimates. In previous work, the emissions surrounding the clusters were estimated and it was assumed that sinks would contain the adequate storage capacity. This work presents further nuance on that. For instance, it is likely that the initial preferred storage in sedimentary basins would be EOR, followed by injection into saline aquifers as they are co-located. Similarly, in the case of coalfields, ECBM would be preferred followed by injection without incremental CBM recovery by considering all constraints in doing so (Pashin et al., 2018). CCS hubs and cluster strategy is often iterated as an effective strategy to share the responsibility of developing full-scale CCS projects. CCS chains developed with this strategy also has a potential to be independent of government subsidies upfront (Global CCS Institute, 2020). Responsibilities of establishing and expanding a hub can be shared among sharing parties, thereby reducing overall cost and risk compared to standalone CCS initiatives (Cavanagh and Ringrose, 2014; Sun et al., 2021b). Several implementations of hubs and cluster based CCS chains including Rotterdam CCUS Porthos in the Netherlands, Sun and Chen (2017) have validated the potential feasibility of this approach in NetZero Teeside in UK and CarbonNet in Australia (Sun and Chen, 2017) attempted to construct a source-sink distance-based hubs and cluster network for China by k-means clustering using InfraCCS based models. All studies unanimously point towards a fact that this hubs and cluster model is more economically viable when the sinks are involved in EOR or ECBM recovery, which may offset the cost of capture, transportation and storage. For this study, we have used LPSs with > 1 Mt/yr CO_2 emission and based on their location and availability of sinks in proximity, 12 clusters have been formed (Figure 5). Here, we identify the key EOR and ECBM opportunities identified with our clusters, followed by an understanding of the bioenergy with CO_2 capture and storage (BECCS) prospects in India.

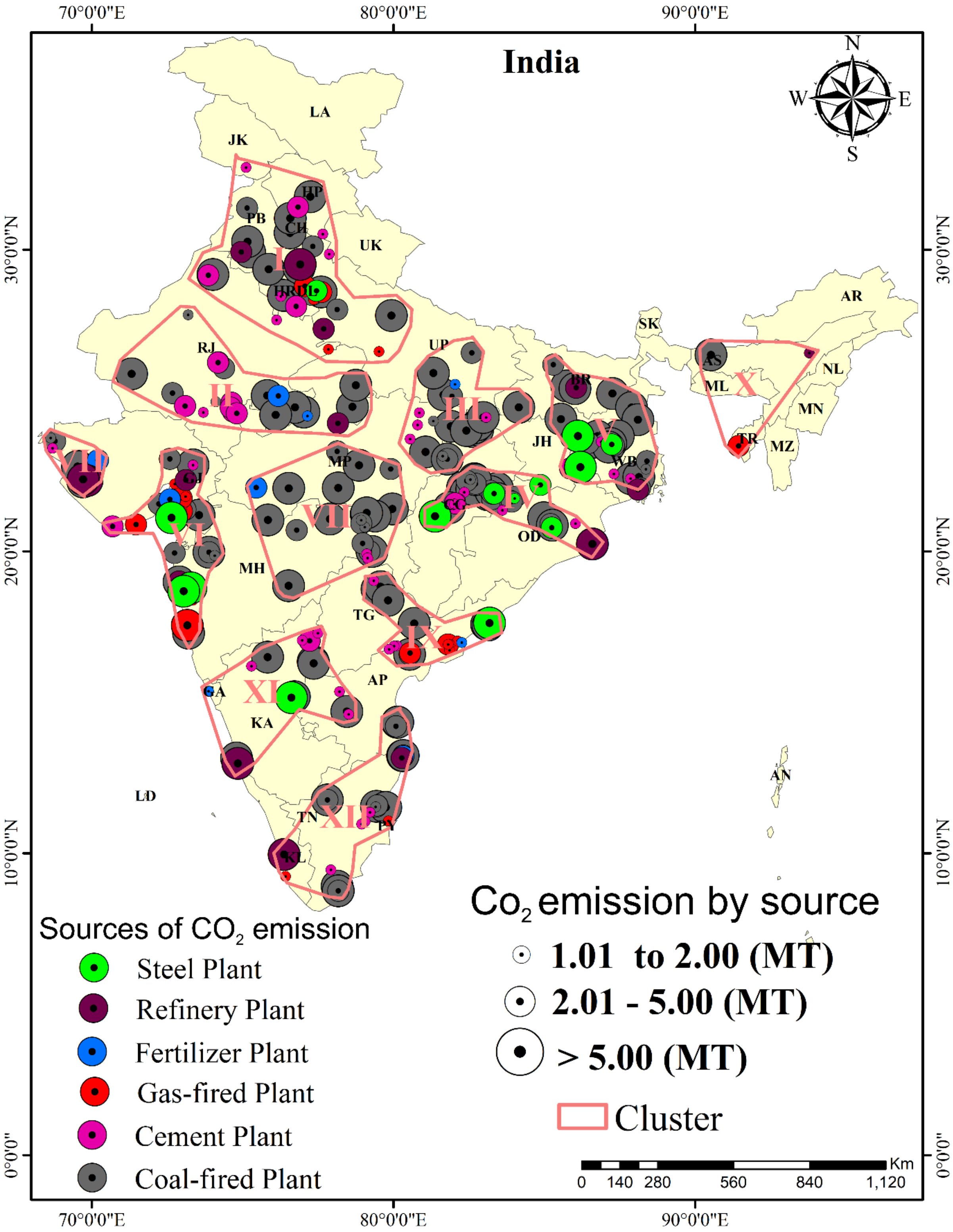

Figure 5: The proposed hubs and clusters for implementing CCS network across India.

3.3.1. EOR feasibility

Table 4 shows the amount of CO_2 that may be stored in each sedimentary basin with EOR assuming that each cluster operates for 30 years. We discussed that the Mumbai High basin has the largest number of sources in proximity. It also, fortitiously, has the largest EOR capacity of 1.6 Gt-CO_2. As such, 65% of the CO_2 may be used to extract the incremental oil in the basin. This value is lower for the Krishna-Godavari Basin (30%) and the Cambay Basin (45%), depicting moderate economic feasibility if the EOR pathway is undertaken. The Cauvery Basin contains only 100 Mt-CO_2 EOR potential, which means that it is likely to rely on storage in saline aquifers. One key trend that is notable here is the potential deployment of EOR in the Cambay Basin with CO_2 sourced from the Indian Oil Koyali Refinery. This project is currently in the design and feasibility stages, and is anticipated to capture 5000 t-CO_2/day. This has also been highlighted by Patange et al. (2022) who note that availability of CO_2 sources in proximity could make EOR viable even below a crude oil price of $45/bbl.

The Rajasthan basin may sequester 88% of the CO_2 with EOR and the Assam and Assam-Arakan basins may sequester all the available CO_2 with EOR. In fact, the emissions adjoining the Assam Basin are only 8% of the EOR capacity over a 30-year period. Our past work reflected on potential opportunities in India where CO_2 could be captured from the ambient air with direct air capture (DAC). Because CO_2 injection in the Assam Basin could help in incremental oil recovery of 178 MMTOE, it is an opportune location for DAC, particularly when paired with the revenues of the California Low-Carbon Fuel Standard, that may incentivize a DAC facility anywhere. The electricity mix in Assam has also been decarbonized with the Assam Solar Energy Policy targeting a 590 MW solar target, which could provide a high carbon sequestration efficacy for such a project even after considering the emissions from the produced oil.

Overall, our estimates show potential recovery of 5290 MMbbl with currently existing LPS over 30 years. This corresponds to 14.5 MMbbl/year is equivalent to about 10% of India's annual oil importance. Thus, our study highlights a tangible potential with bridging the oil dependence through EOR.

3.3.2. ECBM feasibility

The Damodar Valley cluster is highly emission-intensive with the emissions over 30 years corresponding to 39% of the available ECBM capacity. This means that an incremental 19 TCF of methane could be recovered over 30 years, that corresponds to 0.63 TCF annually. It is notable that India's current liquified natural gas imports are 1.2 TCF. Thus, ECBM could be an even more important technology in reducing India's import dependence than EOR. Several studies have indicated on the massive ECBM potential of Damodar Valley coalfields (Chandra and Vishal, 2022; Vishal et al., 2013c, 2013b, 2015a, 2018). Several CBM blocks in the Damodar Valley are already seeing some level of peaking. For instance, the Raniganj Block of Essar Oil Limited saw a CAGR of 111% during 2011-17 and peaked at around 14 BCF. Thus, technical ECBM opportunities may open up over the next decade as production from more wells of private and public players begin to peak.

As ECBM does not provide adequate storage capacity to the region's CO_2 emissions, it is also important to understand possibilities to diversity storage opportunities. For instance, the Rajmahal basalt traps contains a storage capacity of 4.5 Gt-CO_2. Similarly, Singh et al (2021) project sizeable technical opportunities for storage in shale formations in the Damodar Valley. While storage in shales is not technologically established yet, it might develop over the next three decades and provide a backup storage opportunity. Several studies have shown that the shale samples in the region have a very high total organic carbon content, which correlates with high storage capacity per unit volume of shale (Chandra et al., 2020b, 2020a; Chandra and Vishal, 2020; Vishal et al., 2019). More studies looking at these reservoirs from the perspective of CO_2 storage are therefore recommended.

3.3.3. BECCS opportunities

Multiple countries have mapped out the BECCS potential based on co-located bioenergy power plants and CO_2 storage sites. Since, modelling results show higher BECCS requirements in developed countries with high historical emissions, it has not been discussed in India. Our results, however, help shed some light on the early opportunities for BECCS in India. Notably, existing biopower plants emit 5.7 Mt-CO_2, which is low because the capacity of such plants is generally <50 MW. However, NTPC recently announced that it plans for 5% co-firing are in an advanced stage and the company has already ordered procurement of 3 Mt of biomass pellets(Kannappan, 2022). If we consider 5% co-firing for India's entire coal fleet, it would correspond to 70 Mt-CO_2 biogenic emissions. Thus, there is an opportunity for India to leverage so-called "negative emissions" or carbon dioxide removal from the atmosphere.

Apart from the electricity generating infrastructure, low-cost BECCS opportunities also exist in the bioethanol sector, which is likely to grow in Gujarat (near the Cambay Basin). This could also lead to a low-carbon transport fuel option with CO_2 capture possible at <\$45/t-CO_2. The Government of India has announced plans to expand bioethanol production to 10 billion litres by 2025. While such facilities have not been considered in this analysis due to data limitations, it is another potential area of future research.

4. Conclusion

While several advances have been undertaken in the CCS domain in India, system integration analyses were lacking. Due to changing policy circumstances – especially with the announcement of the net-zero target – there is an increased need for overarching assessment of potential CCS clusters that could be developed in India. Our work looks at the existing LPS and aims to understand locations where hubs and clusters may be developed. We discuss the opportunities individually in the power sector and the industrial sector. The power sector offers a large-scale decarbonization of close to 1.5 Gt-CO_2. Cases of co-firing biomass with coal, the power sector could also be integrated with BECCS opportunities to readily offer negative emissions. Our analysis also discusses regions where industrial CCS may be more relevant and be helpful in reducing the emissions of hard-to-decarbonize sector. Here, we describe initiatives that are already being undertaken in the steel, cement, fertilizer and refinery sectors.

The source-sink matching effort in this paper attempts to use our group's novel estimates on the CO_2 storage capacity to describe seven clusters in sedimentary basins (with and without EOR) and one cluster in the Damodar Valley coalfields in eastern India. Cumulatively, these may sequester just over 400 Mt-CO_2/year. Over a 30-year duration, this corresponds to 12 Gt-CO_2, which is coincidentally close to the CCS target estimated by global energy modelling groups for India. We also carried out a first-order estimate of the costs of CCS in these clusters. These are estimated to be \$87-107/t-CO_2 in saline aquifers, - \$31 to -\$15/t-CO_2 for EOR, and \$60/t-CO_2. Financial revenues from EOR and ECBM are, therefore, necessary to jumpstart CCS in India.

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