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

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Title Page

1 **Manuscript title:**

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

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21 **Optimal source-sink matching and prospective hub-** 22 **cluster configurations for CO₂ capture and storage in** 23 **India**

24 **Abstract**

25

26 At COP-26, India announced strong climate commitments of reaching net-zero greenhouse gas
27 emissions by 2070. Meeting this target would likely require substantial deployment of CO₂
28 capture and storage (CCS) to decarbonize existing large point sources of CO₂. This study
29 attempts to evaluate opportunities for deployment of CCS in India in the forthcoming decades.
30 A GIS based approach was adopted for mapping existing sources of CO₂ with the sinks. The
31 results show that regionally-appropriate ways of moving towards CCS at scale exist in both the
32 power and industrial sectors. Coupled analysis of these sectors with sinks shows that 8 clusters
33 may be developed throughout the country to sequester 403 Mt-CO₂ annually. These clusters
34 are concentrated near Category-I oil basins and the Category-I coalfields (Damodar valley),
35 which may also create suitable financial incentives by incremental oil and coalbed methane
36 recovery respectively. Furthermore, a first-order costing analysis evaluates that the cost of
37 avoidance across basins may range from \$31 to \$107/t-CO₂, depending on the type of storage
38 reservoir and the proximity to large point sources. A total of 12 suitable hubs and clusters were
39 created based on annual emissions above 1 Mt of each large point source and their proximity
40 with geological sinks.

41

42 **1. Introduction**

43 India's CO₂ emissions have risen from 980 Mt-CO₂ in 2000 to 2630 Mt-CO₂ in 2019. This
44 represents a cumulative average growth rate (CAGR) of 5.3 % over the past two decades (Garg
45 et al., 2017a). Capacity addition in electricity generation and large-point industrial sources such
46 as iron and steel, cement, fertilisers, and refineries have largely contributed to this increase. In
47 order to achieve sustained economic and societal growth, a similar trajectory in such
48 infrastructure could be anticipated.

49 An increase in energy and industrial production alongside rapid reductions in CO₂ emissions
50 requires a number of technological platforms for decarbonisation. India's nationally
51 determined resolutions, which were submitted during the Paris Climate Agreement in 2015,
52 committed the nation to the reducing of the greenhouse intensity of the economy (the ratio of
53 GHG emissions to gross domestic product) by 33–35 %. The pledged reductions were primarily
54 based on potential additions to renewable-energy capacities by 2022. The capacity addition
55 goals have been met before time (Busby and Shidore, 2021). However, the Prime Minister of
56 India recently committed at the Glasgow Climate Summit that India would reach net-zero CO₂
57 emissions by 2070. In light of this commitment, India would likely need a much steeper
58 decline in CO₂ emissions, which will require the decarbonisation of existing large-point
59 sources. Integrated assessment modelling literature shows that a key feature of energy
60 transitions that are compatible with net-zero emissions is the integration of such infrastructure
61 with CO₂ capture and storage (CCS) (Davis et al., 2018; Fennell et al., 2021; Vishal et al.,
62 2021a; Vishal and Singh, 2016). Analyses by the modelling community show that CCS would
63 be responsible for at least 15% of reductions in CO₂ emissions in net-zero energy systems (Baik
64 et al., 2021; Gabrielli et al., 2020). Currently operational CCS facilities can permanently store
65 40 Mt of CO₂ every year, which is far from the minimum 6000 Mtpa that is needed to meet
66 net-zero targets (Haszeldine et al., 2018). A massive gap seems to exist globally between the
67 current global CCS provision and that which is required to meet the anticipated CCS targets.

68 In the context of Indian energy systems, modelling exercises further suggest that CCS
69 deployment in the power sector alone could be as high as ~850 Mt-CO₂/year in 2 °C scenarios
70 and ~1000 Mt-CO₂/year in 1.5 °C scenarios in peak years (Vishwanathan et al., 2021;
71 Vishwanathan and Garg, 2020). When combined with the CCS of the industry sector, this
72 would lead to a requirement of 7–10 Gt-CO₂ cumulatively by 2050 (Denis et al., 2018). In
73 addition to the decarbonisation benefits of CCS, there are other value additions. (Vishal et al.,

74 2021a) quantitatively highlight the projected benefits that CCS could provide through
75 enhanced energy security, grid resilience and reduced risks of stranded assets. Moreover, the
76 Glasgow agreement focuses on a ‘phase down’ of coal instead of a ‘phase out’ (Andreoni,
77 2022). In the light of this, CCS could play a pivotal role in the gradual reduction of emissions
78 from the coal sector, particularly coal-fired power plants which account for 44 % of India’s
79 CO₂ emissions.

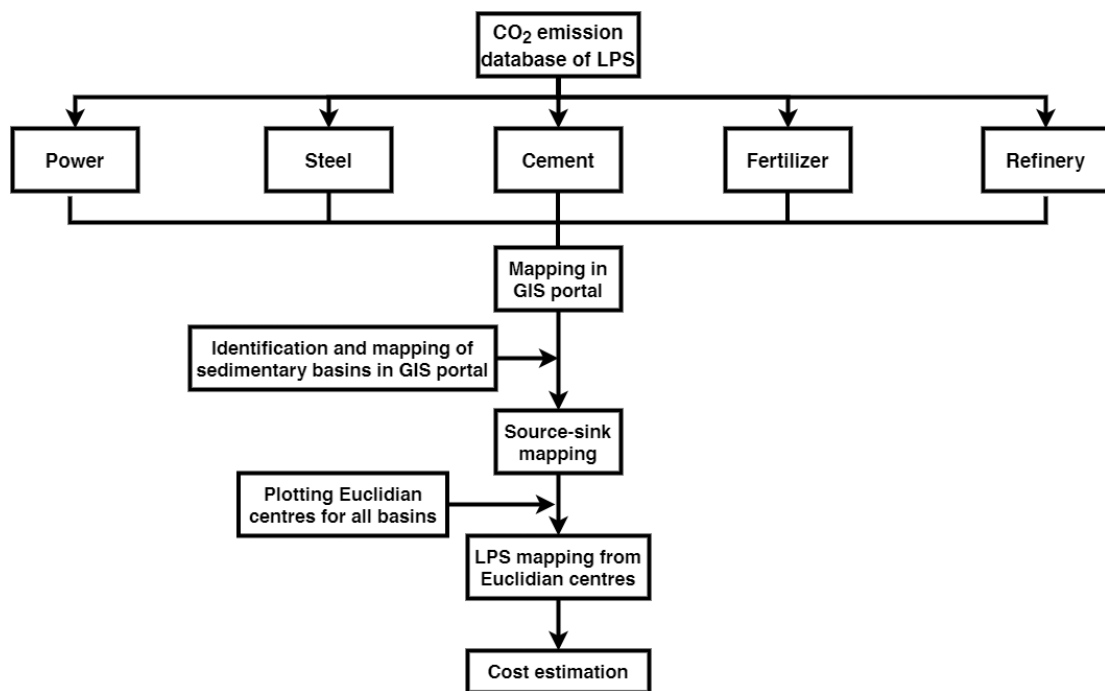
80 Academic literature about India’s CCS readiness is large, diversified and includes
81 policy outlooks (Viebahn et al., 2015; Vishal et al., 2021a), assessment of the potential for
82 geologic storage (Singh et al., 2006, 2021; Vishal et al., 2021b), and retrofitability of existing
83 infrastructure.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

96 To address these gaps, this study undertakes a new source-sink mapping, which
97 incorporates new potential estimates, bio-infrastructure and investment decisions that were
98 made after 2015. In line with global literature, we also seek to inform policy-making through
99 the design of the hubs-and-cluster concept. A second novelty of this study is that it incorporates
100 key costing parameters to address the economic versus storage readiness of individual hubs
101 and clusters. Countries such as India, which have no operational commercial facilities and
102 limited hydrocarbon reserves, could benefit from a hubs-and-clusters strategy that promotes
103 the implementation of this CCS technology. The CCS hubs-and-clusters operations effectively
104 connect a number of nearby CO₂ emitters and storage sites by using shared transportation
105 facilities, which would expedite the development of CCS (Sun et al., 2021a). This appreciably
106 reduces the overall costs and risks when compared to those of standalone projects. Examples

107 of proposed/conceptualized CCS clusters include the Northern Lights facility in Northern
108 Europe (Gough and Mander, 2022) and industrial hubs in the Permian Basin in Texas, United
109 States (Singh and Dunn, 2022).

110 2. Methods

111 As discussed above, our analysis focuses on evolving the past source-sink mapping
112 work that was carried out by Garg et al. (2017); we also introduce several methodological
113 improvements. Figure 1 shows the overarching framework that has been used in this study. The
114 following paragraphs describe the process of the identification of key CO₂ sources, the sinks
115 that were mapped out in this analysis, the data sources for the location, and the characterisation
116 of these sources and sinks. Furthermore, we discuss approaches for the demarcation of hubs
117 and clusters based on defined criteria and the costing methodology that has been used in the
118 analysis to prioritise the defined clusters.



119

120 *Figure 1: Methodological framework for this analysis*

121 2.1. Identifying large point sources of India

122 In line with the previous study by Garg et al (2017), we focussed on five types of large point
123 sources (LPS). These were power, steel, cement, fertilizers and refineries. These sectors
124 represent an estimated 69% of India's CO₂ emissions spread out across 23 states. Considering
125 the wide range of sources with disparate emissions, a geographic information system (GIS)
126 platform was soft-linked to estimation of emissions associated with such infrastructure.

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

129 The power sector has been accompanied by several key changes since the past source-sink
130 analysis was published. One major policy initiative is the increased penetration of biopower
131 plants: both through blending as well as in standalone plants. As such, we mapped out biopower
132 plants in addition to coal and gas fired power plants. Note that CO₂ emissions from biopower
133 plants and other biogenic sources are considered as zero. However, in the CCS clusters, they
134 do emit CO₂ emissions, capturing and storing which then entail so-called “negative emissions”
135 (Bui et al., 2018; Muratori et al., 2020). The data for the locations and the capacity for power
136 plants was downloaded from the World Resources Institute. This dataset was filtered on the
137 basis of primary fuel type. The capacity of these power plants was multiplied by a capacity
138 factor of 81.5%, based on the average utilization rate published by the Central Electricity
139 Authority (CEA). Some plants also have a lower capacity factor due to intermittent fuel
140 shortages, cooling water scarcity and so forth. However, Singh et al., (2017) have estimated
141 that CCS power plants with capacity factors lower than 80% will not be financially appealing
142 even with a carbon price of >\$100/t-CO₂. As such, the aforementioned capacity factor is
143 assumed as the standard value for all power plants. Use of a constant capacity factor also allows
144 for ease of comparison with the past analyses. A total of 192 LPSs were identified and mapped
145 on the basis of their CO₂ emission in Arc-GIS. The data sources were identified from
146 previously published work of Garg et al., (2017a) and other web sources (CIS, 2021; IBM,
147 2020; OGIS, 2022; PDIL, 2022; WRI, 2021). These LPSs include powerplants, cement,
148 fertilizer, steel, biomass plants and refineries. For the source clustering, only LPSs having more
149 than 1 Mt annual CO₂ emission were considered, whereas for source-sink matching, all 192
150 LPSs were considered. The emission factors from the IPCC Emission Factor Database are used
151 to estimate net-emissions.

152 Once the geospatial data for all the sources were collected and overlaid on the basemap, the
153 emissions associated with individual sources were calculated. This was done by multiplying
154 the production of the relevant product of the facility by the emission factors shown in Table 1.
155 A notable feature of the emission factors assumed in Table 1 is that they correspond to national
156 averages in India for the key sectors, which may be different from global averages. For
157 instance, the higher-efficiency, low-emission plants in China have an average emission factor
158 of <0.8 t-CO₂/MWh. However, because of higher-ash coal and lower plant efficiency in older

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

161 **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)

162

163 **2.2. Identifying CO₂ sinks**

164 CO₂ storage is considered in three type of formations: saline aquifers, enhanced oil recovery
165 (EOR) and enhanced coalbed methane (ECBM), in this study. While other analyses do project
166 a substantial basalt storage capacity in India, it is not considered due to lower technological
167 readiness. A total of 26 sedimentary basins that cover an area of 3.4 million sq. km (DGH,
168 2020) represent enormous CO₂ storage potential in India. However, only seven are deemed at
169 a high storage readiness level (Vishal et al., 2021b). The accurate estimation of the storage
170 potential of any reservoir depends on the volume of data available; therefore, the cumulative
171 CO₂ storage capacity in India has varied over time. Previous studies have indicated storage
172 capacities of between 105 and 572 Gt across saline aquifers, basalts and depleted oil and gas
173 reservoirs in India (Dooley et al., 2005; Holloway et al., 2008; Kearns et al., 2017; Singh et al.,
174 2006). However, our recent analysis has indicated 291 Gt of effective CO₂ storage capacity in
175 saline aquifers and 97–316 Gt in basalt formations, which is significant. EOR and ECBM could
176 provide an additional 2.9 Gt and 3.7 Gt of CO₂ can be stored in depleted oil and unminable
177 coal reservoirs, respectively (Vishal et al., 2021b). Although these capacities are significantly
178 lower than those of saline aquifers (Table 2), the financial incentives and ready infrastructure
179 that is available for storage through these pathways render them much more lucrative as sinks.
180 Even the CCUS Roadmap for India by the Technology Information, Forecasting and
181 Assessment Council (TIFAC, 2018) has recommended CO₂-enhanced oil recovery (EOR) and
182 enhanced coalbed methane (ECBM) recovery as the primary drivers to implement CCS at a

183 large scale in India. The more recent 2030 Roadmap for CCUS for oil and gas sector in India
184 lists several policy recommendations in short, medium and long term and also identify key
185 projects on EOR and ECBMR for CO₂ storage with/without petroleum recovery (MoPNG,
186 2022).

187

188 Storage reservoirs are often spread across large geographical areas with volumes >2000 km³.
189 As such, the Euclidean centres for these reservoirs are considered at the location of injection
190 in this source-sink analysis. In order to locate the Euclidean centre for the reservoirs, the
191 reservoir shapefiles were adapted from our previous work (Vishal et al, 2021b) and the “Find
192 Centroid” tool was used in ArcGIS. Vishal et al (2021b) and others (Holloway et al., 2009)
193 have reported that locations with promising saline aquifers are often co-located with oil and
194 gas reservoirs. Thus, the key sedimentary basins analyzed in our study are shown in Table 1.
195 These basins were selected because they have active oil and gas extraction being carried out
196 for the past several decades. CO₂-EOR operations generally commence when the primary and
197 secondary extraction approaches have been used, and CO₂ could be instrumental in recovering
198 residual oil in place. Vishal et al (2021b) concluded that these seven basins have 3.4 Gt-CO₂
199 sequestration capacity within oil and gas reservoirs. The cumulative hydrocarbon in place in
200 these basins is 11023 MMTOE and the above capacity is estimated by assuming that 10% of
201 this repository could be extracted with CO₂ injection.

202 While the above basins are prominent for oil and gas extraction, they are also considered as
203 “Category I” basins for storage in saline aquifers. These basins have adequate reservoir data
204 available for the hydrocarbon industry and also the Directorate General of Hydrocarbons. The
205 cumulative CO₂ storage capacity in these basins is 108.66 Gt-CO₂. Note that there are an
206 additional 19 “Category II” and “Category III” basins where another 182 Gt-CO₂ may be stored
207 in saline aquifers. However, these basins are not incorporated into our analysis due to large
208 data uncertainty, low storage prospectivity and often, lower storage capacities in many of these
209 basins.

210 ***Table 2: Sedimentary basins with CO₂ storage potential via EOR as well as aquifer injection***
211 ***considered in this study (data adapted from Vishal et al, 2021b)***

Basins	EOR	Saline aquifers
--------	-----	-----------------

	EOR (at 10%) (MMTOE)	CO₂ storage capacity (Mt)	Depth classification	Lithology	Volume	CO₂ storage capacity (Gt-CO₂)
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

212 Coal in India occurs through more than 16 operational coalfields and several unallotted coal
213 blocks. While initial expert elicitations showed the coalbed methane (CBM) extraction could
214 be feasible in several of these, on-the-ground operations have revealed that only four of these
215 have appealing resources: Raniganj, Jharia, East Bokaro and North Karanpura. Incidentally,
216 these coalfields are all located within proximity of each other (within a 300 km radius) and are
217 considered within the Damodar Valley basin. Thus, the entire basin is considered as a single
218 reservoir. The cumulative storage capacity - based on relative methane and CO₂ sorption
219 capacities – of these coalfields is 57 TCF or 1.42 Gt-CO₂. It may be noted that these estimates
220 vary widely based on the methodology used and assumptions surrounding the rate of coal
221 extraction in such coalfields.

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

236 2.3. Source-sink mapping

237 Once sources and sinks of CO₂ are separately mapped out on ArcGIS, we consider the “hubs
238 and clusters” concept for demarcation of suitable regions with high CCS potential. This concept
239 essentially demarcates “clusters”, i.e., regions with high density of LPS and adjoining CO₂
240 storage locations. In some cases, the storage location may not be conveniently located in close
241 proximity to the sources. These cases require dedicated “hubs”, which are locations where CO₂
242 from all the LPS may be transported to, and then cumulatively transported to the storage
243 location to introduce economies of scale. In some regions, the storage location may be
244 fortuitously located near the centre of the LPS and it may automatically be designated as the
245 “hub”.

246 In our analysis, we did not consider sector-specific clusters. Instead, all sectors were assumed
247 to potentially contribute to a particular cluster. This is because the Garg et al (2017b) work
248 already showed that integrated clusters showed a cost optimization of \$10/t-CO₂ over sector-
249 specific clusters. We used the “Shortest route” function in ArcGIS for each cluster in different
250 combinatorial sink locations and the storage locations were demarcated as the following (Garg
251 et al., 2017b):

$$252 \quad X_{storage} = \sum_{S=1}^5 \left(\frac{\sum x_i e_i}{\sum e_i} \right) + \Delta_x \quad \text{Eq. 1}$$

$$253 \quad Y_{storage} = \sum_{S=1}^5 \left(\frac{\sum y_i e_i}{\sum e_i} \right) + \Delta_y \quad \text{Eq. 2}$$

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

261 **2.4. Costing analysis**

262 The cost estimation was carried out for each of the clusters visualized based on the
 263 aforementioned methods. The cost components estimated here are: cost of CO₂ capture, cost
 264 of CO₂ transportation, costs associated with CO₂ storage (including injection and monitoring)
 265 and also, any revenues (negative costs) based on additional resource recovery in the case of
 266 EOR and ECBM. All the costs are estimated based on a per t-CO₂ basis with the relevant
 267 parameters shown in Table 3.

268 **Table 3: Cost parameter assumptions for CCS supply chain**

Parameter	Cost	Reference
CO₂ capture (values in \$/t-CO₂)		
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)
CO₂ transport (\$/t-CO₂/km)		
Pipeline transport	0.01	(Singh et al., 2020)
CO₂ storage (\$/t-CO₂)		
Saline aquifers	9-30	Based on reservoir parameters; calculated in IECM framework
EOR	Negative (15-31)	
ECBM	Negative (5.2)	

269
 270 Depending on the point source, the costs of CO₂ capture may be similar or higher for the Indian
 271 context, as compared to global analogues. For instance, the capture cost for a coal-fired power
 272 plant (\$54/t-CO₂) is nearly the same as those based in the United States (Pilorgé et al., 2020).
 273 However, the capture costs for gas-fired power plants is about 50% higher in India due to
 274 historically lower capacity factors for such plants and increased costs of imported natural gas
 275 (Singh and Sharma, 2016). In the case of sectors where considerable CCS experience already
 276 exists in India – such as fertilizers – the capture costs are close to the lower bounds of global
 277 averages.

278 The costs for CO₂ capture and storage were adapted from the literature, as shown in Table 3.
 279 Storage costs were calculated separately for each basin. The Integrated Environmental Control
 280 Model (IECM), developed at the Carnegie Mellon University, was used for these estimations.
 281 IECM is a graphical-user interface software and accepts the reservoir parameters (thickness,

282 depth, temperature, porosity and permeability) to yield the storage costs. For EOR and ECBM,
283 we also assumed that the market price of crude oil and methane are \$60/bbl and \$6/mmBtu.

284 **3. Results and Discussion**

285 **3.1. Evaluating CO₂ capture prospects from large point sources**

286 ***3.1.1. Power sector***

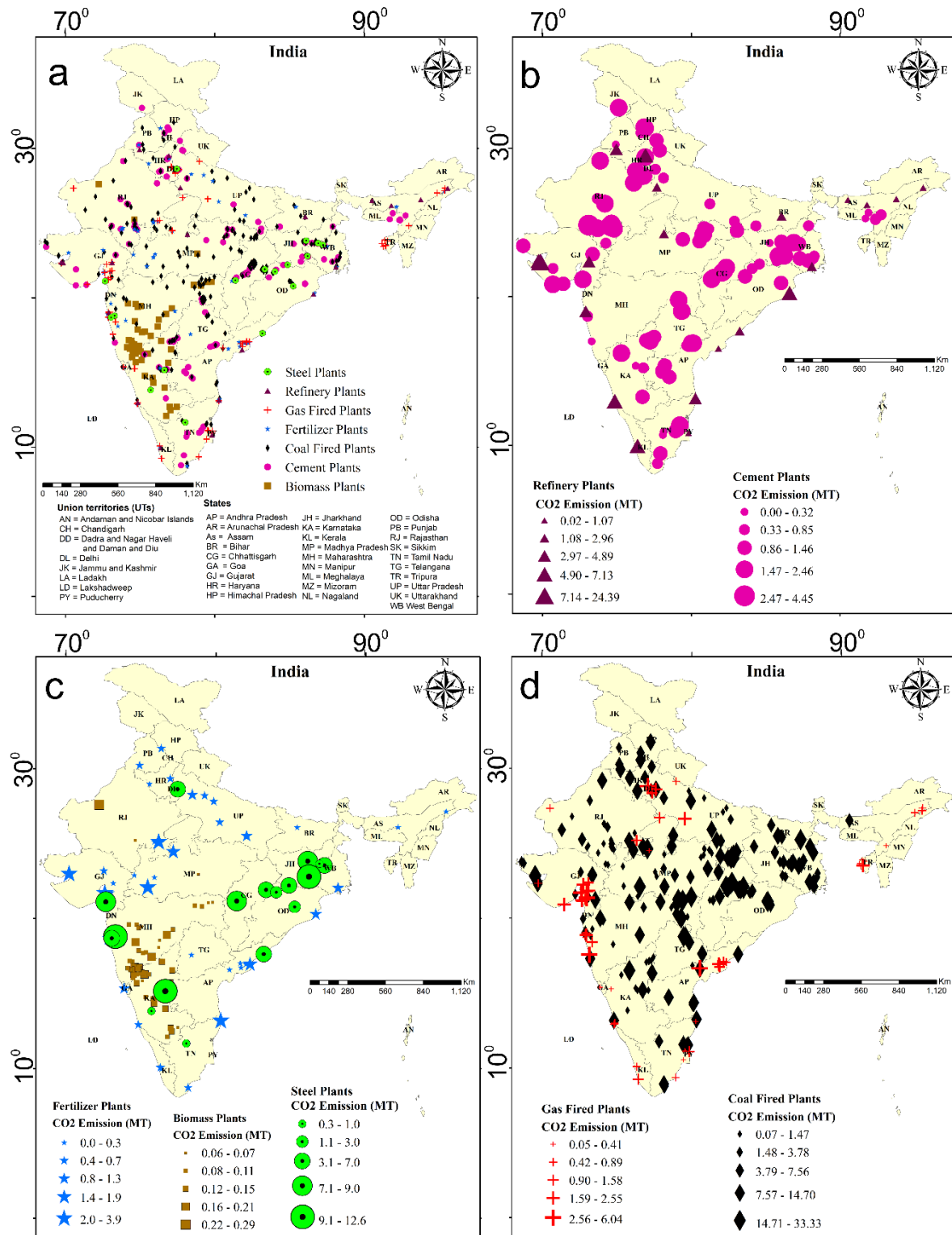
287 We describe the power sector and industrial sources separately due to a number of reasons.
288 First, most of the existing costing literature on CCS in India is related to the power sector
289 (Singh et al., 2017a; Yadav et al., 2016), which provides lesser uncertainty to the cost
290 parameters assumed in Table 3. Second, the power sector has a disproportionately large share
291 of LPS emissions in India due to a higher share of coal in the energy mix. This is different from
292 economies such as the United States, where the transport sector is the highest CO₂ emitter.
293 Third, because of the regulatory structure of the Indian government, the power sector's control
294 is exercised by a single ministry, whereas the industrial sector comes within the oversight of
295 several different ministries (Garg et al, 2017). Finally, the capture technologies associated
296 within the power sector may be different from say, the refinery sector, where the CO₂ stream
297 is derived from multiple different unit operations (Yao et al, 2017).

298 Figure 2 shows the locations and emission intensity associated with key large point sources in
299 India. The maps deliver several pieces of interesting insights. For instance, there is a
300 concentration of large number of coal-fired power plants in the central India. Gas-fired power
301 plants, on the other hand, are located towards northern India as air pollution concerns have
302 created a momentum towards coal phasedown in the region. For instance, the Badarpur power
303 station was shut down as 30-40 % of Delhi's air pollution could be attributed to it. Some
304 pockets of gas-fired plant clusters may also be seen in the western, northeastern and east coastal
305 parts of India due to proximity to indigenous gas resources. The capacity of bioenergy power
306 plants has also been notable with total emissions of 6 Mt-CO₂. This is largely due to co-firing
307 with coal power plants in western India, though such trends are likely to intensify in the future
308 (section 2.4). Currently, there is a presence of biopower infrastructure in Maharashtra,
309 Karnataka, Haryana and Gujarat, in addition to smaller units in other states.

310 As noted earlier, India's annual CO₂ emissions were 2.6 Gt-CO₂ in 2019. Large point sources
311 emit around 80% of this CO₂, which makes CCS retrofitting an appealing possibility. In our
312 analysis, we did not consider all types of LPS due to data limitations. Specifically, our analysis

313 accounts for 1.88 Gt-CO₂ emissions or more than 96% of the LPS emissions. Our analysis
314 shows the relative influence of the power sector in India's GHG emission inventory. For
315 instance, coal-fired power plants alone emit 1.43 Gt-CO₂. This trend has intensified since prior
316 national analysis of GHG inventory, due to commissioning of several new subcritical and
317 supercritical units in existing coal-fired power plants. Moreover, there has been a thrust on
318 larger power plants to increase their capacity factors. Consider the case of the Vindhyachal
319 Super Thermal Power Station in Madhya Pradesh, which is the largest LPS in the country with
320 a capacity of 4,760 MW. The power plant registered a 100% capacity factor last year and the
321 last unit addition for the plant occurred in 2015. As such, the emissions associated with the
322 plant have increased both due to increased capacity and capacity factor. Other large power
323 plants with capacity factors above 90% include: Kahalgaon, Sipat, Talcher and Sasan. This is
324 relevant because expert elicitations indicate that while capacity additions of coal may slow
325 down, increased utilization of existing facilities may add the use of 300 Mt-coal over the next
326 decade. This corresponds to increased CO₂ emissions of 860 Mt-CO₂ by 2030. Interestingly,
327 most of these plants are towards the central part of the country, which has interesting
328 ramifications in terms of hubs and cluster formation, as discussed later.

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



339

340 **Figure 2: Locations and CO₂ emission intensities of all large point sources in India. (b)**
 341 **only for cement industries and refineries. (c) only for steel plants, biomass and fertilizer**
 342 **plants. (d) only for coal and gas-fired power plants**

343

344

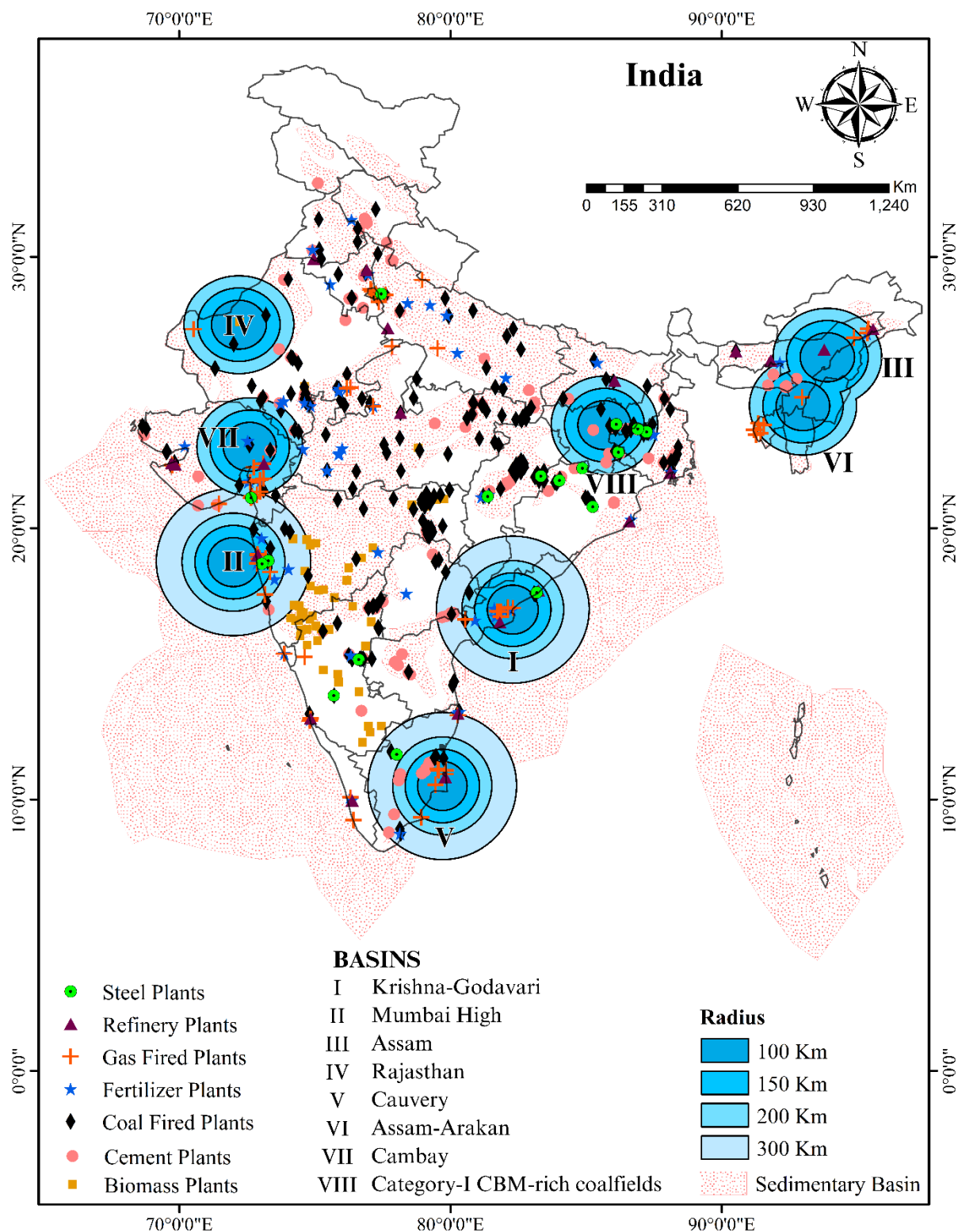
345 **3.1.2. Industrial sector**

346 In addition to the power sector, industrial sectors (steel, cement, fertilizer, refinery) emitted
347 ~600 Mt of CO₂ into the atmosphere. The global CCS literature has provided prominent
348 coverage to industrial sources of CO₂, particularly in developed economies. For instance,
349 Pilorge et al (2020) estimate a CO₂ avoidance potential of 69 Mt-CO₂ at <\$40/t-CO₂. The
350 avoidance potential here may be defined as the reduction in CO₂ emissions without changing
351 the total produced power/commodity at a given cost. One of the reasons here is the decreasing
352 emissions of power sector CO₂ emissions in such countries, which is not the case for India.
353 Nevertheless, our analysis does provide locations where such conditions may be feasible. For
354 instance, steel plants are largely concentrated in eastern and western India due to ease of
355 sourcing of indigenous and imported coking coal respectively. Cement and fertilizer plants, on
356 the other hand, are present throughout the country due to the ubiquitous demand for these
357 products.

358 In India, several key opportunities for industrial CO₂ capture do exist. For instance, we estimate
359 47 Mt-CO₂ from the fertilizer sector. The Indian fertilizer market is anticipated to register a
360 11% CAGR in production over the next five years, with the government considering an
361 additional subsidy of \$3.8 billion. This sector also exhibits a technological readiness for CO₂
362 capture with the Jagdishpur fertilizer plant capturing 150 t-CO₂ daily for internal reuse. With a
363 lower cost of CO₂ capture, there may be a possibility for this sector to pivot to CCS. Other
364 opportunities may exist in the cement sector which emit close to 148 Mt-CO₂ based on our
365 analysis. The Dalmia cement group recently announced plans to retrofit one of their facilities
366 to capture 0.5 Mt-CO₂. The steel sector emits 180 Mt-CO₂ based on a total capacity of 144 Mt.
367 This is anticipated to almost double based on government policy initiatives over the next
368 decade. While the cost of CO₂ capture in this sector is similar to the power sector, there has
369 been a recent industrial breakthrough with Tata Steel commissioning a modular 5 t-CO₂/day
370 capture facility. India also ranks first and second in sponge iron and crude steel production,
371 respectively, which is a result of a rapid increase in high-capacity steel plants since 2005.
372 However, since the efficiency of the plants has increased over time, the CO₂ emission per ton
373 of steel produced has steadily decreased, and it currently stands at 2.5 tCO₂/ton of crude steel.
374 This has resulted in a decreasing cumulative emission of CO₂ from the steel sector since 2015
375 (MoS, 2020).

376 Emissions from refineries and other fuel production sectors contribute 89 Mt CO₂e annually.
377 The greenhouse gas (GHG) emission from refineries in India has increased 150 % between
378 2005 and 2019 due to the rapidly increasing capacity for refining. Of particular interest here is
379 the Jamnagar refinery, which is the world's largest refinery and emits 24 Mt-CO₂ annually.
380 While we discuss the geographical context of this LPS later, it has been deemed as a facility
381 that could enhance the blue hydrogen production at \$1.2-1.5/kg-H₂. This could reduce
382 significant CO₂ emissions here. However, refineries are composed of several CO₂ streams in
383 addition to steam methane reformation (where hydrogen is produced). Particularly, the catalytic
384 cracking unit leads to the largest process emissions within a refinery. Multiple CO₂ emissions
385 add an addition layer of complexity to CO₂ capture from refineries.

386 **3.2. Identifying potential CCS clusters based on source-sink matching**



387
 388 **Figure 3: Identified source-sink clusters for key sedimentary basins and coalfields in**
 389 **India. The concentric circles represent radial distance from the euclidian center of each**
 390 **sink.**

391 As discussed above, source-sink clusters in this study were designed in such a way that
392 optimized the transport cost by reducing the CO₂ transport distance. Having a large number of
393 emission intensive sources also reduced the storage cost due to economies of scale. It was
394 observed that the formation of integrated clusters enabled cost optimisation through sectoral
395 collaboration of industrial partners. Seven clusters were identified in this study around EOR
396 basins and saline aquifers (which occur at similar locations due to their occurrence in
397 sedimentary basin). Based on the abundance of CO₂ sources and their proximity to sink
398 reservoirs, a total of 244 LPSs and seven Category I sedimentary basins (four onshore and three
399 offshore basins) were considered as part of these sinks. By definition, these Category I
400 reservoirs have a higher accessible volume, which implies a higher CO₂ storage capacity.
401 Additionally, extensive studies on these basins have rendered the feasibility assessment of
402 these basins for CO₂ storage easier. For this study, we considered clusters of LPSs that were
403 present within certain distances from the sinks. For the onshore basins, we considered LPSs
404 within 200 km of the sink. In contrast, we considered LPSs within 300 km for offshore basins,
405 because the offshore basins had a higher reservoir capacity than their onshore counterparts.
406 Our study shows that 62 LPSs (32%) of the sources are within a distance of 100 km from the
407 sinks in these seven clusters, whereas 85 LPSs (43%) and 55 LPSs (25%) are within 100–200
408 km and 200–300 km, as shown in Figure 3 and Supplementary Figure 1. It was observed that
409 coal-fired powerplants were significant contributors to the LPS frequency and to the total
410 annual emission in each cluster.

411 **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)
<i>Sedimentary basins (Category I oil and gas basins)</i>						
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
<i>Coalfields (Category I CBM basins)</i>						

Damodar Valley	120	29	116	71	39	3.60
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412

413 Analysis of these clusters reveals several interesting insights (Table 4). First, the maximum
414 abundance of emissions occurs near the Mumbai High basin (81 Mt-CO₂/year). This cluster
415 contains 33 LPS and is actually dominated by industrial sources which contribute to 51% of
416 the emissions here. Particularly, three steel plants near the basin emit 25 Mt-CO₂. This basin is
417 an offshore basin, due to which the distance of most LPS is high, with the average LPS being
418 152 km away from the Euclidean centre of the basin. This necessitates creation of an onshore
419 hub, where the CO₂ streams from various LPS may be assembled and then cumulatively
420 sequestered. The Krishna-Godavari basin may also be treated as a promising cluster with
421 adjoining emissions of 72 Mt-CO₂. Out of these, 78% emissions are from the power sector.
422 Analysis by Garg et al (2017) found that the emission clusters would develop around large
423 UMPPs with each of such plants emitting 28-29 Mt-CO₂. Because of evolving conditions of
424 lesser new plants coming online and addition of newer units on existing plants, this may not
425 always be the case. Thus, the Krishna-Godavari basins has 14 power plants in close proximity,
426 which emit an average of 4 Mt-CO₂. This is a major change in the ways clusters are likely to
427 be designed in the Indian context. Similar trends are seen in the Cauvery and Cambay basins
428 where adjoining emissions are 65 Mt-CO₂/year and 49 Mt-CO₂/year respectively. Again, the
429 average emission from a power plant in these clusters is only 3.5 Mt-CO₂/year and 2.5 Mt-
430 CO₂/year respectively, thus highlighting the increasing importance of several mid-sized power
431 plants to the formation of clusters.

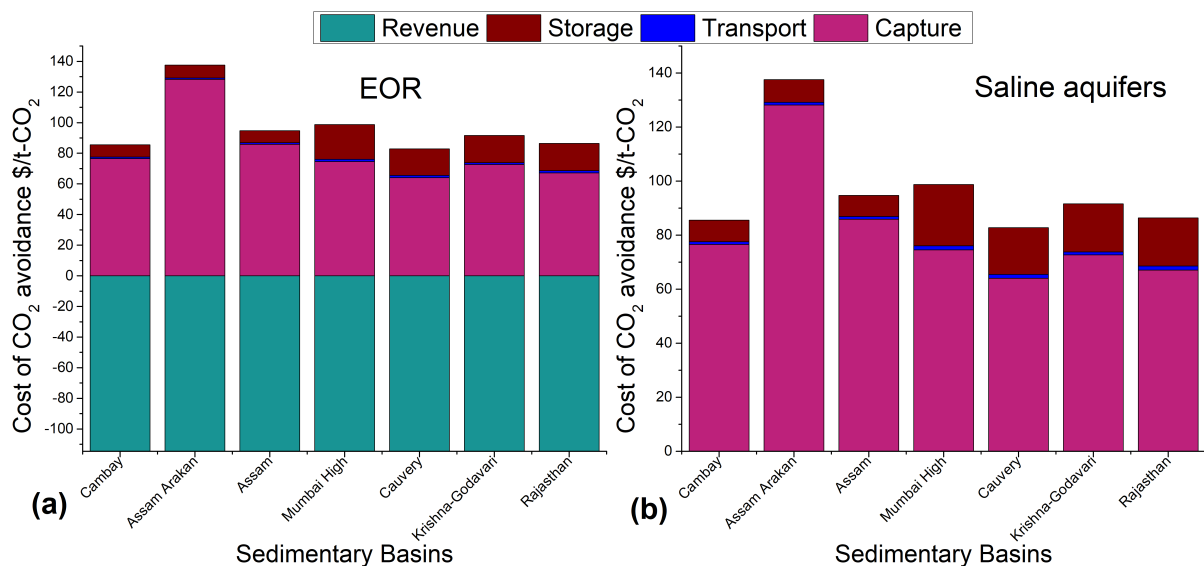
432 Onshore basins are associated with lower emissions in close proximity. This is partly due to
433 lower density of infrastructure around the states considered (e.g. Assam) and also because of
434 more restrictive assumption around such clusters. Emissions around the Assam Basin and the
435 Assam Arakan basins are cumulatively only 3.7 Mt-CO₂. At such rates, the cost of emissions
436 are likely to be higher. Even though there is an opportunity for ~700 Mt-CO₂ sequestration via
437 EOR, it may not be utilized because there are minimal CO₂ sources nearby. This is similar to
438 the concept of “CO₂ deserts” proposed by Middleton et al. (2014), where there is a source-sink
439 “mismatch” at some locations.

440 The Damodar Valley coal basin in eastern India, particularly with four key coalfields
441 (Raniganj, Jharia, East Bokaro and North Karanpura) may be very suitable for formation of
442 clusters and sub-clusters. This was also suggested by Garg et al (2017), though there analysis

443 hinged on provision of CO₂ from three UMPPs (Deoghar, Banka and Tilaiya). As such, they
 444 estimated the availability of 218 Mt-CO₂/year in close proximity to the region. Our analysis
 445 shows that even in the absence of these UMPPs, this cluster still has 120 Mt-CO₂/year in
 446 proximity. This includes annual emissions of 85 Mt-CO₂ from power plants and the remaining
 447 35 Mt-CO₂ from the industrial sector, thus depicting large diversity of sources.

448 3.2.1. Costs of CCS deployment at scale

449 The costs of capture, transport, storage and additional revenue (for EOR and ECBM) were
 450 calculated for each cluster on a \$/t-CO₂ basis (Figure 4). One of the key features of this study
 451 is that we have developed a more detailed estimate of the storage costs as compared to past
 452 work, where a default value was assigned to the parameter.



453 Sedimentary Basins
 454 **Figure 4: Overall system cost of avoidance for sedimentary basins for storage in (a) EOR**
 455 **reservoirs and (b) saline aquifers**

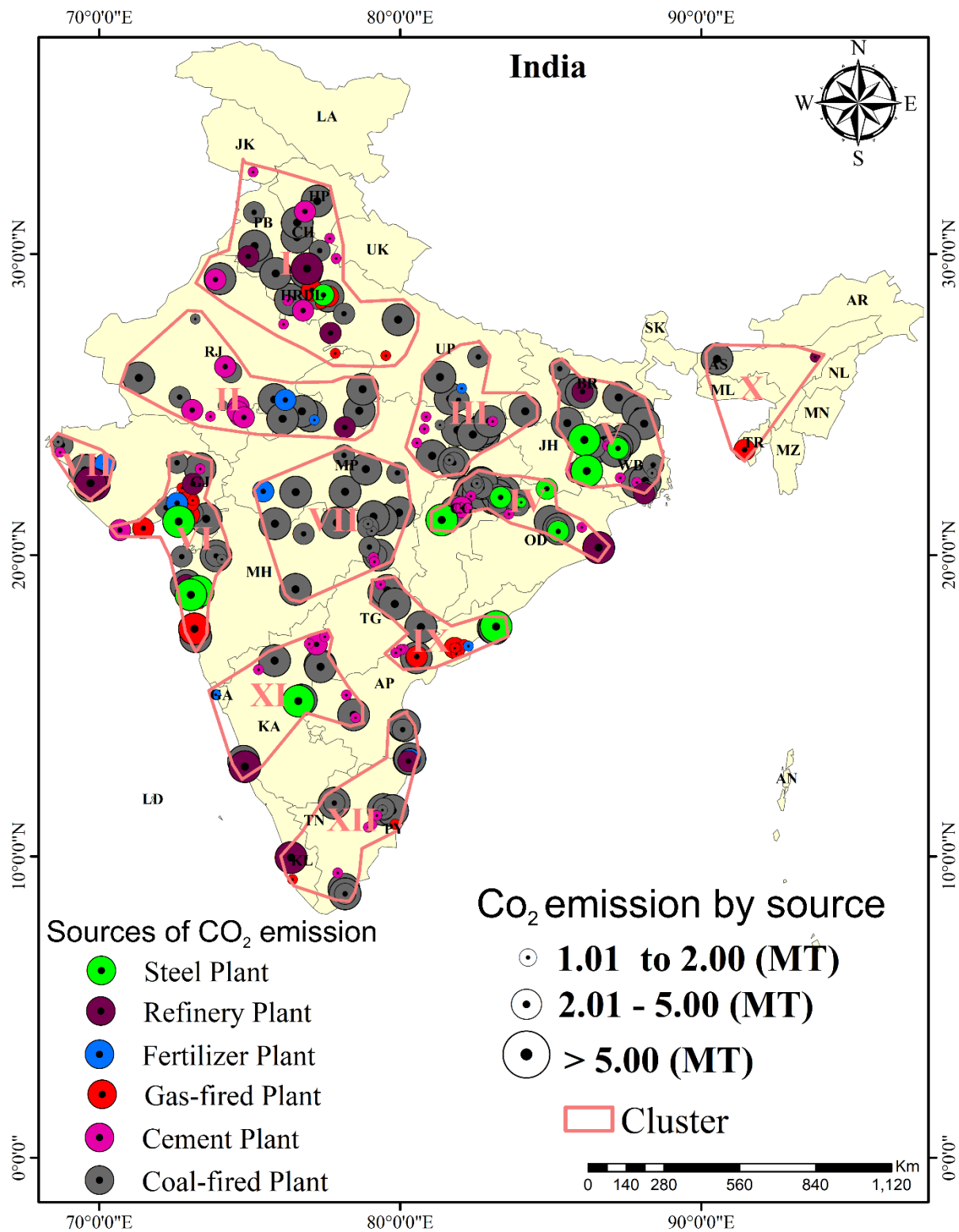
456
 457 The results for saline aquifers show that the overall cost for CCS in India is substantially higher
 458 than global averages (Clarke et al, 2022). This is, in part, due to higher capture costs at coal-
 459 fired power plants due to high ash content and lower efficiency. If we exclude the Assam
 460 Arakan Basin due to low emission sources in proximity, the costs of CO₂ avoidance are \$87-
 461 107/t-CO₂. This is notably due to higher storage cost (\$9-30/t-CO₂) of Indian aquifers. These
 462 aquifers often occur at a higher depth and a lower thickness. Moreover, the permeability is
 463 assumed at a default value of 40 mD, which is a conservative estimate. The economic prospects,
 464 however, change when EOR system costs are evaluated. The past study by Garg et al (2017)
 465 assumed a low crude oil price of \$15/bbl, and accordingly EOR storage costs were around \$-

466 16/t-CO₂. Our analysis assumes a crude oil price of \$60/bbl based on current market conditions
467 and an EOR effectiveness of 1.91 bbl/t-CO₂. This makes the overall system profitable by
468 reducing the total system costs to negative \$31-15/t-CO₂. The system costs present an
469 interesting tradeoff. For instance, we discussed that the Mumbai High basin has a suitable
470 prospect for EOR based on proximity to LPS. However, this cluster has a higher avoidance
471 cost due to a low storage coefficient of 1.5%. Storage in coal basins is somewhat towards the
472 middle of the two sedimentary basin cases and offers a overall system cost of \$60/t-CO₂. We
473 do caveat these results by saying that data limitations have led us to assume default values for
474 critical parameters. As such, these metrics may be treated as indicative and we suggest further
475 refinements based on field data.

476 **3.3. Key opportunities for CCS deployment in proposed clusters**

477 One aspect in which we have helped evolve the findings of Garg et al (2017) is by incorporating
478 the actual storage potential estimates. In previous work, the emissions surrounding the clusters
479 were estimated and it was assumed that sinks would contain the adequate storage capacity. This
480 work presents further nuance on that. For instance, it is likely that the initial preferred storage in
481 sedimentary basins would be EOR, followed by injection into saline aquifers as they are co-
482 located. Similarly, in the case of coalfields, ECBM would be preferred followed by injection
483 without incremental CBM recovery by considering all constraints in doing so (Pashin et al.,
484 2018). CCS hubs and cluster strategy is often iterated as an effective strategy to share the
485 responsibility of developing full-scale CCS projects. CCS chains developed with this strategy
486 also has a potential to be independent of government subsidies upfront (Global CCS Institute,
487 2020). Responsibilities of establishing and expanding a hub can be shared among sharing
488 parties, thereby reducing overall cost and risk compared to standalone CCS initiatives
489 (Cavanagh and Ringrose, 2014; Sun et al., 2021b). Several implementations of hubs and cluster
490 based CCS chains including Rotterdam CCUS Porthos in the Netherlands, Sun and Chen
491 (2017) have validated the potential feasibility of this approach in NetZero Teeside in UK and
492 CarbonNet in Australia (Sun and Chen, 2017) attempted to construct a source-sink distance-
493 based hubs and cluster network for China by k-means clustering using InfraCCS based models.
494 All studies unanimously point towards a fact that this hubs and cluster model is more
495 economically viable when the sinks are involved in EOR or ECBM recovery, which may offset
496 the cost of capture, transportation and storage. For this study, we have used LPSs with > 1
497 Mt/yr CO₂ emission and based on their location and availability of sinks in proximity, 12
498 clusters have been formed (Figure 5). Here, we identify the key EOR and ECBM opportunities

499 identified with our clusters, followed by an understanding of the bioenergy with CO₂ capture
 500 and storage (BECCS) prospects in India.



501
 502 *Figure 5: The proposed hubs and clusters for implementing CCS network across India.*

503 **3.3.1. EOR feasibility**

504 Table 4 shows the amount of CO₂ that may be stored in each sedimentary basin with EOR
505 assuming that each cluster operates for 30 years. We discussed that the Mumbai High basin has
506 the largest number of sources in proximity. It also, fortitiously, has the largest EOR capacity
507 of 1.6 Gt-CO₂. As such, 65% of the CO₂ may be used to extract the incremental oil in the basin.
508 This value is lower for the Krishna-Godavari Basin (30%) and the Cambay Basin (45%),
509 depicting moderate economic feasibility if the EOR pathway is undertaken. The Cauvery Basin
510 contains only 100 Mt-CO₂ EOR potential, which means that it is likely to rely on storage in
511 saline aquifers. One key trend that is notable here is the potential deployment of EOR in the
512 Cambay Basin with CO₂ sourced from the Indian Oil Koyali Refinery. This project is currently
513 in the design and feasibility stages, and is anticipated to capture 5000 t-CO₂/day. This has also
514 been highlighted by Patange et al. (2022) who note that availability of CO₂ sources in proximity
515 could make EOR viable even below a crude oil price of \$45/bbl.

516 The Rajasthan basin may sequester 88% of the CO₂ with EOR and the Assam and Assam-
517 Arakan basins may sequester all the available CO₂ with EOR. In fact, the emissions adjoining
518 the Assam Basin are only 8% of the EOR capacity over a 30-year period. Our past work
519 reflected on potential opportunities in India where CO₂ could be captured from the ambient air
520 with direct air capture (DAC). Because CO₂ injection in the Assam Basin could help in
521 incremental oil recovery of 178 MMTOE, it is an opportune location for DAC, particularly
522 when paired with the revenues of the California Low-Carbon Fuel Standard, that may
523 incentivize a DAC facility anywhere. The electricity mix in Assam has also been decarbonized
524 with the Assam Solar Energy Policy targeting a 590 MW solar target, which could provide a
525 high carbon sequestration efficacy for such a project even after considering the emissions from
526 the produced oil.

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

531 ***3.3.2. ECBM feasibility***

532 The Damodar Valley cluster is highly emission-intensive with the emissions over 30 years
533 corresponding to 39% of the available ECBM capacity. This means that an incremental 19 TCF
534 of methane could be recovered over 30 years, that corresponds to 0.63 TCF annually. It is
535 notable that India's current liquified natural gas imports are 1.2 TCF. Thus, ECBM could be

536 an even more important technology in reducing India's import dependence than EOR. Several
537 studies have indicated on the massive ECBM potential of Damodar Valley coalfields (Chandra
538 and Vishal, 2022; Vishal et al., 2013c, 2013b, 2015a, 2018). Several CBM blocks in the
539 Damodar Valley are already seeing some level of peaking. For instance, the Raniganj Block of
540 Essar Oil Limited saw a CAGR of 111% during 2011-17 and peaked at around 14 BCF. Thus,
541 technical ECBM opportunities may open up over the next decade as production from more
542 wells of private and public players begin to peak.

543 As ECBM does not provide adequate storage capacity to the region's CO₂ emissions, it is also
544 important to understand possibilities to diversity storage opportunities. For instance, the
545 Rajmahal basalt traps contains a storage capacity of 4.5 Gt-CO₂. Similarly, Singh et al (2021)
546 project sizeable technical opportunities for storage in shale formations in the Damodar Valley.
547 While storage in shales is not technologically established yet, it might develop over the next
548 three decades and provide a backup storage opportunity. Several studies have shown that the
549 shale samples in the region have a very high total organic carbon content, which correlates with
550 high storage capacity per unit volume of shale (Chandra et al., 2020b, 2020a; Chandra and
551 Vishal, 2020; Vishal et al., 2019). More studies looking at these reservoirs from the perspective
552 of CO₂ storage are therefore recommended.

553 ***3.3.3. BECCS opportunities***

554 Multiple countries have mapped out the BECCS potential based on co-located bioenergy power
555 plants and CO₂ storage sites. Since, modelling results show higher BECCS requirements in
556 developed countries with high historical emissions, it has not been discussed in India. Our
557 results, however, help shed some light on the early opportunities for BECCS in India. Notably,
558 existing biopower plants emit 5.7 Mt-CO₂, which is low because the capacity of such plants is
559 generally <50 MW. However, NTPC recently announced that it plans for 5% co-firing are in
560 an advanced stage and the company has already ordered procurement of 3 Mt of biomass
561 pellets(Kannappan, 2022). If we consider 5% co-firing for India's entire coal fleet, it would
562 correspond to 70 Mt-CO₂ biogenic emissions. Thus, there is an opportunity for India to
563 leverage so-called "negative emissions" or carbon dioxide removal from the atmosphere.

564 Apart from the electricity generating infrastructure, low-cost BECCS opportunities also exist
565 in the bioethanol sector, which is likely to grow in Gujarat (near the Cambay Basin). This could
566 also lead to a low-carbon transport fuel option with CO₂ capture possible at <\$45/t-CO₂. The
567 Government of India has announced plans to expand bioethanol production to 10 billion litres

568 by 2025. While such facilities have not been considered in this analysis due to data limitations,
569 it is another potential area of future research.

570 **4. Conclusion**

571 While several advances have been undertaken in the CCS domain in India, system integration
572 analyses were lacking. Due to changing policy circumstances – especially with the
573 announcement of the net-zero target – there is an increased need for overarching assessment of
574 potential CCS clusters that could be developed in India. Our work looks at the existing LPS
575 and aims to understand locations where hubs and clusters may be developed. We discuss the
576 opportunities individually in the power sector and the industrial sector. The power sector offers
577 a large-scale decarbonization of close to 1.5 Gt-CO₂. Cases of co-firing biomass with coal, the
578 power sector could also be integrated with BECCS opportunities to readily offer negative
579 emissions. Our analysis also discusses regions where industrial CCS may be more relevant and
580 be helpful in reducing the emissions of hard-to-decarbonize sector. Here, we describe
581 initiatives that are already being undertaken in the steel, cement, fertilizer and refinery sectors.

582 The source-sink matching effort in this paper attempts to use our group's novel estimates on
583 the CO₂ storage capacity to describe seven clusters in sedimentary basins (with and without
584 EOR) and one cluster in the Damodar Valley coalfields in eastern India. Cumulatively, these
585 may sequester just over 400 Mt-CO₂/year. Over a 30-year duration, this corresponds to 12 Gt-
586 CO₂, which is coincidentally close to the CCS target estimated by global energy modelling
587 groups for India. We also carried out a first-order estimate of the costs of CCS in these clusters.
588 These are estimated to be \$87-107/t-CO₂ in saline aquifers, - \$31 to -\$15/t-CO₂ for EOR, and
589 \$60/t-CO₂. Financial revenues from EOR and ECBM are, therefore, necessary to jumpstart
590 CCS in India.

591

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596

597

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