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

Vishal, Vikram; Singh, Udayan; Bakshi, Tuli; Chandra, D.; Verma, Yashvardhan; Kumar Tiwari, Ashwari

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<u>Title Page</u>

1 Manuscript title:

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

Authors:

- 4 Vikram Vishal^{1,2,3*}, Udayan Singh⁴, Tuli Bakshi¹, Debanjan Chandra^{1,5}, Yashvardhan
- 5 Verma^{1,6,7}, Ashwani Kumar Tiwari⁸
- 6 ¹ Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai 400076, India
- 7 ² National Centre of Excellence in Carbon Capture and Utilization, Indian Institute of Technology
- 8 Bombay, Mumbai 400076, India
- 9 ³ Interdisciplinary Programme in Climate Studies, Indian Institute of Technology Bombay,
- 10 Mumbai 400076, India
- ⁴ Department of Chemical and Biological Engineering, Northwestern University, Evanston, IL,
 60208, United States
- ⁵ Department of Geoscience and Engineering, Delft University of Technology, 2628 CN, Delft, The
 Netherlands
- 15 ⁶ Department of Civil Engineering, Monash University, Melbourne, Victoria, 3800, Australia
- 16 ⁷ IITB-Monash Research Academy, Indian Institute of Technology Bombay, Mumbai, 400076,
- 17 India
- 18 ⁸ School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India
- 19

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*Address for correspondence:

Vikram Vishal, PhD Associate Professor Computational and Experimental Geomechanics Laboratory Department of Earth Sciences Indian Institute of Technology (IIT) Bombay Powai, Mumbai - 400076, India Ph: +91-22-2576-7254 Fax: +91-22-2576-7253 Web: https://www.geos.iitb.ac.in/index.php/vv/ Email: v.vishal@iitb.ac.in

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

24 Abstract

25

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

41

42 **1. Introduction**

India's CO₂ emissions have risen from 980 Mt-CO₂ in 2000 to 2630 Mt-CO₂ 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 CO₂ emissions 49 requires a number of technological platforms for decarbonisation. India's nationally 50 determined resolutions, which were submitted during the Paris Climate Agreement in 2015, 51 committed the nation to the reducing of the greenhouse intensity of the economy (the ratio of 52 GHG emissions to gross domestic product) by 33–35 %. The pledged reductions were primarily 53 based on potential additions to renewable-energy capacities by 2022. The capacity addition 54 goals have been met before time (Busby and Shidore, 2021). However, the Prime Minister of 55 India recently committed at the Glasgow Climate Summit that India would reach net-zero CO₂ 56 emissions by 2070. In light of this committment, India would likely need a much steeper 57 decline in CO₂ emissions, which will require the decarbonisation of existing large-point 58 59 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 60 with CO₂ capture and storage (CCS) (Davis et al., 2018; Fennell et al., 2021; Vishal et al., 61 2021a; Vishal and Singh, 2016). Analyses by the modelling community show that CCS would 62 be responsible for at least 15% of reductions in CO₂ emissions in net-zero energy systems (Baik 63 et al., 2021; Gabrielli et al., 2020). Currently operational CCS facilities can permanently store 64 40 Mt of CO₂ every year, which is far from the minimum 6000 Mtpa that is needed to meet 65 net-zero targets (Haszeldine et al., 2018). A massive gap seems to exist globally between the 66 current global CCS provision and that which is required to meet the anticipated CCS targets. 67

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-CO₂/year in 2 °C scenarios and ~1000 Mt-CO₂/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-CO₂ 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
CO₂ emissions.

Academic literature about India's CCS readiness is large, diversified and includes 80 81 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 82 83 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 84 85 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 86 87 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 88 developed newer estimates for such sinks (Vishal et al., 2021b). Second, nine ultra-mega 89 90 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, 91 regulatory and climate risks have led to the cancelling or postponing of several of these 92 UMPPs. Finally, there is an increased drive from the NTPC (previously referred as National 93 Thermal Power Corporation) to blend biomass in existing coal-fired powerplants. This could 94 be an avenue for carbon dioxide removal (CDR) for India. 95

96 To address these gaps, this study undertakes a new source-sink mapping, which incorporates new potential estimates, bio-infrastructure and investment decisions that were 97 98 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 99 100 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 101 limited hydrocarbon reserves, could benefit from a hubs-and-clusters strategy that promotes 102 the implementation of this CCS technology. The CCS hubs-and-clusters operations effectively 103 104 connect a number of nearby CO₂ emitters and storage sites by using shared transportation facilities, which would expedite the development of CCS (Sun et al., 2021a). This appreciably 105 reduces the overall costs and risks when compared to those of standalone projects. Examples 106

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



119

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Figure 1: Methodological framework for this analysis

121 **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 CO₂ 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. 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.

The power sector has been accompanied by several key changes since the past source-sink 129 analysis was published. One major policy initiative is the increased penetration of biopower 130 plants: both through blending as well as in standalone plants. As such, we mapped out biopower 131 plants in addition to coal and gas fired power plants. Note that CO₂ emissions from biopower 132 plants and other biogenic sources are considered as zero. However, in the CCS clusters, they 133 do emit CO₂ emissions, capturing and storing which then entail so-called "negative emissions" 134 (Bui et al., 2018; Muratori et al., 2020). The data for the locations and the capacity for power 135 136 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 137 138 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 139 140 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 141 even with a carbon price of >\$100/t-CO₂. As such, the aforementioned capacity factor is 142 assumed as the standard value for all power plants. Use of a constant capacity factor also allows 143 for ease of comparison with the past analyses. A total of 192 LPSs were identified and mapped 144 on the basis of their CO₂ emission in Arc-GIS. The data sources were identified from 145 previously published work of Garg et al., (2017a) and other web sources (CIS, 2021; IBM, 146 2020; OGIS, 2022; PDIL, 2022; WRI, 2021). These LPSs include powerplants, cement, 147 fertilizer, steel, biomass plants and refineries. For the source clustering, only LPSs having more 148 than 1 Mt annual CO₂ emission were considered, whereas for source-sink matching, all 192 149 LPSs were considered. The emission factors from the IPCC Emission Factor Database are used 150 151 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 $<0.8 \text{ t-CO}_2/\text{MWh}$. 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.

| LPS type | Unit Generation | Emission per unit generation (t-CO ₂) | Reference |
|---------------|-----------------|--|---------------|
| Coal-fired | 1 MWh | 0.98 | CEA, |
| power | | | (2019) |
| Gas-fired | 1 MWh | 0.43 | CEA, |
| power | | | (2019) |
| Biomass-fired | 1 MWh | 0.80 | Singh et al., |
| power | | | (2021) |
| Steel | 1 t | 1.85 | Garg et al., |
| Cement | 1 t | 0.9 | (2017a) |
| Refinery | 1 t | 1.1 | |
| Fertilizers | 1 bbl | 48.5 | Jing et al., |
| | | | (2020) |

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

162

163

3 2.2. Identifying CO₂ sinks

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

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 CO₂ storage with/without petroleum recovery (MoPNG,
2022).

187

Storage reservoirs are often spread across large geographical areas with volumes >2000 km³. 188 As such, the Euclidean centres for these reservoirs are considered at the location of injection 189 190 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 191 192 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 193 194 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 for the past several decades. CO₂-EOR operations generally commence when the primary and 196 secondary extraction approaches have been used, and CO₂ could be instrumental in recovering 197 residual oil in place. Vishal et al (2021b) concluded that these seven basins have 3.4 Gt-CO₂ 198 sequestration capacity within oil and gas reservoirs. The cumulative hydrocarbon in place in 199 these basins is 11023 MMTOE and the above capacity is estimated by assuming that 10% of 200 this repository could be extracted with CO₂ injection. 201

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 available for the hydrocarbon industry and also the Directorate General of Hydrocarbons. The 204 205 cumulative CO₂ storage capacity in these basins is 108.66 Gt-CO₂. Note that there are an additional 19 "Category II" and "Category III" basins where another 182 Gt-CO2 may be stored 206 207 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.

Table 2: Sedimentary basins with CO₂ 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– | 197.7 | 658.69 | Median | Sandstone | 6,900.00 | 13.39 |
| Godavari | | | | | | |
| 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 212 blocks. While initial expert elicitations showed the coalbed methane (CBM) extraction could 213 be feasible in several of these, on-the-ground operations have revealed that only four of these 214 have appealing resources: Raniganj, Jharia, East Bokaro and North Karanpura. Incidentally, 215 these coalfields are all located within proximity of each other (within a 300 km radius) and are 216 considered within the Damodar Valley basin. Thus, the entire basin is considered as a single 217 reservoir. The cumulative storage capacity - based on relative methane and CO₂ sorption 218 capacities – of these coalfields is 57 TCF or 1.42 Gt-CO₂. It may be noted that these estimates 219 vary widely based on the methodology used and assumptions surrounding the rate of coal 220 extraction in such coalfields. 221

222 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 223 satisfy the technical criteria for profitable CBM operations on the basis of depth, porosity, 224 permeability and gas resources (Singh and Hajra, 2018). This is also reflected in the field 225 226 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 the flow-deformation attributes of liquid and supercritical CO2 in coal from these basins 228 (Vishal et al., 2013c; Vishal 2017a, 2017b; Vishal and Singh, 2015). Preliminary numerical 229 models for Jharia and Raniganj coalfields indicate high potential for these coal to uptake CO₂ 230 with/without CBM recovery (Vishal, 2017a, 2017b; Vishal et al., 2015b, 2013a; Vishal and 231 Singh, 2015). Indeed, the tertiary coalfields in northeastern India generally occur at a shallower 232 depth (<300m) (Mishra and Ghosh, 1996). And while the Cambay Basin and Barmer-Sanchor 233 coalfields in Eastern India might be viable candidate purely from a geographical standpoint, 234 these are mostly lignite reserves with low gas production potential. 235

236 **2.3.** Source-sink mapping

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

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-CO₂ over sectorspecific 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):

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

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

261 **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.

| 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 | | | | |
| EOR | Negative (15-31) | parameters; calculated in | | | | |
| ECBM | Negative (5.2) | IECM framework | | | | |

268 Table 3: Cost parameter assumptions for CCS supply chain

269

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

The costs for CO₂ 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

285 3.1. Evaluating CO₂ capture prospects from large point sources

286 *3.1.1. Power sector*

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

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

As noted earlier, India's annual CO₂ emissions were 2.6 Gt-CO₂ in 2019. Large point sources emit around 80% of this CO₂, 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-CO₂ emissions or more than 96% of the LPS emissions. Our analysis 313 shows the relative influence of the power sector in India's GHG emission inventory. For 314 instance, coal-fired power plants alone emit 1.43 Gt-CO₂. This trend has intensified since prior 315 national analysis of GHG inventory, due to commissioning of several new subcritical and 316 supercritical units in existing coal-fired power plants. Moreover, there has been a thrust on 317 larger power plants to increase their capacity factors. Consider the case of the Vindhyachal 318 Super Thermal Power Station in Madhya Pradesh, which is the largest LPS in the county with 319 a capacity of 4,760 MW. The power plant registered a 100% capacity factor last year and the 320 321 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 322 plants with capacity factors above 90% include: Kahalgaon, Sipat, Talcher and Sasan. This is 323 relevant because expert elicitations indicate that while capacity additions of coal may slow 324 down, increased utilization of existing facilities may add the use of 300 Mt-coal over the next 325 decade. This corresponds to increased CO₂ emissions of 860 Mt-CO₂ by 2030. Interestingly, 326 most of these plants are towards the central part of the country, which has interesting 327 328 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 329 themselves. Even though a substantial capacity for gas plants exists (26 GW), the operational 330 capacity factor is low, i.e. 22.6%. This may partly be attributed to the low gas availability. For 331 instance, the 2017 gas requirement for these power plants 117 MMSCMD. However, the actual 332 gas supply remained at 31 MMSCMD or about 26% of this demand. That said, the development 333 of CCS hubs and clusters could lead to a financial incentive for CCS for two reasons. First, 334 many such plants could become part of integrated clusters close to larger coal power plants, 335 thus reducing the transport costs and infrastructural liability if they choose to retrofit with CCS. 336 337 Moreover, many CCS clusters might come around sites which could increase gas production through ECBM (discussed in section 2.4). 338





Figure 2: Locations and CO₂ 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

345 3.1.2. Industrial sector

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

In India, several key opportunities for industrial CO₂ capture do exist. For instance, we estimate 358 47 Mt-CO₂ from the fertilizer sector. The Indian fertilizer market is anticipated to register a 359 11% CAGR in production over the next five years, with the government considering an 360 additional subsidy of \$3.8 billion. This sector also exhibits a technological readiness for CO₂ 361 capture with the Jagdishpur fertilizer plant capturing 150 t-CO₂ daily for internal reuse. With a 362 lower cost of CO₂ capture, there may be a possibility for this sector to pivot to CCS. Other 363 opportunities may exist in the cement sector which emit close to 148 Mt-CO₂ based on our 364 analysis. The Dalmia cement group recently announced plans to retrofit one of their facilities 365 to capture 0.5 Mt-CO₂. The steel sector emits 180 Mt-CO₂ based on a total capacity of 144 Mt. 366 This is anticipated to almost double based on government policy initiatives over the next 367 decade. While the cost of CO_2 capture in this sector is similar to the power sector, there has 368 been a recent industrial breakthrough with Tata Steel commissioning a modular 5 t-CO₂/day 369 capture facility. India also ranks first and second in sponge iron and crude steel production, 370 respectively, which is a result of a rapid increase in high-capacity steel plants since 2005. 371 However, since the efficiency of the plants has increased over time, the CO₂ emission per ton 372 of steel produced has steadily decreased, and it currently stands at 2.5 tCO₂/ton of crude steel. 373 This has resulted in a decreasing cumulative emission of CO₂ from the steel sector since 2015 374 (MoS, 2020). 375

- Emissions from refineries and other fuel production sectors contribute 89 Mt CO₂e 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-CO₂ annually.
- 380 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
- 384 cracking unit leads to the largest process emissions within a refinery. Multiple CO₂ emissions
- add an addition layer of complexity to CO₂ 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 391 optimized the transport cost by reducing the CO₂ transport distance. Having a large number of 392 emission intensive sources also reduced the storage cost due to economies of scale. It was 393 observed that the formation of integrated clusters enabled cost optimisation through sectoral 394 collaboration of industrial partners. Seven clusters were identified in this study around EOR 395 basins and saline aquifers (which occur at similar locations due to their occurrence in 396 sedminentary basin). Based on the abundance of CO₂ sources and their proximity to sink 397 reservoirs, a total of 244 LPSs and seven Category I sedimentary basins (four onshore and three 398 399 offshore basins) were considered as part of these sinks. By definition, these Category I reservoirs have a higher accessible volume, which implies a higher CO₂ storage capacity. 400 Additionally, extensive studies on these basins have rendered the feasibility assessment of 401 these basins for CO₂ storage easier. For this study, we considered clusters of LPSs that were 402 present within certain distances from the sinks. For the onshore basins, we considered LPSs 403 within 200 km of the sink. In contrast, we considered LPSs within 300 km for offshore basins, 404 because the offshore basins had a higher reservoir capacity than their onshore counterparts. 405 406 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 100-200 407 408 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 409 annual emission in each cluster. 410

| 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) |
|------------------------------------|---|------------------|---|--|--|--|
| | Sediment | ary basins | (Category I o | il and gas bas | ins) | |
| Mumbai | 81 | 33 | 160 | 49 | 65 | 2.43 |
| High | | | | | | |
| Krishna- | 72 | 27 | 114 | 78 | 30 | 2.16 |
| Godavari | | | | | | |
| 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- | 2.0 | 6 | 102 | 22 | 100 | 0.06 |
| Arakar | | | | | | |
| Fold Belt | | | | | | |
| Assam | 1.7 | 2 | 82 | 38 | 100 | 0.05 |
| Coalfields (Category I CBM basins) | | | | | | |

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

| Damodar | 120 | 29 | 116 | 71 | 39 | 3.60 |
|---------|-----|----|-----|----|----|------|
| Valley | | | | | | |

412

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

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

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

448 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.



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

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453

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

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

476 **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 477 the actual storage potential estimates. In previous work, the emissions surrounding the clusters 478 479 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 480 481 sedimentary basins would be EOR, followed by injection into saline aquifers as they are colocated. Similarly, in the case of coalfields, ECBM would be preferred followed by injection 482 483 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 484 responsibility of developing full-scale CCS projects. CCS chains developed with this strategy 485 also has a potential to be independent of government subsidies upfront (Global CCS Institute, 486 2020). Responsibilities of establishing and expanding a hub can be shared among sharing 487 parties, thereby reducing overall cost and risk compared to standalone CCS initiatives 488 (Cavanagh and Ringrose, 2014; Sun et al., 2021b). Several implementations of hubs and cluster 489 based CCS chains including Rotterdam CCUS Porthos in the Netherlands, Sun and Chen 490 (2017) have validated the potential feasibility of this approach in NetZero Teeside in UK and 491 CarbonNet in Australia (Sun and Chen, 2017) attempted to construct a source-sink distance-492 based hubs and cluster network for China by k-means clustering using InfraCCS based models. 493 494 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 495 the cost of capture, transportation and storage. For this study, we have used LPSs with > 1496 Mt/yr CO₂ emission and based on their location and availability of sinks in proximity, 12 497 clusters have been formed (Figure 5). Here, we identify the key EOR and ECBM opportunities 498

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



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

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⁵⁰³ **3.3.1.** EOR feasibility

Table 4 shows the amount of CO_2 that may be stored in each sedimentary basin with EOR 504 assuming that each cluster operates for 30 years. We discussed that the Mumbai High basin has 505 the largest number of sources in proximity. It also, fortitiously, has the largest EOR capacity 506 of 1.6 Gt-CO₂. As such, 65% of the CO₂ may be used to extract the incremental oil in the basin. 507 This value is lower for the Krishna-Godavari Basin (30%) and the Cambay Basin (45%), 508 depicting moderate economic feasibility if the EOR pathway is undertaken. The Cauvery Basin 509 contains only 100 Mt-CO₂ EOR potential, which means that it is likely to rely on storage in 510 saline aquifers. One key trend that is notable here is the potential deployment of EOR in the 511 512 Cambay Basin with CO₂ sourced from the Indian Oil Koyali Refinery. This project is currently in the design and feasibility stages, and is anticipated to capture 5000 t-CO₂/day. This has also 513 been highlighted by Patange et al. (2022) who note that availability of CO₂ sources in proximity 514 could make EOR viable even below a crude oil price of \$45/bbl. 515

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

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

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.

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 Rajmahal basalt traps contains a storage capacity of 4.5 Gt-CO₂. Similarly, Singh et al (2021) 545 project sizeable technical opportunities for storage in shale formations in the Damodar Valley. 546 547 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 548 549 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 550 Vishal, 2020; Vishal et al., 2019). More studies looking at these reservoirs from the perspective 551 of CO₂ storage are therefore recommended. 552

553 3.3.3. BECCS opportunities

Multiple countries have mapped out the BECCS potential based on co-located bioenergy power 554 plants and CO₂ storage sites. Since, modelling results show higher BECCS requirements in 555 developed countries with high historical emissions, it has not been discussed in India. Our 556 results, however, help shed some light on the early opportunities for BECCS in India. Notably, 557 558 existing biopower plants emit 5.7 Mt-CO₂, 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 559 560 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 561 562 correspond to 70 Mt-CO₂ biogenic emissions. Thus, there is an opportunity for India to leverage so-called "negative emissions" or carbon dioxide removal from the atmosphere. 563

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.

570 **4. Conclusion**

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

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

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