Potential matching of carbon capture storage and utilization (CCSU) as enhanced oil recovery in perspective to Indian oil refineries

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Abstract
Carbon capture storage and utilization is not a new technology, but its application to reduce CO2 emissions from the refinery sector is just now emerging as promising mitigation. This study will look closely at opportunities to match CO2 sources with potential sinks by matching carbon-capturing projects at Indian oil refineries with Enhanced Oil Recovery (EOR) operations at nearby oil fields in India. This study has identified four such pairings of source-sink matching along with the challenges the first of the kind implementation of CCSU technology in specific projects. The study concludes with a discussion on the way forward and policy implications for the commercial use of the CCSU in India.

Graphical abstract
CCS Carbon Capture Storage; CCU Carbon Capture Utilization, EOR. Source: Authors’ design.

Keywords Carbon capture storage and utilization (CCSU) · Post-combustion · Pre-combustion · Oxyfuel combustion · EOR · Amine-based solvents · CO2 · CCS · CCUS

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**Introduction**

Carbon capture storage and utilization (CCSU) is a method to capture carbon dioxide emissions from industrial flue gas streams. Most of the world’s carbon dioxide emissions come from coal and gas-fired power plants, petrochemical and natural gas processing plants, and other industrial processes such as steel and cement factories. Technologies for capturing carbon dioxide vary greatly but can be divided into three main categories: chemical, physical, and biological. The chemical and biological methods combine to capture and use/store in a single facility. Because of the vast volumes achievable with physical capture methods, these technologies are paired with geologic carbon dioxide storage in underground formations. The underground formations such as depleted oil and gas reservoirs, un-mineable coal seams, deep saline reservoirs, and deep oceans are the storage space, where CO2 is expected to be sequestered and remain there for millions of years (Howard and Dan 2004). Industries that are major sources of CO2 emissions, such as heavy petroleum refining and fossil fuel-based power plants, focus on CO2 capture projects that target underground geological formations for storage (Metz et al. 2005). Apart from climate mitigation, there are a number of companies investigating utilization of captured CO2 as a potentially profitable activity because if it can be converted into valuable chemicals, polymers, and synthetic fuels, high transportation and sequestration costs can be avoided while creating a revenue stream for the new products (Styring et al. 2011).

According to the International Energy Agency (IEA), the total amount of carbon emissions resulting from gas and oil operations is presently 5200 million tonnes of carbon dioxide equivalent, accounting for 15% of the global energy system’s carbon emissions. These emissions came from various gas and oil industry sources, including processing and collection of gas, conventional and unconventional production, and its distribution and transmission to end-use consumers (IEA 2020).

Future scenarios depicted by the IEA reveal that reducing carbon dioxide emissions through renewable energy production is limited. Hence, a need arises for another strategy to cut CO2 emissions to achieve sustainable development goals in the short term. It is claimed that CCSU is a technology with the potential for significant reductions in CO2 emissions within the next 10 to 20 years (Nikita 2021).

The worldwide market for carbon management systems was priced at 10.93 billion USD in 2020 and is expected to grow to 19.83 billion USD by, 2026which is a Compound Annual Growth Rate (CAGR) of 12.31% over the forecast period from 2021 to 2026 (Mordor Intelligence 2021). Moreover, the carbon capture and storage sector was estimated to be 1.7 billion tons in 2021 and is projected to show a CAGR of over 10% throughout the projection time (2022–2027) globally (R&M 2022). The size and growth of CO2 capture and utilization played an important role in this industry to gain more attention and acceptance in the sustainable economy.

The annual CO2 discharges fell to 30 million metric tonnes of CO2 in India’s financial year 2019–2020 (Myllyvirta and Dahiya 2020) due to the slowdown in economic activities arising from the coronavirus outbreak (COVID-19). However, on average, carbon emissions have been increasing over the years. The carbon emissions in 2018 were 123 million metric tonnes of CO2, which increased to 132 million metric tonnes of CO2 in 2019 in India (Myllyvirta and Dahiya 2020). Therefore, this study focuses on the concept of carbon capture, storage, and utilization and explores current technologies and new, emerging technologies from the perspective of Indian refineries. Additionally, the challenges for CCSU in oil refineries are identified, and policy implications are discussed.

**Understanding CO2 capturing and utilization**

**CO2 capturing**

Carbon capture is carried out by post-combustion, pre-combustion, Oxyfuel combustion, and direct-air capture method (Cuellar and Azapagic 2015). The post-combustion technology for carbon dioxide capture is the most suitable (Yanez et al. 2020).

- **Pre-combustion capture method** This method is generally used during coal gasification to produce electricity. In the gasification units of the integrated gasification combined cycle power plants (IGCC), coal is converted to syngas in the presence of heat, oxygen, and steam. This syngas is used to run a gas turbine and produce electricity. The heat recovered from the syngas is also used to drive the turbine and produce electricity. Before the syngas undergoes combustion in the turbines, the carbon from the process is captured (UNIDO 2011).

- **Post-combustion capture method** The carbon is captured from the flue gases after burning the natural gas, coal, or oil (Metz et al. 2005).

- **Oxyfuel combustion method** The fuel undergoes combustion in the presence of an oxygen-rich, nitrogen-free atmosphere generating flue gas. This flue gas is majorly comprised of carbon dioxide and water. While this process produces concentrated carbon dioxide gas that is more easily purified, it is very costly (Azapagic et al. 2004).
Generally, in industries that use CCSU, the CO2 generated from the above methods is captured by solvents, sorbents, and membrane technology (Songolzadeh et al. 2014).

(a) **Solvent** Conventional amine-based solvents, in particular, monoethanolamine (MEA) and diglycolamine (DGA), and non-amine-based solvents (namely sodium carbonates), are used to adsorb the carbon dioxide forming soluble carbonate salts. The solvent used in the process is then regenerated by decreasing the pressure or increasing the temperature to make it ready to go through the process again (Songolzadeh et al. 2014).

(b) **Sorbent** Solid sorbents include polymeric materials, activated carbonaceous materials, zeolites, metal-organic frameworks (MOFs), silica, and alkali metal carbonates. Solid sorbents have a high capacity for adsorption loading and good performance at high temperatures (Leung et al. 2014).

(c) **Membrane technology** In this technology, the desired molecules (CO2) for separation are allowed to pass through a membrane. In contrast, the unwanted molecules nitrogen oxide (NOX) and sulphur oxide (SOX) are prevented from entering the membranes (Songolzadeh et al. 2014), as shown in Fig. 1. Membrane technology has been well established in various applications, including ultra-filtration, reverse osmosis, micro-filtration, desalination, forward osmosis, and medical applications. However, the membrane technology method for CO2 separation is still developing.

Membrane technology has become popular in the Carbon Capture and Sequestration field on account of the characteristics of the process listed as follows (Ji and Zhao 2017):

**Lower capital expenditure** The membrane coating must have enough mechanical strength, and the membrane requires some small substances to coat. Additional facilities such as large pre-treatment vessels or solvent storage are not required as other capture methods.

**Lower operating expense** The membrane replacement is the major operating cost for membrane technology. The cost is much lower than conventional techniques such as adsorption and absorption because of the membrane’s small size and lightweight, which allows the membrane to replace a large amount of solvent or sorbent required for other CCSU techniques.

**Credibility** Membranes can be used and reused for long periods because membranes do not degrade with use, whereas used solvents or sorbents do. The degradation in performance of solvents or sorbents occurs when they contact a high concentration of water vapour for a prolonged period. Another intake property of the membrane is that it will not react or stay with the gas, so frequent shutdown and can avoid start-up.

**Easy positioning for remote sites** Several membranes can be stacked into one unit to decrease size and weight, which increases membrane area in unit volume and makes it simple to transport to remote sites. The installation process is simple, particularly beneficial in places where spare parts are uncommon, labourers are untrained, and additional facilities (such as solvent storage, water supply, and power generation) are in short supply.

**CO2 utilization options**

**Enhanced oil recovery**

In the conventional oil recovery method, the oil from the oil wells is brought to the surface either via pressure from the pumps or through the reservoir’s natural pressure, which typically results in 25% oil recovery from the oil wells. The secondary EOR method increases oil recovery by 15% by injecting substances into underground oil wells (Student energy 2021), which increases the pressure in the reservoir and reduces the oil viscosity. There are various EOR methods:

- The heat application, such as steam injection in thermal recovery, lowers the oil’s viscosity and enhances the oil’s flow through the reservoir.
- Various gases such as nitrogen, natural gas, and carbon dioxide are injected into the oil wells. The gases expand in the reservoirs, lowering the oil’s viscosity and pushing the additional oil to the surface.
The captured carbon is sequestered in underground oil fields to squeeze the remaining oil from the older fields (Fig. 2). The EOR technology increases oil supplies, reduces our dependence on oil imports, and provides a safe and permanent method to store carbon dioxide underground.

Furthermore, there are tertiary oil recovery methods such as polymer injection or polymer flooding. Polymers are long-chain molecules composed of various repeated subunits with high molecular weight. When added to water, they increase the water viscosity either as a solution or as powder. A more viscous mixture of polymer water is injected into the reservoir for EOR. Consequently, more oil will be pushed out and recovered from the reservoir than would come with water flooding alone. An illustration of a typical polymer flood operation is given in Fig. 3.

The combination of the polymer flooding and the CO2 injection method shows that the mobility ratio improves with the viscosity of the polymer solution. This combination reduces the drop in pressure across the core and increases the recovery of the oil from an oil field. Also, this combination method reduces the consumption of the polymer solution compared to the polymer flooding only method. Polymer flooding and the CO2 injection method are highly efficient and reliable (Zhang et al. 2010).

Feedstock for diverse fuels and chemicals

Various chemicals and fuels are produced using CO2 as a primary raw material, where the CO2 molecule acts as an originator for producing urea, carbonates, acrylates, polymers, and formic acid. Here, urea occupies the largest share of CO2 utilization and polymer synthesis process. In the reduction reactions that consume most CO2, the C=O bonds break, producing methane, methanol, syngas, and alkane (Styring et al. 2011). Furthermore, fuels produced from reduction reactions are utilized in power plants and transportation (Steynberg 2006). In addition, carbon dioxide is also used in various applications within the food and processing industries for preserving food items like fruits, vegetables, meats, food grains, and liquid foods (Kaliyan et al. 2007).

Mineral carbonation

CO2 is also used in the mineral carbonation process to produce carbonates. CO2 reacts with a metal oxide such as magnesium or calcium oxides in this chemical reaction. These metal oxides are available underneath land as silicate crystals, such as serpentine, olivine, and wollastonite. The mineral carbonation is used to develop steady carbonates for long periods of CO2 storage. Because of high energy costs, this process is not accepted commercially (Metz et al. 2005).

Biofuels from microalgae

Biodiesel and various biomass-derived substances are produced using CO2 as a feedstock in the biological process. These substances are used as food, silage, biogas, and fertilizer (Angunn et al. 2014). The conversion of captured carbon into useful chemicals is summarized in Fig. 4.
Methodology

This study initially reviewed the available literature on CCSU in the global oil industry. We also explored the literature on CCS-EOR projects globally and reviewed the available literature in the public domain on the capture and utilization of CO2 from the oil industry. The literature we reviewed gave us ideas about the available CO2 capture and utilization technology. The literature also informed us about how the CO2 is captured and converted into useful chemicals and how it is used in enhanced oil recovery. Further, in this study, we explore the status of CO2 sourcing and utilization technology available in India using available literature. Indian oil and gas operations accounted for 15% of the total energy system’s carbon emissions in 2019 (Nikita 2021). Hence, we focused on how CCSU has the potential to reduce CO2 emissions from oil and gas operations.

CCSU technology in the refinery sector has not yet been implemented in India. The available literature revealed that there is no progressive research on CO2 emission reduction and capture from India’s refining industry because of the complexity. Additionally, no CO2 source and sink are matched in existing studies relevant to Indian refineries. Hence, one possibility moving forward could be that the refineries situated close to the depleted oil fields can be considered for matching the carbon capture, storage, and utilization implementation.

The matching process involves two main steps: (i) identification of clusters to deploy CCS-EOR projects and (ii) a CO2 source-sink matching process. Further, each cluster is ranked based on the weight fractions. The geographical regions (clusters) are identified as demarcated by the occurrence of CO2 sources and potential sinks. To match the clusters, we should consider the potential project’s proximity to the oil field and the infrastructure near the site, such as transport roads and gas pipelines. In the initial stage, the technical and logistical measures are used to categorize sources and sinks. In the case of CO2 sources, the viability of a CCS-EOR project is strongest if the plant is currently running with a high CO2 concentration and is close to an oil field. The viability of the oil field improves with decreasing distance to the sources and increasing storage capacity and oil recovery potential. One very high priority target is indicated by Source-Sink matching for large concentrated CO2 sources. In India, oil refineries are most suitable for implementing CCS-EOR projects. Therefore, in this study, the potential oil field close to the oil refinery in India has been selected for source-sink matching.

Additionally, we identify challenges in implementing CCSU projects as per the literature. Biodiesel and various biomass-derived substances are produced using CO2 as a
feedstock in the biological process. These substances are used as food, silage, biogas, and fertilizer (Angunn et al. 2014). The conversion of captured carbon into useful chemicals is summarized in Fig. 4.

Analysis and discussion

CCSU in global oil industries

CO2 capture and conversion to chemicals are among the most appropriate strategies to reduce CO2 emissions from oil refineries. The CO2 obtained from various operations is separated and converted into valued products via multiple means, including thermochemical reactions, electrochemical reduction, and photo-catalytic reduction. The CO2 emission sources from oil refineries include gases generated from hydrogen units, utility plants, boilers, and furnaces. Chemical absorption, physical adsorption, or oxyfuel combustion approaches are widely used in CO2 capturing oil refineries. The CO2 concentrations obtained from the hydrogen manufacturing units of a refinery are high (Chan et al. 2016). Hence, the hydrogen unit is the instantaneous target for CO2 capturing. The CO2 from the hydrogen unit is captured using two methods: (1) In the hydrogen unit, the water–gas shift reactor produces a syngas mixture, and the CO2 is captured from the syngas mixture before hydrogen is separated from it by physical absorptions, e.g., SelexolTM, and chemical absorption via activated methyl diethanolamine, and (2) the CO2 is captured from the flue gas of the reformer furnace by chemical absorption through using monoethanolamine, or pressure swing adsorption. A different option would be to use the oxyfuel combustion method for capture, which uses oxygen in place of air for combustion.

Despite a large amount of CO2 emitted from the oil refineries, only 1% of CO2 is consumed in manufacturing sectors (Hu et al. 2013). Moreover, very little literature is available in the public domain that studies the use of CO2 emitted from oil refineries. Font and Gonzalez (2017) noted that the CO2 captured from oil refineries in Mexico could be used in nearby oil fields for EOR. They discovered that 68% of the CO2 emitted from the oil refineries could be utilized in the EOR process. In line with this, Yanez et al. (2020) proposed that the cost of carbon capture and storage is largely reduced by integrating CO2 storage and utilization facility for EOR. They also concluded that around 25% of the CO2 emitted from Colombian oil refineries could be reduced with this approach. Cora et al. (2018) showed that multi-product CCSU systems are valuable opportunities that could reduce CO2 emissions from oil refineries. They also explored the competitive advantage of utilization configurations with storage of CO2 alone in oil refineries. Carbon storage alone is not profitable as it increases the total cost of the process by 7%. They also suggested that carbon utilization can improve an organization’s profit as CCSU converts CO2 into marketable products. Middleton et al. (2011) studied the installation of CCSU configuration to capture CO2 emitted from oil refineries and used for EOR. They also studied the potential long-term CO2 geologic storage facility for the U.S. Gulf States, which balanced the CO2 storage costs for EOR oil fields. Cora et al. (2017) presented the potential of CO2 captured from a hydrogen unit, where the stored CO2 is used for polyols production. The study found that CO2 capture and partial utilization arrangement delivers an enhanced business case over capture and storage alone.

Yao et al. (2018) integrated a techno-economic analysis and bottom-up modelling to provide an intuitive and quantitative understanding of CO2 emission reduction potential and costs of three technologies for carbon-capturing from U.S. oil refineries. The study estimated that 110–126 million tons of CO2/year could be mitigated by applying carbon capture to U.S. refineries. In line with this, Jiri et al. (2010) evaluated the prospects and related expenses for the post-combustion capture process in complex refineries at the world level. The study indicated that around 50% of the released CO2 might be captured at the same cost, whereas nearly 10–20% of concentrated CO2 emitted from hydrogen manufacturing may be captured at lower costs. They concluded that either a substantial increase in carbon trading values, mandatory regulations, or a major technological change is required for a cost-effective application of the post-combustion capture process at refineries.

Min et al. (2018) studied through process simulation a solvent-based carbon capture plant for FCCU (Fluidised Catalytic Cracking unit). In a solvent-based carbon capture plant, heat is required to remove the CO2 from an amine rich solution, and it requires an additional energy cost. Hence, energy consumption from the reboiler of the carbon capture plant will reduce the economic benefits of the refinery. The study specified that an appropriate design of heat integration would considerably decrease the energy consumption when the solvent-based carbon capture plant is integrated with an industrial FCCU.

Global CCS-EOR projects

The CCSU projects have been commissioned successfully across the globe, with around 43 large-scale carbon capture and storage facilities in existence. Most of these facilities are in the USA. Evidence suggests that captured carbons are mostly used for EOR. In addition, the USA is the first country that has invested in CCSU projects for EOR. As per the database of the International Energy Agency (IEA), most of the CCSU projects at the global level have been commissioned in coal power generation, refining, hydrogen production, natural gas processing, and chemicals sectors in
the USA and rest of the world as depicted in Tables 1 and 2. The IEA database reveals that probably the first CCSU project started in the Val Verde area of Texas, in the USA by Terrell Natural Gas Processing Plant (formerly, Val Verde Natural Gas Plant) in 1972 with annual CO2 capture of 1.3 million tonnes as per available records. Since 1972, Terrell Natural Gas Processing Plant has been using captured CO2 at the Sharon Ridge oilfield for EOR (Zeroco2 2021). Since then, many industries have started CO2 capture and utilization, some of which are presented in Table 1. In 1998, Enid Fertilizer started a new project in Oklahoma, the United States, in the chemical industry, capturing CO2 at the rate of 0.7 Mtpa (Million Tonnes per annum). The Lost Cabin Gas Plant was retrofitted for a CCSU project in Wyoming, United States, in 2013, and it has been capturing CO2 at a rate of 0.9 Mtpa. The captured CO2 is then transported to an onshore EOR project through the pipeline to a distance of 374 km.

Recently, Petra Nova Carbon Capture (2017) in Texas, United States, retrofitted a coal-based power generating plant with a CCSU project and started capturing CO2 at 1.4 Mtpa. Petro Nova is transporting captured CO2 through a pipeline to an onshore CO2-EOR project located at 132 km. Most USA-based CCSU projects are used onshore for storage and CO2 for EOR from the existing oil fields, as per data available in Table 1. While Terrell Natural Gas Processing Plant (1972) has a very low capture rate of 0.45 Mtpa, the Century Plant (2010) has a very high capture rate of 8.4 Mtpa in the Natural gas processing sector. The Shute Creek Gas Processing Plant is transporting CO2 through the pipeline to a distance of 460 km. Most of the CCSU projects capture CO2 using a post-combustion separation process.

Besides the USA, many countries, including Australia, China, the UAE, Canada, Saudi Arabia, Brazil, and Norway, have invested in CCSU projects. These countries, like the USA, concentrate on CCSU projects mostly for EOR in their respective oilfields, as shown in Table 2. Injection in Western Australia started capturing CO2 in 2019 from the natural gas processing industry at a maximum of 3.7 Mtpa. Using natural gas as feedstock, they follow the industrial separation process. CO2 is transported through a pipeline for 7 km and stored onshore in a saline aquifer through an oil well. Similarly, Great Plains Synfuel Plant and Weyburn-Midale in North Dakota, United States & Saskatchewan, Canada, started capturing CO2 in 2000 from the oil refining sector with a capture rate of 3.0 Mtpa using lignite/brown coal as feedstock following the pre-combustion process. Great Plains Synfuel Plant and Weyburn-Midale transport CO2 329 km through a pipeline to store onshore and utilize for EOR.

### Table 1: The CCSU Projects for EOR in the USA

| Year | CCSU projects | Industry | Capture rate (in Mtpa) | Feedstock | Capture type | Distance transported (in km) | Storage/utilization |
|------|---------------|----------|------------------------|-----------|--------------|-----------------------------|-------------------|
| 2017 | Petra Nova Carbon Capture | Power, Coal Power Generation | 1.4 | Sub-bituminous Coal | Post-combustion capture | 132 | Onshore, CO2-EOR |
| 2017 | Illinois Industrial Carbon Capture and Storage | Refining (biofuels) | 1.0 | Corn | Post-combustion capture | 1.6 | Onshore, Saline aquifer |
| 2013 | Air Products Steam Methane Reformer | Hydrogen Production | 1.0 | Natural Gas | Post-combustion capture | 158 | Onshore, CO2-EOR |
| 2013 | Lost Cabin Gas Plant | Natural Gas Processing | 0.9 | Natural Gas | Post-combustion capture | 374 | Onshore, CO2-EOR |
| 2013 | Coffeyville Gasification Plant | Chemicals (ammonia) | 1.0 | Petroleum Coke | Post-combustion capture | 112 | Onshore, CO2-EOR |
| 2010 | Century Plant | Natural Gas Processing | 8.4 | Natural gas | Post-combustion capture | 255 | Onshore, CO2-EOR |
| 1986 | Shute Creek Gas Processing Plant | Natural Gas Processing | 7.0 | Natural Gas | Post-combustion capture | 460 | Onshore, CO2-EOR |
| 1982 | Enid Fertilizer | Chemicals (ammonia) | 0.7 | Natural Gas | Post-combustion capture | 225 | CO2-EOR |
| 1972 | Terrell Natural Gas Processing Plant (formerly Val Verde) | Natural Gas Processing | 0.45 | Natural Gas | Post-combustion capture | 316 | Onshore, CO2-EOR |
Thus, CCSU projects are running at a large scale at the global level. Now, the following section highlights the status of CCSU in India.

**CCSU status and possible opportunities at present in India**

The Indian Farmers Fertilizer Co-Operative uses the Mitsubishi Heavy Industries carbon capture unit located at Vijaipur, India. The plant captures 450 tons of CO\(_2\) per day from a natural gas-fired, steam reformer flue gas. The captured carbon dioxide is used to manufacture urea. The Aonla Urea Plant has been operating since 2006 (Gupta and Paul 2019). The exhaust gas stream cools in a cooling tower first, then moves to an absorption tower, where it interacts with the amine solvent. The solvent absorbs the CO\(_2\) from the exhaust gas stream. The solvent is then forwarded to a regeneration tower, where it is heated to release the captured CO\(_2\). The solvent is then sent back to the absorption column and recycled for carbon capture. The process enables the recovery of more than 90% of the CO\(_2\) from the exhaust gas (containing a purity of greater than 99.9% by volume).

Other post-combustion capture units include (1) Jagdishpur—India Urea Plant (Indo Gulf Co-operation Ltd.), an amine-based post-combustion capture unit having a CO\(_2\) absorption capacity of 150 tons per day, and (2) Phulpur Urea Plant (India Farmers Fertilizer Co-Operative), an amine-based post-combustion capture unit having a carbon dioxide absorption capacity of 450 tons per day (Sood and Vyas 2017).

The Linde Engineering India Pvt. Ltd provides post-combustion capture and oxyfuel combustion technologies. The post-combustion capture process includes:
• A gas pre-treatment unit.
• A carbon-emission–absorption unit.
• A solvent regeneration unit.

To cater to the growing demands of strict environmental regulations, Badische Anilin und Soda Fabrik (BASF), Linde, and RWE Power\(^1\) partnered to develop an advanced Post Combustion Capture technology unit. The technology provides low solvent losses, low energy consumption, and an exceptionally flexible operating range. BASF has also involved itself in a joint venture with the U.S. research institute RTI International to produce a new and exceptionally affordable carbon dioxide capture technology. The technology includes a non-aqueous solvent system that uses 40% less energy than traditional capture processes, and the solvent can be recycled effectively (Linde 2021).

In the conventional carbon capture technologies, the absorption columns use MEA (Ethanolamine) and MDEA (Methyl diethanolamine) solvents which are highly corrosive. This creates environmental and equipment maintenance issues, increasing the overall cost. Various organizations such as Carbon Clean Solutions, National Aluminium Company, Oil and Natural Gas Corporation Limited, Indian Oil Corporation Limited, and Breath have developed green and efficient carbon capture storage and utilization (CCSU) technologies.

The CDRMAX technology introduces a new class of solvent termed the APBS solvents. CDRMax is commercially available and operates at atmospheric pressure, enabling > 90% CO\(_2\) capture from low-pressure flue gas (CO\(_2\) concentrations in the source gas from 3 to 25%) to produce high purity (> 99.5%) industrial-grade CO\(_2\) for downstream use (APBS-CDRMAVTM 2021). The technology uses industrial carbon dioxide released from oil and gas companies, power plants, boilers, coal-fired burners, flue gas, chemical industries, and other industries such as cement and metals. This CDRMAX technology allows for a 35% reduction in the operating cost, $ 5.6/t carbon dioxide solvent savings, $ 17.4/t carbon dioxide steam savings, and up to 90% carbon dioxide recovery. In Tuticorin, India, a 10 MW commercial-scale coal-fired 174 TPD ICCU facility captures flue gas that delivers high-quality CO\(_2\). The plant features ~ $40-$50/metric tonne CO\(_2\) capture cost, ion exchange re-claimer, and an absorber. The captured CO\(_2\) is converted to chemicals such as sodium carbonate & ammonium chloride. Tuticorin Alkali Chemicals & Fertilizers (TACFL) utilize the captured carbon for producing soda ash (CCSL 2021).

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\(^1\) RWE Power is the company which produces electricity from lignite and nuclear energy.

National Aluminium Company NALCO, in association with Indo-Can Technology Solutions, has commissioned a unique pilot-scale project for carbon sequestration by algae. The construction started in 2011, and the pilot plant began operating in 2013. The pilot plant, bio-CCS, captures the flue gases from the captive power plant in Odisha, India. The company has operations in mining, metal, and power. It is an integrated aluminium manufacturer company. Flue gases emitted from the furnace of the thermal power plant (generation capacity of 1200 MW) contain about 12% carbon dioxide, which is purified and utilized as the carbon source for algae growth. The plant can sequester 32 tons/acre/year of carbon dioxide and produce 20 tons/acre/year of algae biomass (NALCO 2013).

**Breakthrough in research technologies on CO\(_2\) utilization**

• The research group at IIT Delhi has developed a process to efficiently convert industrial carbon dioxide to methane and other valuable products like hydrogen gas and formic acid using a Fe–Co bimetallic catalyst. The derived methane can not only be used as a fuel for transportation but can also serve as stored energy, which can be used later. Hence, methane as a fuel provides an alternative to depleting non-renewable sources of energy like petroleum and coal (Ejaz et al. 2019).

• One emerging research field is the conversion of carbon dioxide into valuable products. Succinic acid is an essential C4 building block chemical. The research group at the Bioengineering and Environmental Sciences (BEES) at CSIR-Indian Institute of Chemical Technology (CSIR-IICT), Hyderabad, India, produces succinic acid from captured carbon dioxide by biological sequestration of CO\(_2\). The CO\(_2\) is stored in vegetation, soils, and woody products in this biological sequestration process. Succinic acid with high productivity is produced by an isolated strain of the genus Citrobacter (Kotamraju and Venkata 2019).

• Researchers at Rajiv Gandhi Proudyogiki Vishwavidyalaya Bhopal, Madhya Pradesh, India, are developing a pilot plant to capture carbon emissions from a biomass gasifier unit present at the University and to produce essential multi-purpose fuels such as methane and hydrogen. They are also using carbon emissions as a source to grow microalgae that can produce methane gas and biodiesel. A metallic solvent captures the carbon released from flue gas in the gasifier unit. The captured carbon emissions are converted to biodiesel in its Biodiesel Reactor (100 LPD) unit at the University. (RGPV 2021).

• The laboratory effectively demonstrates the decline of CO\(_2\) by utilizing a low-cost molybdenum carbide Mo2C catalyst using H2 as a reducing agent. The products are
synthesized by a reverse water–gas shift (RWGS) reaction. It was observed that the molybdenum carbide catalyst with a CO2: H2 (1: 3) ratio gives a high carbon dioxide conversion of 58% and selectivity of 62% towards carbon monoxide (Reddy et al. 2019).

Breathe Applied Sciences Pvt. Ltd. is a company located in Bangalore, India. They focus on the development of materials capable of carrying out the effective conversion of captured carbon emissions to methanol. The conversion steps involve various complex reaction steps and mechanisms that make it difficult to conduct the selective conversion of carbon dioxide to the desired product. In addition to this challenge, carbon dioxide reduction requires hydrogen. However, a substantial amount of hydrogen generation is difficult to achieve. The research proposes bimetallic core–shell materials that include Ni, Cu, and Fe catalysts. The catalyst is also abundantly available and low in cost. The company consists of different scales of reactors at their facility, such as bench scale, pilot scale, demo scale, and commercial scale, processing carbon dioxide at capacities of 1, 5, 300, and 2000 kg/day, respectively. The group development was planned in four stages: bench, pilot, demo, and commercial. The group has completed the demonstration in the first three stages and is working on scaling up (BASPL 2021).

**Opportunities for source, sink, matching, and ranking of CO2 emission in Indian refineries**

As discussed in the following sections, India has a tremendous opportunity to source, sink, match, and rank CO2 emissions, especially in the refinery sector.

**The CO2 emission source from oil refinery in India**

The fluid catalytic cracking (FCC) and co-generation of heat and power (CHP) units are the most significant sources of emission (approximately 80% of the refinery CO2 emissions) and denote the 49% of the potential capture from the oil refinery. The hydrotreatment (HDT), steam methane reformer (SMR), and hydro-cracking (HCK) units display higher CO2 concentrations of between 40 and 95% CO2. These refineries’ units might account for about 50% and 21% of the CO2 capture potentials for Indian refineries. The refineries with their location and capacity are shown in Table 3.

**The oil field for CCS-EOR**

India has assessed a sedimentary basin of 3.36 million square kilometres (sq. km) covering 26 sedimentary basins, out of which 1.63 million sq. km. area is on-land. India’s shallow offshore isobaths have an aerial extent of 0.41 million sq. km. and deep-water isobaths have a sedimentary area of 1.32 million sq. km. These 26 Indian sedimentary basins have been separated into four categories based on their degree of prospectivity (MoPNG 2021).

- **Category I** Basins with reserves being produced and potential to be exploited at increased recovery.
- **Category II** Basins with contingent resources to be developed and produced.
- **Category III** Basins with only prospective resources to be explored and discovered.
- **Category IV** Uncertain potential, which may be prospective by analogy with similar basins in the world.

In this study, the sedimentary basin in category-I is taken into account for analysis to recover oil from the oil field. Based on conservative resource potential, seven basins are clustered under Category-I, holding 85% of the total conventional hydrocarbon in place of 41.8 billion tonnes of oil and oil-equivalent gas and covering 30% of the total basin area. These seven basins are Krishna-Godavari (KG), Mumbai Offshore, Assam Shelf, Rajasthan, Cauvery, Assam-Arakan Fold Belt, and Cambay. These basins are equally assessed to the extent of 47% of the country’s total assessed area (1.6 million square kilometres) with 65% of the country’s total active operational area (0.3 million square kilometres). Table 4 summarizes the sedimentary basins of category-I in India.

Despite having a large oil field area, there must be potential for oil recovery from the given oil field. We can combine CO2 generated from the oil refineries if there is a potential to recover oil from the oil field. The proven potential oil recovery from the Indian basin is summarized in Table 5.

**CO2 source-sink matching**

The matching process was built preliminary with the sources and sinks. In addition, a proper storage facility is required to store the captured CO2 and be used in the EOR process. As suggested by Bachu (2016), this potential matching of the clusters should be at distances around 400 km and at sites where infrastructure is available, such as transport roads and/or gas pipelines. Hence, the refineries situated close to the depleted oil fields can be considered to match the source-sink (Viebahn et al. 2012). The viability of a source-sink matching would be possible if the plant is currently running with a high CO2 concentration and is close to the oil fields. For the oil fields, the viability improves with decreasing distance to the sources and increasing storage capacity and oil recovery potential. The current source of CO2 in terms of oil refineries and sink sources like nearby oil fields are identified considering the closest distance criteria (Bachu 2016). In this study, we extended our scope of distance to around 400 km for source-sink matching. Fig. 5 presents the CO2 sources and potential storage available in India.
In India, potential storage locations could be positioned in saline aquifers, depleted oil and gas fields, coal seams, and basalt formations. The sedimentary basins of India, where saline aquifers can be found, are at the boundaries of the peninsula, in the states of Rajasthan, Gujarat, Assam, Tripura (Cachar), Mizoram, and the Mumbai/Cambay/Barmer/Jaisalmer basin area in the West of India (Garg and Shukla 2009). The related formations are at the Krishna—the Godavari, and the Cauvery Basins, located in the southeastern coastal zones. These basins are acknowledged to deliver...
For deploying CO2-EOR projects in India are identified. Based on the location of the CO2 sources and appropriate oil fields within a range of 400 km and infrastructure availability, there are three relevant oil fields identified for CO2-EOR projects in a radius less than 400 km. First, the oilfield of Mumbai offshore, Rajasthan, and Cambay account for the land area of 174,882 sq. km. on land area. The Second oil fields of the Krishna- the Godavari and the Cauvery are selected, accounting for 69,821 sq. km. land area for the CO2-EOR project. The third is the Assam shelf, accounting for 56,000 sq km land area. These three clusters match CO2 sources and sinking and can be developed for the CO2-EOR oil field.

Figure 6 presents the potential CO2 source and sink matching for the CCS-EOR project. The red-coloured mark locations are CO2 sources from the oil refineries, and green areas show the potential oil fields which can be used for the EOR project. It displays the geographical connection between the major current and strategic sources of CO2 from an oil refinery in India and areas comprising the sedimentary basins considered based on this first-pass assessment to have good, fair, and limited storage potential. The hydrocarbon-bearing basins are rated as good, so they also comprise the potential in oil and gas fields. This stored CO2 will be injected into the oil or gas field to enhance the oil recovery.

In Fig. 6, Cluster-1 contains the CO2 source from the oil refineries named Reliance industries limited, Nayara energy limited, Koyali refinery, HPCL-Mumbai, and BPCL-Mumbai oil refineries. The current oil field of Mumbai offshore, Rajasthan, and Cambay can potentially use the CO2 of these oil refineries for oil recovery. Similarly, CO2 captured from refineries in cluster 2, including Chennai Petroleum Corporation Limited, HPCL-Vizag oil refinery, Tatipaka oil refinery, Paradeep oil refinery, Haldia oil refinery, and Kochi oil refinery, can be used in the oil field of Krishna-Godavari and Cauvery basins. In cluster-3, CO2 captured from Barauni oil refinery, Bongaigaon oil refinery, Digboi oil refinery, Guwahati oil refinery, and Numrligarh oil refinery can be used in the potential oil field of the Assam shelf basin.

**Ranking**

Further, the clusters are ranked based on the weighting fraction. The three clusters are ranked on the criteria (1) potential oil recovery from the basins comes under the clusters, and (2) CO2 storage capacity of oil fields comes under each cluster. The weighting fraction for each cluster is derived from the following Eqs. (1), (2), and (3), as shown below:

Cluster – I weight fraction = \[ \frac{A_1}{A_1 + A_2 + A_3} + \frac{B_1}{B_1 + B_2 + B_3} \]  

Cluster – II weight fraction = \[ \frac{A_2}{A_1 + A_2 + A_3} + \frac{B_2}{B_1 + B_2 + B_3} \]  

Cluster – III weight fraction = \[ \frac{A_3}{A_1 + A_2 + A_3} + \frac{B_3}{B_1 + B_2 + B_3} \]  

where A1, A2, and A3 are the potential oil recovery in MMTOE (Million Metric tonne oil equivalent) for clusters I, II, and III, whereas B1, B2, and B3 are the CO2 storage capacity in Million metric tonnes for clusters I, II, and III. Table 7 represents the weight fractions for each cluster, and clusters are ranked based on the weight fraction. The cluster with more weight fraction is ranked one, having a large potential for oil recovery and storage facility. This cluster is roughly more economical than the other clusters to implement the CCS-EOR project. It is, therefore, more logical to consider the refinery and oil field in such a cluster to source and sink. Table 6 shows that cluster I shows the highest weight fraction score against the other cluster. Before executing the CCS-EOR project in cluster-I, it is also necessary to conduct a feasibility study for economic viability.

**Challenges of CCSU in India**

Although the CO2 sources are identified close to the potential oil field, it also requires the infrastructures to transport the CO2 from the oil refinery to the potential storage facility. The CO2 capturing installation at the refinery site needs to be undertaken with sophisticated technology. The implementation of carbon capturing and utilization requires huge investment from the government bodies, but the financing for implementing commercial utilization of CO2 is lacking in India. A large investment is required to utilize the CO2 generated from the oil refineries successfully. A CCSU project needs technological

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**Table 5** Proven potential oil recovery from the India Basin 
Source: Ministry of Petroleum and Natural gas, Govt. of India

| Basin name                  | Potential oil recovery (in Million metric tonne oil equivalent) |
|-----------------------------|---------------------------------------------------------------|
| Krishna-Godawari Basin      | 9555                                                          |
| Mumbai Offshore Basin        | 9646                                                          |
| Assam Shelf Basin           | 6002                                                          |
| Rajasthan Basin             | 4125                                                          |
| Cauvery Basin               | 1963                                                          |
| Cambay                      | 2585                                                          |
| Total                       | 33,876                                                        |

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“good” storage potential. The theoretical CO2 storage capacity of oil fields in Indian basins is summarized in Table 6.
intervention, which is not yet proven cost-effective even at the global level. Therefore, more research and development are needed, which is a challenging task for India in the short-run (Gupta and Paul 2019). There is a lack of energy and environmental policy provisions supporting CCSU projects in India. The ecosystem should be built and reinforced around the key pillars, specifically research & development, funding, governance, and energy/environmental policy.

Presently, Energy demand is growing in India with urbanization and population size. In these scenarios, CO2 capturing and utilization processes add supplementary energy demand. Hence, the energy penalty plays an obstacle in India. Additional energy demands and additional energy infrastructure are required for the successful implementation of the CCSU project in India. However, due to the rising frequency of extreme events like cyclones along the Indian coasts, these infrastructures need to be cyclone resilient.
Land acquisition is a challenging task in India. In a democratic country like India, it is often a challenging affair for the government to acquire land for any welfare purpose. Due to socio-economic, religious, and political diversity, public authorities face problems with land acquisition and several other problems. Therefore, a balanced approach to keep everyone happy is needed for land acquisition, which is a unique barrier to handling and executing the CCS-EOR project. Not only concerns related to land acquisition but also concerns related to groundwater pollution and panic of CO2 leakage must be addressed judiciously.

### Conclusion

Due to the strict governmental regulations for reducing greenhouse gas emissions, there is a growing demand for carbon emissions management systems. Companies and research and development institutes have begun investing in sustainable and innovative carbon management technologies. As reported by the International Energy Agency (IEA), despite renewable energy technologies, oil is still the dominating energy source and will remain so for at least two decades ahead. Moreover, developing countries depend largely on fossil fuels for their exponential growth in transportation, heating, and cooling. Hence we anticipate that the carbon sequestration technique with the EOR method will grow in the coming years. Global experience shows that carbon capture and utilization provide emission reductions and help to generate additional revenue.

This study provided potential sources for CO2 capture from oil refineries and their usage in oil recovery projects to mitigate CO2 emissions in India. The oil refineries were identified as potential sources for CO2 capture and supply for EOR operations. A total of three clusters are identified as potential CO2 sources, storage, and utilization for oil recovery. The geographical analysis of the recognized matches assessed a CO2 storage potential of 37,250 million metric tonnes of CO2 and additional oil recovery of 33,876 million metric tonnes of oil equivalent. Furthermore, the clusters are ranked to find more economic clusters to address feasibility study and financial support. The highest-ranked cluster will result in more oil recovery from the oil fields. This study shows that cluster I has the highest potential oil recovery, i.e. 16,356 MMTOE, and has the 20,950 X 106 tonnes of CO2 storage capacity among all three clusters. This study shows the combined weightage of cluster ranking is 1.05, 0.63, and 0.33 for clusters I, II, and III, respectively. Hence, cluster I should be the first choice in India for CCS-EOR projects.

Refiners looking to implement carbon capture storage and utilization may face challenges like lack of financing, research and development, concerns about land acquisition, groundwater pollution, transportation, and panic of CO2 leakage. But the Government of India and the Indian industries are working on this technology to understand the technical and economic viability and reliability of CCSU. Therefore, the recommendations for Indian refiners to address these challenges are: (1) the facility for the CO2 capture, storage, and utilization should be installed near the oil refinery for the project’s economic viability. The CO2 emitted from the oil refinery is to be stored in a potential oil field as suggested in each cluster, followed by injection in an oil well to recover oil from the oil field;

(2) The next step is to evaluate each of these source-sink matchings in detail so that future proposals for CCS-EOR projects for Indian sedimentary basins can meet the local government requirement and sufficient budget; (3) the policies should be reformed to attract foreign direct investment for financing the feasible carbon capture storage and utilization projects; and (4) the government should offer the local investors additional tax benefits to attract them to invest in an expensive yet relevant carbon capture storage and utilization project. Moreover, the commercial viability of the CCSU is also dependent on the demand for CO2-based products. In that case, transport infrastructure such as pipelines and terminals for CO2 storage will have to be advantageously situated to cut transportation costs and accommodate the CO2 supply for industries manufacturing CO2-based products.

The investment in the CCSU projects will reduce CO2 emissions and thus help in mitigating climate change. Besides this research, it is also required on the policy front to understand the changing requirements and implications of policies on the role of CCSU, especially in the industrial sector. The policy ecosystem should be built and reinforced around crucial aspects such as research & development, procedure, investment, and governance. An extensive study needs to be undertaken to know the challenges and the probable solutions. CCUS technology is comparatively new to India compared to the developed countries, so it necessitates more exhaustive research and dramatic actions to keep the

### Table 6 CO2 storage capacity of oil fields in Indian basins

| Basin       | Theoretical CO2 Storage Capacity* (Million metric tonne of CO2) |
|-------------|---------------------------------------------------------------|
| Krishna-Godawari | 5200                                                        |
| Mumbai Offshore    | 11,600                                                      |
| Assam Shelf       | 5600                                                        |
| Rajasthan         | 4000                                                        |
| Cauvery           | 5500                                                        |
| Cambay            | 5350                                                        |
| Total             | 37,250                                                       |

*Calculated with a specific storage density of 0.2 Million metric tonne of CO2/km2 following Wildenborg et al. (2004)
Table 7  Ranking of clusters

| Cluster name | Potential oil recovery (MMTOE) | CO2 storage capacity (Million metric tonne) | Weighting fraction of (A) | Weighting fraction of (B) | Combined weightage of clusters |
|--------------|-------------------------------|---------------------------------------------|---------------------------|---------------------------|-------------------------------|
| Cluster-I    | 16,356                        | 20,950                                      | 0.48                      | 0.56                      | 1.05                          |
| Cluster-II   | 11,518                        | 10,700                                      | 0.34                      | 0.29                      | 0.63                          |
| Cluster-III  | 6002                          | 5600                                        | 0.18                      | 0.15                      | 0.33                          |

Source: Authors’ computation

Fig. 6  Potential clusters for CCS-EOR projects in India (Source: Authors’ compilation)

Indian Sedimentary Basins
additional datasets were generated or analyzed during the current study

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Declarations

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