Carbon Dioxide Removal (CDR) Technologies and Cities' Net Zero goals in India

Transitions Research

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Disclaimer:

The opinions and arguments presented herein are solely those of the Transitions Research team and do not necessarily reflect the official views of the organisations interviewed.

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People's Urban Living Lab

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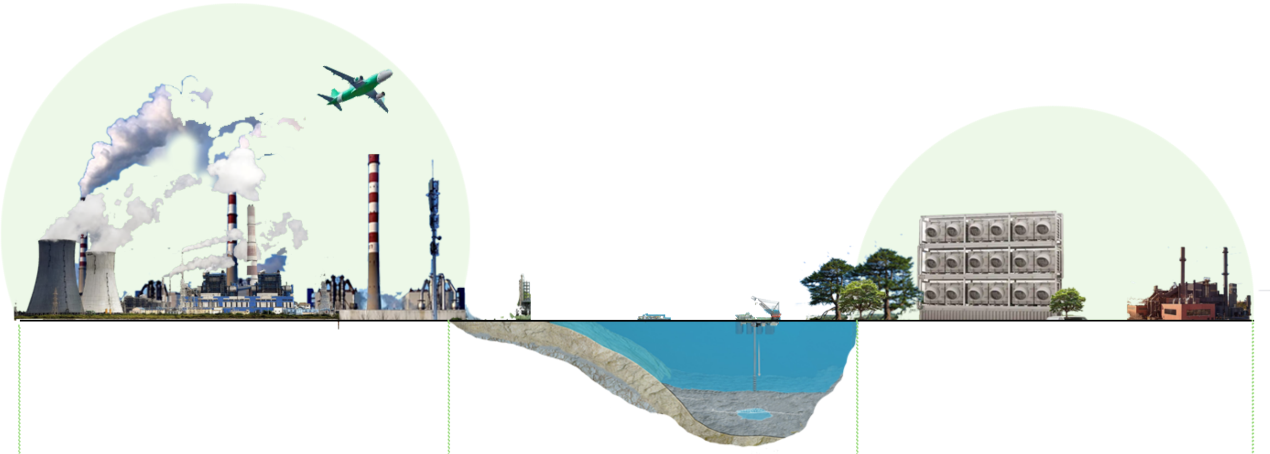
Abstract

Cities worldwide are working to achieve net-zero emissions in the coming decades. Carbon dioxide removal is now essential to limit warming to 1.5° C along with deep decarbonisation (J. Mazurek, F. Wang, and D. Plechaty, 2022). Durable Carbon Dioxide Removal (CDR) is an emerging solution with significant CO_2 removal capacity.

However, the integration of these technologies in the urban context requires further analysis. This policy brief explores the current approaches, benefits, and limitations of durable CDR adoption in urban India. It also provides policy recommendations to support the effective deployment and scaling of durable CDR solutions in cities, aiming to support India's net-zero goals.



CCU	CCS	CDR
Carbon Capture and Utilization	Carbon Capture and Storage	Carbon Dioxide Removal
Carbon is captured typically from point source (e.g. power plants, industries, etc.)	Carbon is captured typically from point source.	Carbon is captured from ambient air or natural sinks (e.g. forests, oceans, etc.)
Captured CO_2 is utilised (e.g. for synthetic fuels, carbonated drinks)	Carbon captured is stored, usually underground.	CO_2 is removed from the air and stored (natural or engineered means)
Carbon Positive in process (CO_2 generated is utilised before directly being released in atmosphere)	Carbon Neutral in nature (CO_2 generated is stored and not released in atmosphere directly)	Carbon Negative in nature (actively reduces CO_2 levels in atmosphere)
Example: CO_2 from cement plant is captured and used to make synthetic fuels or carbonated drinks.	Example: CO_2 from a power plant is captured and injected into deep saline aquifers for storage.	Example: Direct Air Capture (DAC) plant by Climateworks in Iceland storing CO_2 in basalt rocks.

Figure 1: Difference between Carbon Capture and utilisation (CCU), Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR)

Introduction

Indian cities remain significant contributors to Greenhouse Gas (GHG) emissions (K. Pandey, 2024) despite the adoption of renewable and energy-efficient solutions in the transportation, industrial, and energy sectors. India's GHG emissions have more than doubled since 2000 (M. Crippa et al., 2024.), and 44% of the country's rapidly increasing carbon emissions stem from urban areas (M. Crippa et al., 2021).

In order to tackle rising urban emissions and contribute to India's net zero pledge by 2070, urgent decarbonisation is essential. However, beyond transitioning transportation, energy systems, and the built environment, responsible carbon dioxide removal is still required to achieve net zero goals. The IPCC report highlighted that nearly all scenarios that meet the Paris Agreement goals to limit warming to 1.5°C or below 2°C include some CO_2 removal (H. Lee and J. Romero, 2023).

Carbon Dioxide Removal (CDR)

Also known as Negative Emissions - Carbon Dioxide Removal (CDR) refers to methods for active removal of carbon dioxide from the atmosphere and permanently storing it in terrestrial, geological, or ocean reservoirs to combat global warming. CDR includes both nature-based (conventional) and technological (novel) solutions. Conventional CDR methods are often short-term or temporary, and the stored carbon may be released relatively quicker than 'Durable' CDR, i.e. novel technologies, that can store carbon for long periods, typically centuries or millennia. The storage sites may be remote or located far from capture points, demanding efficient transportation of captured carbon.

Since reducing emissions to zero within the necessary timeframe is highly challenging, it is imperative to explore effective methods for carbon removal directly from the atmosphere or the source. However, techniques for achieving this, aside from those directly associated with urban nature-based solutions, have not undergone large-scale testing. Current CDR actions remain limited and uninformed due to knowledge gaps, insufficient technical capacity, and a lack of established best practices. We must bridge this gap so cities can actively adopt innovative sequestration strategies for climate mitigation.

Context

Government of India (GoI) is exploring ways to adopt and promote Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) technologies. The current focus largely remains on offsetting residual emissions from hard-to-abate industrial sectors (e.g. aviation, agriculture, shipping, industrial processes). However, durable CDR includes a range of solutions and the integration of durable CDR in other sectors, especially in cities, is vital for decreasing CO_2 emissions and addressing climate change (E. Parry et al., 2022).

Current CDR Technologies and Their Urban Applications

Broadly, the durable carbon dioxide removal technologies relevant for urban areas would have the following characteristics:

- Technologies able to maximise carbon sequestration per unit area. Space constraints are important due to limited available space in urban areas.
- Easy integration with existing city infrastructure for capturing emissions at source or aligning with freight operations for captured carbon transportation.
- Scalable and adaptable solutions that can be deployed in multiple urban locations.
- Solutions that provide additional benefits beyond carbon removal, such as improved air quality or waste management.
- Technologies that capture or store carbon for long periods.

Based on our research, including thorough literature review, the following categories of CDR technologies are applicable in Indian cities:

Engineered Solutions

- **Carbon Capture and Storage (CCS) and Utilisation (CCUS)**
- **Direct Air Capture (DAC)**
- **Bioenergy with Carbon Capture and Storage (BECCS)**

Hybrid Solutions

- **Enhanced Rock Weathering (ERW)**
- **Biochar Sequestration**
- **Microalgal cultivation**
- **Ocean fertilisation**

Engineered Solutions

Engineered solutions include using advanced technology to capture and store carbon directly from the atmosphere.

Carbon Capture And Storage (CCS) And Utilisation (CCUS)

CCS involves capturing, treating, transporting, and storing CO_2 emissions, serving as a solution for emission reduction alongside renewable energy sources. Techniques like chemical absorption and physical separation are used to capture CO_2, from its source with processes categorised as pre-combustion or post-combustion. In addition to storage, Carbon Capture and Utilisation (CCU) technologies provide opportunities to recycle captured CO_2 into valuable products such as chemicals, solvents, raw materials for fuel production, and agents for enhanced oil recovery, reflecting a growing interest in sustainable industrial practices.

The Tuticorin CCU project, developed by Carbon Clean Solutions Limited (CCSL) and Tuticorin Alkali Chemicals and Fertilisers (TACFL), in India, captures 60,000 tonnes of CO_2 annually from a coal power plant to produce soda ash, which is a key ingredient in glass, detergents, and other industrial products. With a cost of $30 per tonne of CO_2, the plant is more economical than traditional CCS projects due to innovative chemical solvents. The focus is on utilisation; thus, there is no permanent carbon removal.

Direct Air Capture (DAC)

Large machines capture carbon dioxide from the atmosphere, and the captured CO_2 is either stored underground or utilised in various products. However, this technology is still in the prototype phase, and its energy intensity and costs remain significant barriers to widespread urban deployment.

Climeworks, a Swiss start-up, in partnership with Icelandic firm Carbfix, developed a direct air capture and storage (DAC+S) plant in Iceland, the 'Orca' plant. It can capture up to 4,000 tons of CO2 annually—equivalent to the annual emissions from about 870 cars. However, the net annual carbon removal capacity - the amount that Climeworks can sell to customers - is around 3,000 tons annually. This is after factoring in potential losses from plant downtime (targeted to 10%), CO2 recovery losses (aiming for 5%), and grey emissions, which are the carbon footprint associated with the plant's lifecycle (potentially restricted to 15%).

The plant uses high-tech filters and fans to extract carbon dioxide released (together with geothermal fluids) from the Hellisheidi power plant. The captured carbon is then injected into deep basalt rock formations, where it reacts with the minerals to form stable carbonate minerals, effectively locking the CO_2 and preventing its release back into the atmosphere. However, its widespread use is challenged by the significant need for water, porous basaltic rock, and considerable investment in carbon capture facilities. The Orca plant cost 10–15 million USD to build.

Bioenergy With Carbon Capture And Storage (BECCS)

BECCS generates energy by burning biomass and capturing the resultant CO_2 emissions. The captured CO_2 is then stored in geological reservoirs. However, the land and biomass availability can hinder adoption. The theoretical sequestration capacity of BECCS ranges from 1 to 85 gigatons per year (R. Bellamy, J. Lezaun, and J. Palmer, 2019), but it remains under-researched, particularly in developing countries.

The Drax BECCS Pilot Project, financed through private investment and managed by the Drax Group at the Drax Power Station in North Yorkshire, integrates biomass combustion with CCS technology. The project captures 300 tonnes of CO_2 per day (Ricardo Energy & Environment, 2020). Preliminary outcomes indicate that BECCS can substantially reduce CO_2 emissions when coupled with efficient capture systems.

However, the project has highlighted the importance of establishing a reliable and sustainable biomass supply chain and managing retrofitting challenges (Ricardo Energy & Environment, 2020). Further, the high capital cost is a considerable setback for scaling the technology.

Hybrid Solutions

Hybrid solutions combine natural processes with technology to maximise CO_2 removal. Examples include:

Enhanced Rock Weathering (ERW)

ERW involves distributing crushed basalt to agricultural lands to capture atmospheric carbon. ERW practices can cost between 200 to 500 euros (Climate Seed, 2023). The benefits include crop yields, improved soil quality, reduced fertiliser use, and enhanced water retention. Basalt, a volcanic rock rich in olivine, is considered the most suitable option for ERW due to its faster reaction with water and CO_2.

The University of Sheffield and the Department for Environment, Food & Rural Affairs (DEFRA) launched the UK Enhanced Rock Weathering GGR Demonstrator project in 2021, funded by £4,635,236 from UKRI (UKRI, 'Greenhouse gas removal with UK agriculture via enhanced rock weathering'). The aim was to improve soil alkalinity and capture atmospheric CO_2 by spreading finely ground basalt on agricultural fields in the UK. Initial trials showed a subtle increase in soil carbon sequestration and improved soil quality. However, high energy requirements for crushing the basalt, uncertainties about long-term CO_2 removal rates, and potential impacts on local soil chemistry are significant challenges

(N. Forrest and J. Wentworth, 2024). The effectiveness of ERW may also be affected by rainfall variability, and further research is required to assess its scalability across different agricultural landscapes.

Biochar Sequestration

Carbon sequestration with biochar involves heating plant waste in low-oxygen conditions. This process is called pyrolysis or gasification. The resulting biochar can be mixed into soil, acting as a fertiliser and storing carbon for about 2,000 years (B. Glaser, M. Parr, C. Braun, and G. Kopolo, 2009).

PyroCCS, a Germany-based ClimateTech startup, is working on biochar projects in Namibia and India, converting biomass to address environmental issues. Projects in Namibia include a total investment of N$14 million (equivalent to 745,000 USD) (M. Endjala, 'PyroNam plans to set up 50 plants by 2030'), with each plant costing N$6 million and an estimated annual production capacity of 1,000 tons of biochar (International Biochar Initiative, 2024). Pilot projects show improved soil quality and sequestered carbon; however, an essential aspect of their business model is the development of markets for biochar and carbon credits to ensure long-term success.

Microalgal Cultivation

Microalgae cultivation involves growing microscopic algae to capture CO_2 and produce valuable compounds. This method utilises saline water and does not compete with food crops, allowing for significantly greater CO_2 sequestration than terrestrial plants. Selected microalgae strains can be grown in ponds or photo-bioreactors; however, optimal growth conditions and strain selection are critical.

AgroMorph, an India based organisation, is working with industrial clients, to decarbonise flue gas, primarily methane and CO2, through a natural CO_2 scrubbing method using microalgae, which can capture carbon up to 50 times more efficiently than traditional plants. They utilise open-air algal photobioreactors to absorb CO_2 and optimize pH levels for algal growth, enhancing dissolved CO_2 absorption. Since monetising carbon credits is currently not feasible, the organisation is exploring repurposing cultivated algae, which are rich in proteins, vitamins, and lipids, for use in sectors like cosmetics and aquaculture. Their revenue model prioritises algae commercialisation while aiming for CO2 capture as a potential future income stream.

Ocean Fertilisation

Ocean fertilisation, or ocean nourishment, focuses on increasing the growth of organisms in the upper ocean by adding nutrients like iron, nitrogen, and phosphorus, thus increasing CO_2 absorption by phytoplankton. However, it is deemed a speculative approach to carbon dioxide removal (CDR) due to weak knowledge-base on the potential intended and unintended impacts on marine ecosystems (National Academies of Sciences, Engineering, and Medicine, 2021). Given a conducive environment, coastal cities could explore this solution.

In 2009, The LOHAFEX Experiment, a joint Indo-German initiative organised by GEOMAR and INCOIS, tested iron fertilisation in the Southern Ocean to stimulate phytoplankton blooms for enhanced CO_2 uptake. The experiment produced mixed results in terms of long-term CO_2 sequestration - the scientists did succeed in producing a phytoplankton bloom; however, most of the experimental bloom was consumed by zooplankton near the surface and failed to reach the ocean floor (J. Hance, 2023). Further, the project faced widespread environmental concerns (Q. Schiermeie, 2009), and there was only one other large-scale experiment on ocean iron fertilisation. The key learnings from LOHAFEX include the potential ecological impacts, uncertainties surrounding the permanence of carbon removal, and the challenges of securing public and regulatory acceptance for large-scale ocean fertilisation.

Recently, Scientists with the Woods Hole Oceanographic Institution in Massachusetts, U.S., received 2 million USD in funding (J. Hance, 2023) from the U.S. government to enable computer modeling research that could pave the way for eventual in-ocean testing, effectively reviving research into ocean iron fertilization.

Durable CDR Potential and Challenges in Indian Cities

India has significant potential for CO_2 sequestration, with Indian reservoirs capable of storing 629 gigatons of unconstrained CO_2 (T. Bakshi, H. Mallya, and D. Yadav). Specifically, 326 Gt can be stored in deep saline formations and 316 Gt in basalts, while oil fields and coal formations comprise 2.6 Gt and 4 Gt, respectively (T. Bakshi, H. Mallya, and D. Yadav, 2023). Coastal regions of Gujarat and Rajasthan and the Deccan trap basalt areas also show promise for carbon storage. Additionally, the low-permeability siltstone found in the Ganga foreland basin and the Siwalik formations show promise for CCS with reduced transportation costs due to proximity to large-scale point sources.

However, deep underground CO_2 storage sites in India are constrained by various factors such as environmental, social, and local opposition, known as 'above-ground challenges'. These factors limit the potential storage capacity to a range of 101 to 359 billion metric tons, depending on the availability of arable land and population density. As of 2023, India emitted approximately 4.1 billion tonnes (Gt) of CO_2-equivalent annually (I. Tiseo, 2024), excluding land use changes. Projections suggest that emissions could rise to 11.8 $GtCO_2e$ by 2070 (R. Gupta et al., 2023). Injecting 5.3 and 10 gigatonnes (Gt) of CO2 by 2050 can help India meet the 1.5°C temperature increase scenarios by mitigating the emissions from fossil fuel use.

India emits 4.1 $GtCO_2e$ annually as of 2023 and is projected to reach 11.8 $GtCO_2e$ by 2070. Now let's breakdown India's total CO_2 storage potential

Total CO2 storage potential

629 Gigatons (Gt)

including deep saline formations, basalts, oil fields and coal formations

Practical storage potential (after above-ground constraints)

101–359 Gt

is realistically usable, considering environmental and social limitations

Required storage to meet climate goals

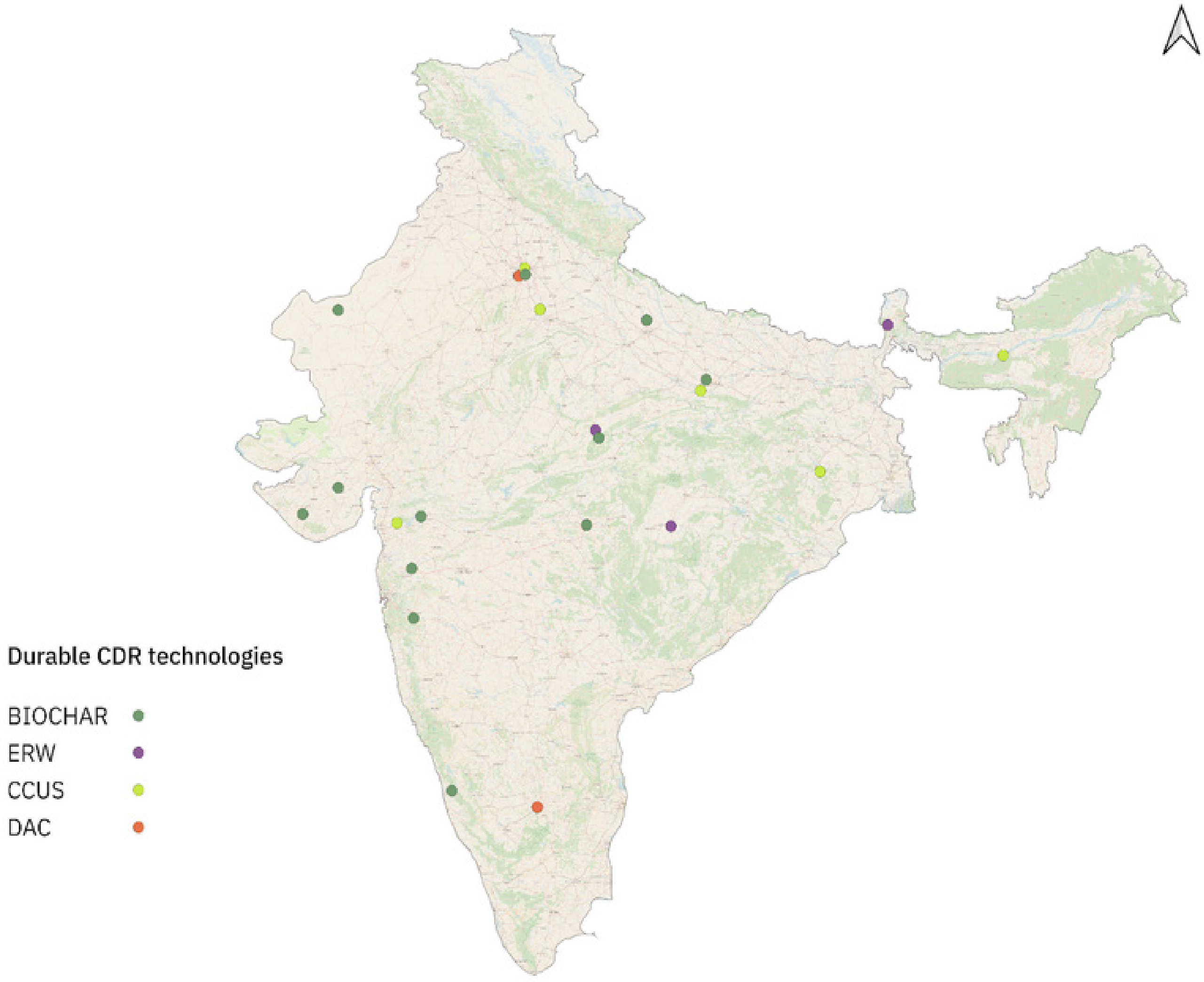
5.3–10 Gt of CO_2

needs to be injected by 2050 to align with 1.5°C targets

One source-sink matching of storage basins by the Global CCS Institute identified that the most suitable storage basins are situated along India's west coast and options for storing emissions from interior regions are more limited and less favourable. These options include using India's old onshore rift basins, employing mineral carbonation in basalts, or transporting emissions to the larger offshore basins (J. Minervini, C. Consoli, D. Kearns, 2021).

Currently, little is known about the potential for CDR in cities, with the majority of organisations and research based in either rural or industrial contexts. While technologies such as Biochar and ERW have potential to be employed in urban environments, our research reveals that presently, they are primarily used in rural areas only. On the other hand, DAC and CCUS are often found in or around industrial settings (urban and peri-urban), given the focus on 'utilising' the captured carbon. Urban CDR is not yet part of city planning; however, there is a considerable scope for incorporating standalone carbon dioxide removal solutions in urban areas (D. Marks, 2023). Further, we see that the storage of captured carbon remains unexplored despite the vast storing potential in the country.

Several start-ups/private organisations are also working on other durable CDR solutions in India. The focus of these projects, however, remains rural or industrial (more details in Annexure).



Base map and data from OpenStreetMap and OpenStreetMap Foundation (CC-BY-SA). © https://www.openstreetmap.org and contributors.
Durable CDR technologies mapping by Transitions Research team based on publicly available data.

Map 1: Spatial distribution of different organisations working on durable CDR in India.

Challenges and Trade-offs

The successful implementation of Durable Carbon Dioxide Removal (CDR) technology in Indian cities requires a comprehensive approach encompassing infrastructure development, substantial financial investments and incentives, and robust policy and regulatory frameworks. However, the present state of durable CDR strategies remains exploratory and faces several challenges:

High Costs And Funding Gaps

Research indicates that carbon capture technologies may need substantial subsidies to be viable (Y. Qiu et al., 2022). NITI Aayog predicts that Rs. 210,000 crores will be necessary to support 750 million tons per annum (mtpa) of Carbon Capture, Utilisation, and Storage (CCUS) by 2050 (A. Mukherjee and S. Chatterjee, 2022). However, most carbon dioxide removal (CDR) technologies are still in the early stages of development.

Biochar and ERW projects are still nascent and not easily scalable because of their high capital expenditures (CapEx), which makes implementation on a large scale difficult. For instance, PyroCCS, an organisation working on Biochar in India, has developed a low-cost pyrolysis machine specifically for the Global South; however, land requirements and consistent availability of raw materials remain prominent factors. There are several factors impacting the durable CDR funding in India:

- The current climate finance arrangements in India are often linked to pre-determined goals and targets (A. Sharma, B. Müller and P. Roy, 2015), such as specific allocations for the eight missions under the National Adaptation Fund for Climate Change (NAFCC) allocates funds specifically for adaptation projects identified within the (SAPCC), which is then dispersed to cities for urban projects aligning with the state's overall mitigation and adaptation goals, leaving little room to adapt to urban centres' priorities and contexts, especially emerging interest in durable CDR. The high upfront costs for establishing durable CDR projects coupled with inadequate financial capacity hinder the scalable deployment of emerging durable CDR technologies in urban India.

- Urban Local Bodies (ULBs) in India, at present, have limited fiscal autonomy due to state control over tax levies, exemptions, borrowing, and inter-governmental transfers; and insufficient revenues (RBI, 2022), making them reliant on grants from the centre and state for 'climate financing'. This also negatively impacts their eligibility for meeting global funding requirements (L. Schalatek, 2024).

- Limited national policy directives guiding CDR deployment and inadequate climate-related funding (M. Thakre, 2024) mechanisms also hinder progress. For example, SEBI requires the ULBs to meet several eligibility criteria for a municipal bond issuance (GIZ 2017). However, most ULBs have a low credit rating and a general lack of awareness (GIZ, 2017) about the concept of green bonds, which hinders their access to municipal bonds that could be useful for a potential CDR carbon market.

In such a scenario, since cities already face budget constraints, they face a difficult choice between investing in emerging durable CDR solutions, which come with no guarantees at this point and have few success stories, or allocating funds to other climate mitigation strategies and urgent infrastructure needs, thus putting durable CDR initiatives on the back burner.

High Energy And Land Demand

Some durable CDR approaches relying on bigger machines, such as DAC and BECCS, demand high land availability and energy inputs. In a country like India, where there is an overall shortage of ~10.1 mn affordable housing units and the cumulative housing demand for Economically Weaker Section (EWS) and Low Income Group (LIG) in urban centres is expected to be 79% by 2030, dedicating land for a technology which has minimal proof of success may not be a top priority for urban decision-makers.

There are a few factors cities must consider while weighing the trade-off between dedicating energy and land resources for basic infrastructure vs emerging technologies:

- Studies project that DAC could amount to annual sequestration of 40 Gt of CO_2; however, the capture efficiency is directly linked to operational efficiency and energy sources, raising concerns about their overall carbon balance unless powered by renewable sources. At the same time, in India, coal is still predicted to meet about 69% of energy demands by 2030, and only a handful of states, including Delhi, Kerala and Gujarat, have managed to maintain a reliable 24x7 power supply (IRES 2020). This raises questions not only about the existing reliability of energy sources and slow transition towards renewable energy sources in urban areas but also about choosing between addressing the current power supply inconsistencies and redirecting energy to nascent, durable CDR methods.

- For instance, the National Thermal Power Corporation (NTPC), Dadri Pilot Project faced operational challenges due to high energy consumption and the cost of retrofitting plants for CO_2 capture. It challenges the existing practices and shows why cities must move away from fossil fuels as they continue moving towards renewable energy sources and durable CDR to truly make a positive impact on the environment.

- Research also suggests that other technological solutions, such as algae-based bioreactors, require enough water, space, and light sources, demanding specific locations for large-scale algae farms. Nevertheless, there are specifically designed algal bioreactors available in the Indian market that can also be established in compact spaces, for example, those used by AgroMorph, making them suitable for urban environments where land is limited. Their vertical growth capability and potential to be installed on rooftops or other structures make them feasible without significant land encroachment. The likelihood of adoption of this technology in urban areas could be high. City water treatment plans, for example, can adopt this technology to reduce the emissions from the wastewater treatment processes.

Policy And Regulatory Barriers

A supportive policy and regulatory environment is crucial for the successful implementation of durable CDR. India currently lacks a clear policy framework and financial incentives for the private sector to commit to large-scale durable CDR projects. Even the Nationally Determined Contributions (NDC) do not acknowledge Carbon, Capture, Storage, and Utilisation (CCUS) despite one of the national targets being increasing the carbon sink by 2.5 - 3 billion metric tons of CO2 equivalent by 2030. This latter goal is mainly tied to the sequestration potential of forest covers.

There are several reasons for why large-scale adoption of durable CDR technologies in India face policy and regulatory barriers at different levels:

- The National Action Plan on Climate Change (NAPCC) focuses heavily on mitigation (Ministry of Environment, Forest and Climate Change NAPCC, 2021) rather than carbon removal. As a result, CDR is often sidelined in State Action Plans on Climate Change (SAPCCs) due to the perceived urgency of mitigation driven by short-term emission reduction targets (E. Gogoi, 'India's State Action Plans on Climate Change: towards meaningful action', 2017). Similarly, urban planning frameworks under missions like the Smart Cities Mission (SCM) prioritise mitigation, such as renewable energy, water management, infrastructural upgrades (Ministry of Housing and Urban Affairs and GIZ India, 2019), etc., and lack long-term climate adaptation and removal components. For instance, waste-to-energy plants in Indore ('Transforming Waste into Wealth with Asia's Largest Bio-CNG Plant', 2024) and Jabalpur ('Efficient Disposal: Jabalpur sets the bar for waste-to-energy conversion', 2020) focus on emission reduction but have not incorporated biochar or other carbon removal techniques into waste management systems.

- Second, the 74th Amendment decentralised governance, enabling Urban Local Bodies (ULBs) to act on local planning issues. However, it does not explicitly mandate climate action, leaving ULBs without a clear role in carbon removal efforts. While a few cities have recently started developing Climate Action Plans (CAP); however, they are typically confined to climate risk assessment, GHG inventories, and strategy recommendations for mitigation and adaptation (P. Langa, S. Dharani, M. Bhaisare, 2024). A focused approach to durable CDR is needed for cities to effectively map the risks and vulnerability of potential CDR projects, which can then be translated into spatial plans, i.e., risk-informed land-use planning and zoning proposals, as well as development control regulations. For instance, CCS projects' infrastructure will likely require interdepartmental coordination, which becomes difficult in absence of set guidelines or policy direction and more so, without common goals.

- The inability to monetise carbon credits further limits the commercial-adoption of durable CDR solutions in different urban sectors. The private sector remains hesitant due to unclear fiscal incentives and the lack of tax credits or carbon trading mechanisms for urban-scale CDR projects. India's Perform, Achieve, Trade (PAT) scheme, designed for industrial energy efficiency, does not extend its carbon trading benefits to CDR initiatives yet although a phased transition (International Carbon Action Partnership, (ICAP), 2022) is expected. However, this regulatory void currently prevents private companies in cities from innovating in durable CDR initiatives.

Uncertain Effectiveness Of Durable CDR

Data gaps and limited success stories make scaling durable CDR extremely challenging. Although various pilot projects are implemented in India and globally, there is insufficient data available in the public domain to do a comprehensive feasibility study. Fragmented efforts due to limited policy support and unclear roles and responsibilities among stakeholders, including the public and private sectors, also exacerbate the existing challenges. For instance, Canada's Boundary Dam Carbon Capture and Storage Project is appalled for paving the way for integrating large-scale post-combustion carbon capture with any coal-fired power station worldwide. However, a recent study done in Saskatchewan showed that while the project aimed to capture 90% of its carbon emissions, it has only achieved a 57% capture rate (B. Weber, 2024), which halted future expansion.

Inadequate Transportation Infrastructure

A significant part of carbon capture and storage (CCS) is the transportation of the captured carbon, which presents various issues. Pipelines are the most efficient transport option; however, there is not enough infrastructure in place at present. Until widespread pipeline deployment is achieved, moving away from fossil-fuel vehicles is essential. Switching to cleaner alternatives such as electrified railways, low-carbon trucks, and advancements in maritime shipping (J. Burger et al., 2024) can help reduce emissions from the transportation stage. This stage still requires proper route-planning to avoid densely populated areas while managing secure transport of the captured carbon.

Raw Material Availability And Operational Issues

India's biochar potential is calculated to be 225 Mt CO_2e per year (D. Lefebvre et al., 2023). However, in the urban context, the availability of raw material - such as tree cuttings or municipal waste biomass- is currently limited and a significant barrier to large-scale implementation of biochar plants in urban centres. Biochar projects in India also face workforce issues since the plant must continue working 24x7; however, there is often an issue with availability of hourly workers despite a good salary. Further, diverse climatic conditions, such as high monsoon rainfall can also increase costs and disrupt carbon sequestration processes.

Health And Safety Concerns

Safety concerns mainly focus on pipelines and tanker ships; however, there are doubts regarding slow leakage of CO_2 from underground reservoirs as well. While container transport presents low injury risks, accidents pose challenges. Exposure to considerable concentrations of CO_2 can cause several health impacts in humans - headache, shortness of breath, dizziness, confusion, hearing and visual impairment, and higher levels of CO_2, are also known to cause asphyxiation within minutes (C. E.H. Barber and S. Perkins, 2024). In 2020, in a village near Mississippi, a CO_2 pipeline rupture (D. Zegart, 2021) led to the evacuation of over 200 people and the hospitalization of 45 people. Although no one died, many victims reported long-term respiratory and neurological problems. There have been several other cases of CO_2 leakage in recent years (V. Bohacikova, 2024). Therefore, preventing leakage across all CCTS stages is crucial and effective leakage management should be a priority for operators.

Carbon Capture v/s Carbon Removal

Carbon capture alone does not always effectively reduce CO_2 levels. When CO_2 is captured and subsequently released back into the atmosphere through CCUS, it results in a 'carbon neutral' outcome rather than a reduction in carbon levels (J. Timperley, 2023). It is not considered a removal if used for activities such as enhanced oil recovery (EOR), synthetic fuels, or in food & beverage production (J. Mota-Nieto, 2024). Furthermore, while capturing emissions from burning fossil fuels with CCS, as seen in post-combustion carbon capture with coal-fired power stations - it prevents those emissions from entering the atmosphere but does not decrease the existing CO_2 levels in the atmosphere (J. Timperley, 2023). Negative emissions are only realised through long-term storage methods.

Policy Response

To begin to address these challenges, India requires a more robust CCUS policy. The government has initiated a Draft CCUS policy and Credit Trading Scheme; however, neither currently incorporates an urban context. NITI Aayog is exploring CCUS as a technology to help decarbonise the industrial sector, focusing on leveraging research centres and the private sector to advance CCUS technologies.

The **Draft CCUS Policy Framework by NITI Aayog** proposes three types of subsidies for storage, utilisation, and Enhanced Oil Recovery (EOR). It also recommends establishing a Carbon Capture Finance Corporation (CCFC) to fund CCUS projects through:

- Clean Energy Cess: levied on coal at a rate of USD 5.3/tonne (Rs. 400 per tonne) starting April 2026 and expected to generate USD 6-7 BB$ (Rs. 48,000 – 53,000 crores) annually.
- Bond and Budgetary Support: Government financing through bonds is estimated to finance the 750 mtpa of CCUS by 2050.

The framework was expected to be finalised by the end of 2024.

India’s Carbon Credit Trading Scheme (CCTS): In June 2023, the Ministry of Power introduced the Carbon Credit Trading Scheme (CCTS), including compliance and voluntary markets. The scheme allows entities to buy, sell or trade credits to offset their emissions.

Policy Recommendations for Advancing durable CDR in Cities

Cities can employ durable CDR methods in different sectors:

- Storing carbon in vegetation - urban forests, parks, street trees, green corridors, and green roofs;
- Biochar soil addition to urban green spaces and green storm-water infrastructure;
- Utilising captured CO_2 in cement manufacturing and construction of new settlements;
- Direct Air Capture through ventilation systems, especially in highly occupied and poorly ventilated buildings where the energy demand for dehumidification can exceed the energy demand for heating/cooling (L. Baus, and S. Nehr, '2022)

At present, India's approach to CDR is largely focused on CCUS - utilising the captured carbon via industries, specifically steel, cement, green hydrogen, manufacturing, and Enhanced Oil Recovery. Collaborative efforts involving government agencies, research institutions, and industry are essential for advancing durable CDR implementation.

The following policy recommendations are crucial for cities to adapt durable CDR technologies:

Policy Alignment

A unified National policy for CDR that aligns various ministries is an important step in India's CDR journey. Additionally, cities should explicitly incorporate durable CDR strategies into their net-zero roadmaps and urban initiatives. This will help integrate the technology into the existing and planned infrastructure (e.g. allocated space for CCS pipelines and storage facilities), industries, and utilities (such as power plants and water treatment facilities) to enable large-scale adoption faster.

Monetisation Of Carbon/Carbon Credits

There is a need for supportive policies that would allow private organisations to monetise carbon credits effectively. The Bureau of Energy Efficiency is working on building the domestic Indian Carbon Market (Bureau of Energy Efficiency, 'Detailed Procedure for Compliance Mechanism under the Indian Carbon Market') over the next few years. It provides an opportunity to incorporate durable CDR-specific incentives (D. Klier, 2024) to promote the adoption of durable carbon dioxide removal. Carbon credits, in particular, allow companies to offset their carbon footprint by purchasing credits from projects that reduce or remove emissions. Research shows that monetising the carbon credits would benefit several businesses and private sector players working on durable CDR projects and increase the technology's adoption at scale.

Our research found that the economic incentives derived from premium biogas and the salable byproducts could motivate urban industries to adopt durable CDR technologies. Cities can generate carbon credits through projects like green roofs, biochar production from organic waste, or carbon capture at municipal facilities. However, ULBs often lack expertise in setting baselines, monitoring, and verification—key requirements for carbon credit certification. Therefore, training and capacity building for ULB officials in green finance mechanisms and carbon market operations is crucial. Further, collaborations with financial institutions or research organisations can help.

Carbon Removal Budget As A Tool

Establishing carbon removal budgets could play a key role in helping policymakers, investors, and project developers to better understand how much carbon removal capacity is needed and by when, what projects and methods should be prioritised (B. Caldecott and I. Johnstone, 2024). Further, separate budgets for emission reduction projects and durable CDR projects is vital for negative emissions in the long-term.

Ensuring Carbon Dioxide Removal Does Not Become An Excuse For Overshoot

It is essential that cities prevent carbon dioxide removal (CDR) from becoming an excuse for overshoot by prioritising carbon emission reduction and capture at source, regularly reassessing climate plans, setting transparent monitoring, reporting, and verification systems for emission reduction and durable CDR projects, and regulate private sector participation/investment to avoid greenwashing.

Research And Development Incentives

Financial support or grants for R&D in carbon dioxide removal technologies and the scale-up infrastructure. Government support through new policies and investments could foster market entry for CDR innovations and attract private-sector funding. The USA, Canada, and Europe are leading the way in showing how investing in CDR-related R&D can provide clarity and stability for the market. R&D organisations can conduct city-specific research to identify potential areas for CDR projects. Indian cities must prioritise practice implementations to ensure research findings influence policy and foster collaboration across private, public, and local agencies.

Fostering Public-Private Partnerships

Partnerships between government agencies, private sector companies, and research institutes to co-develop and co-finance durable CDR projects can expand the reach and impact of durable CDR strategies in India. Canada and Norway are prime examples of leveraging Public-Private Partnerships (K. Monahan, M. Beck, 2023) for infrastructural development, operational upgrades, and monitoring processes related to different carbon-capture plants.

Recognition Of The Algae And Biochar In Urban Settings

Promoting awareness and understanding of the benefits of algae and biochar in environmental applications could foster a more supportive regulatory environment for these solutions.

Facilitating Knowledge-Exchange

Facilitating knowledge exchange on current research and development across different regions of India can help build trust among various stakeholders and foster innovation. It can also help fill the data gaps and conduct broader viability studies to understand the performances of different durable CDR technologies.

Stakeholder Mapping

In order to advance these efforts in cities, the following stakeholders would play key roles:

Stakeholders	Role
Governments and Regulatory Bodies	**National Government:** • Integrating carbon removal targets into NAPCC • Guidelines on financing and implementing durable CDR projects • National guidelines for incorporating durable CDR in City Development Plans and Land use Plans • Govt funding for RD&D projects • Durable CDR-specific subsidies or tax breaks • Connections to Innovators and Investors • Training and Capacity Building programs (on planning and implementing durable CDR projects) for State agencies and ULBs **State Government:** • Translate National CDR policies into SAPCC with urban-specific durable CDR efforts • Knowledge exchange on innovation gaps and RD&D needs • Budget allocation for regional durable CDR projects • Infrastructure development for CO_2 transportation pipelines and vehicle movement • Measurement, monitoring, and verification of durable CDR methods **Urban Local Bodies (ULBs):** • Durable CDR projects and infrastructure integration with Land Use Planning and City Master Plans • Budget allocation and Interdepartmental collaboration for local durable CDR projects • Urban Green Bonds for durable CDR projects • Carbon Budgets to track emission reduction and carbon removal targets • Route planning for CO_2 transportation through vehicles and prioritise carbon-neutral modes • Public-Private Partnerships (PPP) for implementing durable CDR projects • Health and Safety measures for citizens safety • Citizen Awareness and Public Engagement on benefits and potential implications of durable CDR projects

Stakeholders	Role
Research and Development Organisations	• Co-development and testing of methodologies for innovative CDR Technologies • Insights on tech to market strategies • Knowledge exchange on innovation gaps and RD&D needs • Compilation of lessons learned from innovators from durable CDR projects
Industries and Refineries	• Innovators for first-generation CDR Projects • Techno-economic analysis for different durable CDR techniques • Measurement, monitoring, and verification of adapted solutions
Private sector players	• Private-sector funding and/or expertise to scale up CDR Technologies • Explore new applications for byproducts of the decarbonisation process • Cross-promotion of objectives and activities

Conclusion

As Indian cities continue to work towards their net-zero goals, CDR technology can make a substantial difference in the long-term. However, the identified challenges and limitations suggest that the adoption and implementation of durable CDR technology in Indian urban agglomerations require considerable efforts.

Cities must not only navigate the financial requirements for initial investment and the long-term operation costs but also focus on policy support, stakeholder collaborations, and the viability of sector-specific opportunities for CO_2 utilisation. Given that many urban areas are still working on infrastructural investment for decarbonisation efforts, there is a need to align durable CDR technologies parallely with the same efforts.

> The successful implementation of CDR relies on overcoming considerable barriers, including operational and infrastructure limitations, financial constraints, and regulatory hurdles. Retrofitting existing urban infrastructure to accommodate durable CDR technologies is costly, and adoption remains limited without subsidies or clear financial incentives. Durable CDR requires transparent, and practical guidelines. A National policy followed by State-level or City-level guidelines is essential to create a stable base. In addition, stakeholder collaborations and PPP opportunities can help create a conducive environment for CDR adoption and make way for a better future.

Finally, citizen awareness through targeted outreach, workshops, and educational programs is essential to empower people with the knowledge of CDR co-benefits as well as the potential tradeoffs of large-scale project carbon-capture plants.

References

Agrawal, S., et al., 'State of Electricity Access in India - Insights from the India Residential Energy Survey (IRES 2020)', Council on Energy, Environment and Water [report], 2020. https://www.ceew.in/publications/access-to-electricity-availability-and-electrification-percentage-in-india#462

Alfa Laval, 'Cleaner industry with carbon capture', Alfa Laval [document on the web], 2023. https://assets.alfalaval.com/documents/p1fdf25f6/alfa-laval-cleaner-industry-with-carbon-capture-casestory-en-lowres.pdf

Bakshi, T., Mallya, H., and Yadav, D., 'Assessing India's CO_2 Storage Potential - A Critical Analysis of What Lies Beyond the Theoretical Potential', Council on Energy, Environment and Water [report], 2023, https://www.ceew.in/publications/how-can-india-scale-carbon-capture-storage-projects- CO_2-storage-potential-sequestration

Baus, L., and Nehr, S., 'Potentials and limitations of direct air capturing in the built environment', Building and Environment, vol. 208, 2022. https://doi.org/10.1016/j.buildenv.2021.108629

Bellamy, R., Lezaun, J., and Palmer, J., 'Perceptions of Bioenergy with Carbon Capture and Storage in Different Policy Scenarios', Nature Communications, vol. 10, 2019, article 743, https://doi.org/10.1038/s41467-019-08592-5.

Biniek, K., De Luna, P., Di Fiori, L., Stackhouse, B., and Hamilton, A., 'Scaling the CCUS Industry to Achieve Net-Zero Emissions', McKinsey & Company [article], 28 October 2022, https://www.mckinsey.com/industries/oil-and-gas/our-insights/scaling-the-ccus-industry-to-achieve-net-zero-emissions#/

Bohacikova, V., ' CO_2 hazards in Carbon Capture, Utilisation, and Storage (CCUS)', Gexcon [blog], 18th November 2024. https://www.gexcon.com/blog/ CO_2-hazards-in-carbon-capture-utilisation-and-storage-ccus/

Bureau of Energy Efficiency, 'Detailed Procedure for Compliance Mechanism under the Indian Carbon Market', Government of India, 2023, https://beeindia.gov.in/sites/default/files/Draft_Compliance_Procedure_October_2023.pdf

Burger, J., et al., 'Environmental impacts of carbon capture, transport, and storage supply chains: Status and the way forward', International Journal of Greenhouse Gas Control, vol. 132, 2024. https://doi.org/10.1016/j.ijggc.2023.104039

Caldecott, B., and Johnstone, I., 'The Carbon Removal Budget: theory and practice', Carbon Management, vol. 15, issue 1, 2024. https://doi.org/10.1080/17583004.2024.2374515

Climate Seed, 'Carbon Removal Methods Our position and guidance on carbon removal in the VCM', ClimateSeed SAS, 5 September 2023. https://25025637.fs1.hubspotusercontent-eu1.net/hubfs/25025637/Removals%20Guidebook%20-%20CCU_CCS-2.pdf

Crippa, M. et al., 'Global anthropogenic emissions in urban areas: patterns, trends, and challenges', Environ. Res. Lett., vol. 16, no.7, 2021. https://doi.org/10.1088/1748-9326/ac00e2

Crippa, M. et al., 'GHG emissions of all world countries', Publications Office of the European Union, 2024. https://doi.org/10.2760/4002897

Dhanapal, G., Gupta, D., and Prakash, A., 'Barriers and opportunities in achieving climate and sustainable development goals in India: a multilevel analysis', Journal of Integrative Environmental Sciences, vol. 20, issue 1, pp 1–16, 2023. https://doi.org/10.1080/1943815X.2022.2163665

E.H. Barber, C., and Perkins, S., 'What are the health and safety risks of storing our CO_2 forever?', Canada's National Observer [opinion piece], 27 December 2024. https://www.nationalobserver.com/2024/12/22/opinion/health-safety-risks- CO_2-storage

Endjala, M., 'PyroNam plans to set up 50 plants by 2030', WINDHOEK OBSERVER [news article], n.d. https://www.observer24.com.na/pyronam-plans-to-set-up-50-plants-by-2030/

Forrest, N., and Wentworth, J., 'Enhanced rock weathering: Potential UK greenhouse gas removal' The Parliamentary Office of Science and Technology (POST) [research briefing], 15 August 2024. https://doi.org/10.58248/PN726

GIZ, 'Green Municipal Bonds in India: Potential, Barriers and Advantages', Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2017. https://niua.in/csc/assets/pdf/RepositoryData/UP_Green_Cover/GIZ_Green_Municipal_Bonds_eReport.pdf

Glaser, B., Parr, M., Braun, C., and Kopolo, G., 'Biochar is Carbon Negative', Nature Geoscience, vol. 2, 2009, https://doi.org/10.1038/ngeo395.

Global CCS et al., 'CCUS in The Indian Cement Industry Policy & Financing Frameworks', Global CCS Institute, 2024. https://www.globalccsinstitute.com/wp-content/uploads/2024/09/CCUS-India-Cement-Outcome-2-FINAL-06.09-1.pdf

Gogoi, E., 'India's State Action Plans on Climate Change: towards meaningful action', Oxford Policy Management [In depth], 2017. https://www.opml.co.uk/sites/default/files/migrated_bolt_files/id-state-action-plan-climate-india.pdf

Gupta, R., et al., 'Decarbonising India: Charting a pathway for sustainable growth', McKinsey & Company [report], 2023. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/decarbonizing%20india%20charting%20a%20pathway%20for%20sustainable%20growth/decarbonising-india-charting-a-pathway-for-sustainable-growth-full-f.pdf

Hance, J., 'Is ocean iron fertilization back from the dead as a CO_2 removal tool?', Mongabay [blog], 14 November 2023. https://news.mongabay.com/2023/11/is-ocean-iron-fertilization-back-from-the-dead-as-a-co%E2%82%82-removal-tool/

International Biochar Initiative, 'Empowering the Global South with Biochar Carbon Removal', IBI [blog], 11 December 2024. https://biochar-international.org/news/empowering-the-global-south-with-biochar-carbon-removal/

International Carbon Action Partnership, 'Indian Carbon Credit Trading Scheme', International Carbon Action Partnership (ICAP), 2022. https://icapcarbonaction.com/system/files/ets_pdfs/icap-etsmap-factsheet-125.pdf

Klier, D., 'There is No Net Zero Without a High Integrity, Functioning Carbon Market', South Pole [web blog], 25 June 2024 https://www.southpole.com/blog/net-zero-and-high-integrity-functioning-carbon-market#:~:text=Carbon%20markets%20provide%20a%20mechanism,most%20cost%2Deffective%20emission%20reductions

Langa, P., Dharani, S., Bhaisare, M., 'Climate action plans for India's emerging cities', India Development Review [blog], 26 September 2024. https://idronline.org/article/climate-emergency/why-urban-india-needs-climate-action-plans-now/

Lee, H., and Romero, J., 'Section 3: Long-Term Climate and Development Futures in Climate Change 2023: Synthesis Report - Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change', IPCC, pp. 68-89, 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647

Lefebvre, D., et al., 'Biomass residue to carbon dioxide removal: quantifying the global impact of biochar', Biochar - Springer Nature, vol. 5, article 65, 2023. https://doi.org/10.1007/s42773-023-00258-2

Marks, D., 'CDR in the city: are urban areas a 'sleeping giant' for carbon removals?', South Pole [blog], 13 April 2023. https://www.southpole.com/blog/cdr-in-the-city-are-urban-areas-a-sleeping-giant-for-carbon-removals

Mazurek, J., Wang, F., and Plechaty, D., 'The science community says carbon dioxide removal is now essential to limit warming to 1.5° C along with deep decarbonization', ClimateWorks Foundation [blog], 6 April 2022. https://www.climateworks.org/blog/carbon-dioxide-removal-is-now-essential/

Minervini, J., Consoli, C., Kearns, D., 'CCS Networks in The Circular Carbon Economy: Linking Emissions Sources to Geologic Storage SinkS', Global CCS Institute, 2021. https://www.globalccsinstitute.com/wp-content/uploads/2022/03/CCE-CCS-Networks-22-5.pdf

Ministry of Environment, Forest and Climate Change, 'National Action Plan on Climate Change (NAPCC)', Press Information Bureau - Government of India. 2021. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2021/dec/doc202112101.pdf

Ministry of Housing and Urban Affairs and GIZ India, 'Best Practices Compendium: ClimateSmart CITIES', Ministry of Housing and Urban Affairs, Government of India, 2019. https://niua.in/csc/assets/pdf/key-documents/Best-Practices-Compendium-full-version.pdf

Ministry of Jal Shakti, 'Transforming Waste into Wealth with Asia's Largest Bio-CNG Plant', Press Information Bureau - Government of India, 2024. https://pib.gov.in/PressNoteDetails.aspx?NoteId=152161&ModuleId=3&reg=3&lang=1

Monahan, K., Beck, M., Longship Carbon Capture and Storage in Norway's North Sea, The Canadian Climate Institute [case study], 14 February 2023, https://climateinstitute.ca/publications/longship-carbon-capture-and-storage-in-norways-north-sea/#lessons

Morrow, D. R., et al., 'Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy' One Earth, vol. 3, issue 2, pp 150-153, 2020, https://doi.org/10.1016/j.oneear.2020.07.015

Mota-Nieto, J., 'Carbon Dioxide Removal (CDR): A Key Pillar of Carbon Management and Sustainability', The Oxford Institute for Energy Studies, 2024. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/11/Insight-158-Carbon-Dioxide-Removals.pdf

Mukherjee, A., and Chatterjee, S., 'Carbon Capture Utilization and Storage (CCUS) – Policy Framework and Deployment Mechanism in India', NITI Aayog, 2022, https://www.niti.gov.in/sites/default/files/2022-12/CCUS-Report.pdf.

National Academies of Sciences, Engineering, and Medicine, 'A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration', The National Academies Press, 2021. https://doi.org/10.17226/26278.

Pandey, K., 'Indian cities witness a growing momentum for climate action', Mongabay-India's Climate Connections [blog], 6 Sep 2024. https://india.mongabay.com/2024/09/indian-cities-witness-a-growing-momentum-for-climate-action/#:~:text=For%20instance%2C%20in%202018%2D19,million%20tonnes%20for%20that%20period

Parry, E. et al., 'Now the IPCC has recognized that carbon removals are critical to addressing climate change, it's time to act', McKinsey & Company [blog], 10 June 2022. https://www.mckinsey.com/capabilities/sustainability/our-insights/sustainability-blog/now-the-ipcc-has-recognized-that-carbon-removals-are-critical-to-addressing-climate-change-its-time-to-act

Pinto, E., India's Carbon Credit Trading Scheme & the Indian Government's CCUS Report, Global CCS Institute, 2023, https://www.globalccsinstitute.com/wp-content/uploads/2023/07/India%E2%80%99s-Carbon-Credit-Trading-Scheme-the-Indian-Government%E2%80%99s-CCUS-Report.pdf

Pontecorvo, E., 'The World's Biggest Carbon Removal Plant Just Turned 2. So, Uh, Is It Working?', HEATMAP [blog], 31 October 2023. https://heatmap.news/economy/climeworks-orca-data-carbon-removal-direct-air-capture

Pour, N., 'How governments can help finance, build and scale the carbon dioxide removal industry', World Economic Forum, 3 July 2024, https://www.weforum.org/stories/2024/07/why-carbon-dioxide-removal-needs-more-government-support/

Qiu, Y. et al., 'Environmental Trade-Offs of Direct Air Capture Technologies in Climate Change Mitigation Toward 2100', Nature Communications, vol. 13, 2022, article 3635, https://doi.org/10.1038/s41467-022-31146-1.

Renewable Watch, 'Efficient Disposal: Jabalpur sets the bar for waste-to-energy conversion', Renewable Watch [article], 2020. https://renewablewatch.in/2020/10/02/efficient-disposal-2/#:~:text=October%202%2C%202020,of%20the%20city's%20carbon%20emissions

Reserve Bank of India, 'Report on Municipal Finances', RBI, 2022. https://rbidocs.rbi.org.in/rdocs//PublicationReport/Pdfs/RMF10112022428A45038BB44324B9CC0F3D9DBD3F7A.PDF

Ricardo Energy & Environment, 'Analysing the potential of bioenergy with carbon capture in the UK to 2050: Summary for policymakers', Department for Business, Energy and Industrial Strategy, UK [report], 1 August 2020. https://assets.publishing.service.gov.uk/media/5f3fe1f28fa8f55df267bc17/potential-of-bioenergy-with-carbon-capture.pdf

Schalatek, L., 'Green Climate Fund', Climate Finance Fundamentals Series - Climate Funds Update, 2024. https://climatefundsupdate.org/wp-content/uploads/2024/04/CFF11-2024-ENG-GCF-DIGITAL.pdf

Schiermeie, Q., 'Ocean fertilization experiment draws fire', Geoengineering Monitor [blog], 9 January 2009. https://www.geoengineeringmonitor.org/ocean-fertilization-experiment-draws-fire

Sharma, A., Müller, B. and Roy, P., 'Consolidation and devolution of national climate finance - The case of India', European Capacity Building Initiative, 2015. https://oxfordclimatepolicy.org/publications/documents/Consolidation_and_Devolution_final.pdf

Thakre, M., 'Enhancing Access to Urban Climate Finance: Learnings from Four Cities in India, Observer Research Foundation [issue brief], 22 May 2024. https://www.orfonline.org/research/enhancing-access-to-urban-climate-finance-learnings-from-four-cities-in-india

Timperley, J., 'Climate change: Can we really take CO_2 back out the air?', BBC [blog], 21 March 2023. https://www.bbc.com/future/article/20230321-ipcc-the-rising-need-for-negative-emissions

Tiseo, I., 'GHG emissions in India', Statista [Energy & Environment, Emissions], 28 February 2024. https://www.statista.com/topics/8881/emissions-in-india/#editorsPicks

UKRI, 'Greenhouse gas removal with UK agriculture via enhanced rock weathering', UK Research and Innovation (UKRI) [webpage]. https://gtr.ukri.org/projects?ref=BB/V011359/1

UNESCO, 'Iceland: Carbon Capture plant operational', United Nations [blog], n.d. https://unric.org/en/iceland-carbon-capture-plant-operational/

Venkatesh, S., 'Affordable Housing in India', Knight Frank [report], 2024. https://content.knightfrank.com/research/2940/documents/en/affordable-housing-in-india-2024-11745.pdf

Weber, B., 'Saskatchewan's Boundary Dam Carbon Capture Project Underperforms, Report says', BNN

Bloomberg [web blog], 2 May 2024, https://www.bnnbloomberg.ca/business/politics/2024/05/02/saskatchewans-boundary-dam-carbon-capture-project-underperforms-report-says/.

Zegart, D., 'The Gassing Of Satartia', Huffpost [blog], 26 August 2021. https://www.huffpost.com/entry/gassing-satartia-mississippi- CO_2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f
Zhao, X. et al., 'Trade-offs in Land-Based Carbon Removal Measures under 1.5 °C and 2 °C Futures'. Nature Communications, vol. 15, 2024, article 2297. https://doi.org/10.1038/s41467-024-46575-3

Annexure

Table: Organisations working on durable CDR projects in India

Organisations employing these CDR techniques	Technology/ Processes	Urban/Rural Focus	Website
Agromorph Technosolutions Private Limited	CCUS	Urban (Industries)	https://agromorph.com/
Caliche Private Limited	CCUS	Urban (Industries)	https://www.calicheglobal.com/portfolio/carbonone/
Carbon Clean Solutions (CCSL)	CCUS	Urban (Industries)	https://www.carbonclean.com/our-projects
Greengine Environmental Technologies Private Limited	CCUS	Urban (Industries)	https://www.greengine.co.in/
Varahaa	BIOCHAR	Rural	https://www.varaha.earth/
Takachar	BIOCHAR	Rural	https://takachar.com/technology/
MASH Makes	BIOCHAR	Rural	https://www.mashmakes.com/who-are-we
Circonomy	BIOCHAR	Rural	https://www.circonomy.co/about
PyroCCS	BIOCHAR	Rural	https://pyroccs.com/indiaartisan/
AgrocCCS	BIOCHAR	Rural	https://agroccs.com/en
Varhad Capital Pvt Ltd	BIOCHAR	Rural	https://varhad.in/about-us/

Organisations employing these CDR techniques	Technology/ Processes	Urban/Rural Focus	Website
Matterak Technologies	DACU	Urban (Industries)	https://matterak.com/
Climatech Environment	DACU	-	-
Greengine Environmental Technologies Private Limited	DACU	Urban	https://www.greengine.co.in/
Alt Carbon	ERW	Rural	https://www.alt-carbon.com/
Varahaa	ERW	Rural	https://www.varaha.earth/
Mati Carbon	ERW	Rural	https://www.mati.earth/our-work/

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